

Impact response of various concretes at 2.8-second drop shaft

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Abstract. This paper presents experimental testing of various types of concrete under impact loading by using a 2.8-second drop shaft. The drop shaft is located in the *Josef Underground Laboratory* and allows dropping a projectile from 40 meters that results in a maximal velocity of 100 km/h. Three basic types of concrete were used in the framework of this study. This was normal strength concrete, fibre-reinforced concrete, and high-performance fibre-reinforced concrete. The slabs were constructed 1700 mm × 500 mm × 70 mm in size and the clear span of the impacted slab was 1500 mm. Damage of the slab was recorded and the velocity of the projectile was measured with the high-speed camera before and after the impact. It was demonstrated that high-performance fibre-reinforced concrete has a higher ability to absorb and dissipate the kinetic energy of the impact than their lower strength counterparts.

1 Introduction

Concrete is the most widely used building material in the world and is often used for various fortifications. Current research in concrete and concrete structures resulted in the development of high-performance fibre-reinforced concrete (HPFRC) with enhanced strength and toughness, which benefits mainly from the fibre reinforcement. This is particularly advantageous in case of elevated strain rate loading. Elevated strain rate loading is very fast and results in extensive damage because most of the energy is dissipated for the fracture rather than for the deformation of the loaded element. Previous research on the dynamic testing of high-performance fibre-reinforced concrete and foam concrete is described in [5, 6, 7, 8].

Two different loading rates are compared in this study. The first is quasi-static loading and the second is impact loading. The strain rate for quasi-static loading is usually around 10^{-6}s^{-1} and the strain rate for impact loading is usually around 10^2s^{-1} [1]. It is hypothesized that in

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the case of cementitious composites with dispersed reinforcement, the damage can stay more localized and thus not propagate furthermore into the structure.

2 Materials and methods

Three basic types of concrete were used in the framework of this study. Conventionally used concrete was characterised by the standard amount of cement and the usual compressive strength typically achieved for normal strength concrete. Fibre-reinforced concrete was specified by addition of steel macro fibres 30 mm in length that resulted in enhanced ductility. High-performance fibre-reinforced concrete was used because many authors suggest that HPFRC with dispersed fibre reinforcement have a much higher ability to absorb and dissipate the kinetic energy of the impact [2–3]. HPFRC has improved compressive strength and performs strain hardening behaviour in tension. HPFRC was constructed by using fibres both 13 mm and 30 mm in length (Table 1).

Composition of individual mixtures are provided in Table 1. Basic mechanical properties such as compressive strength and modulus of rupture were investigated on cubes 150 mm in size and on prisms 100 mm × 100 mm × 400 mm in size in four-point bending configuration, respectively.

Table 1. Composition relative to cement and mechanical properties of the resulting mixtures.

	NSC	FRC	HPFRC
Cement	1	1	1
Silica fume	0	0	0.12
Water	0.35	0.35	0.27
Aggregate	4.8	3.53	2.52
HRWR	0.01	0.01	0.04
Fibres 13 mm / 30 mm	0 / 0	0 / 0.12	0.09 / 0.09
Compressive strength (MPa)	74.7	73.5	154.2
Modulus of rupture (MPa)	6.2	6.1	13.0
Bulk density (kg/m ³)	2382	2382	2651

Impact resistance was tested in a 2.8-second drop shaft, which is in the *Josef Underground Laboratory* [4] and allows dropping a projectile with a mass of 95.4 kg from the height of 40 meters. This results in the impact energy 36806 J. The projectile used in this study had a quasi-hemispherical nose made of two steel plates welded to the top of the steel cylinder (Fig. 1). The diameter of the projectile was 150 mm and the impact velocities were around 100 km/h (27.8 m/s).



Fig. 1. Details of the 95.4 kg projectile and its positioning on the slab before the test.

The slabs were 1700 mm in length and the clear span was 1500 mm. The width of the slab was 500 mm and the thickness of the slab was 70 mm. The impact process was recorded with two high-speed cameras with sampling frequencies 600 fps and 4000 fps. The projectile was unstrung from the top of the shaft by using a flame to rupture the cable. The flame was used to keep the projectile stable when rupturing the rope. The projectile was falling freely and hit the centre of the slab at the bottom of the shaft with a velocity close to 100 km/h. Two samples for impact were tested for each mixture.

Besides, static loading was performed on slabs with comparable loading configuration. Herein, a point loading was applied in the centre of the slab and load-deflection diagrams were determined (Fig. 2). The deflection was measured in the mid-span on the sides of the slab. The clear span was 1500 mm and the support reactions were constant along the width of the slab, according to the supports provided under the projectile impact.

The plates cracked as is typical for bending under quasi-static loading with one or more cracks for NSC, FRC and HPFRC, respectively, which formed at the bottom surface of the plate. Configuration of the bending experiment and load-deflection diagrams of various concrete under quasi-static loading are shown in Fig. 2. Here, the deflection is plotted as an average from both sides' measurements of the slab at the mid-span of the specimen. The graph shows a significantly higher ductility and stiffness of the HPFRC bent element than its FRC and NSC counterparts. The NSC performed quasi-brittle behaviour. The NSC plate failed right after the crack occurred.

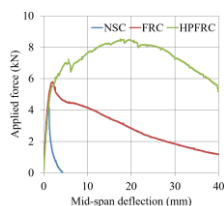


Fig. 2. Quasi-static loading of the slab and its load-deflection response.

3 Discussion of results

Regarding the projectile impact, the penetration of the projectile through the slab is shown in two 3ms steps for individual concretes (Fig. 3). The crack pattern of the NSC, FRC and HPFRC slabs is shown in Fig. 4. Normal strength concrete is a quasi-brittle material, and this resulted in many cracks that divided the slab into many pieces. Fewer cracks and fewer fragments were found in the case of FRC, which is probably the consequence of an increased ductility and so enhanced flexural toughness of the material. The best performance was achieved in the case of HPFRC which performed the highest flexural toughness, compressive strength and resulted in the least cracks between the tested concretes. Improved behaviour benefits mainly from the fine microstructure and dispersed fibre reinforcement which was the main inhibitor of the damage.

The speed of the projectile was recorded during each impact and penetration of the projectile through the concrete plate (Fig. 5). The difference of kinetic energy ΔE_k was determined and it was related to the thickness of the slabs ($\Delta E_k/t$) and it is shown in joules per mm, further termed as K . Furthermore, the diameter of the projectile was considered and the parameter K/ϕ was determined in joules per cubic centimetre (Table 2).

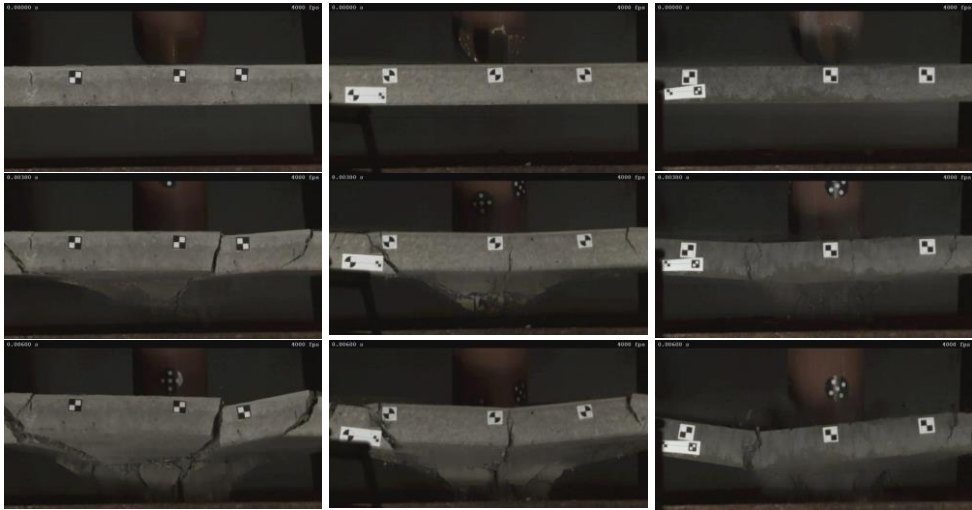


Fig. 3. View on the side of the slabs made of NSC, FRC, and HPFRC during the impact of the projectile in 3 ms time steps.

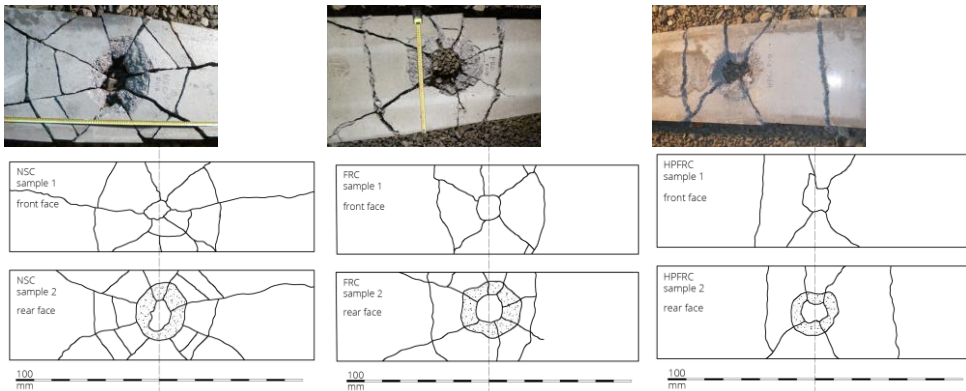


Fig. 4. Photographs of the cratering damage (taken from the rear side) and schematic of the crack pattern of the NSC, FRC and HPFRC slabs from the front and rear side after the projectile impact.

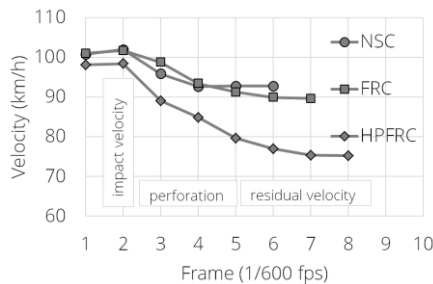


Fig. 5. Velocity of the projectile before (impact velocity) and after (residual velocity) perforation through the concrete slabs.

From the measured velocity and the calculated value of the kinetic energy E_k of the projectile, it can be seen that the HPFRC material has the greatest ability to absorb and dissipate the

kinetic energy of the projectile. This can be demonstrated by the value of K that was determined to be 93 J/mm, 114 J/mm and 199 J/mm for NSC, FRC and HPFRC, respectively. By including the diameter of the projectile in the calculation, the value of K/ϕ^2 was determined to be 4.13 J/cm³, 5.07 J/cm³ and 8.84 J/cm³ for NSC, FRC and HPFRC, respectively (Table 2). From both calculations, it can be seen that the ability of HPFRC to dissipate the kinetic energy of the projectile is more than two times higher than that of NSC and more than 1.7 times higher compared to FRC.

Table 2. Velocity of the projectile before (impact velocity) and after (residual velocity) perforation through the concrete slabs made of NSC, FRC and HPFRC.

	NSC	FRC	HPFRC
Sample 1 - velocity before/after (km/h)	100.6 / 91.5	100.9 / 90.3	99.1 / 79.30
Sample 2 - velocity before/after (km/h)	101.9 / 92.7	101.7 / 89.6	98.4 / 75.25
Impact energy - sample 1/2 (kJ)	37.25 / 38.22	37.47 / 38.07	36.15 / 35.64
ΔE_k - sample 1/2 (kJ)	6.43 / 6.59	7.46 / 8.52	13.00 / 14.80
$\Delta E_k/t$ (K) - average (J/mm)	93	114	199
K/ϕ^2 (J/cm ³)	4.13	5.07	8.84

4 Conclusions

The study presented herein showed the results of the impact resistance of various types of concrete at the 2.8-second drop shaft and demonstrated better energy absorption and dissipation capacity of high-performance fibre-reinforced concrete compared to the conventional fibre-reinforced or normal strength concrete. Enhanced behaviour resulted mainly from dispersed reinforcement which was the main inhibitor of the damage and resulted in higher energy absorption characteristics and less crack development.

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