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Experimental Investigation of Ultra-high Performance Fiber Reinforced Concrete Slabs Subjected to Deformable Projectile Impact

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Abstract

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is currently one of the biggest challenging issues in modern concrete technology. The UHPFRC represents a concrete with improved durability and strength, which is significantly higher than in conventional normal strength concrete. This may result in reduced cross-sections and as a consequence smaller dead-load of the structure. The uniaxial compressive cylinder strength of UHPFRC used in this study exceeded 150 MPa and the uniaxial direct tensile strength exceeded 10 MPa. Several UHPFRC mixtures with different content of fibers were subjected to deformable projectile impact. The ogive-nose projectile weighed 8.04 grams and its average velocity was determined to be 710 m/s. It was shown that plain UHPC specimen failed in the brittle manner which caused that the slab split into several pieces. Further, it was demonstrated that addition of steel micro fibers enhanced the resistance to deformable projectile impact and it was specified that specimens containing 2% of fibers by volume have optimal resistance against impact loading. In addition, response of slabs made of conventional fiber reinforced concrete (FRC) and normal strength concrete (NSC) was studied for comparison. The magnitude of the damage was assessed based on the penetration depth, crater diameter and mass loss. Experimental results clearly showed that implementation of high strength steel micro fibers significantly increased the resistance to projectile impact. It was stated, that UHPFRC has much better resistance to projectile impact in comparison to conventional FRC.

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1. Introduction

Current world events clearly showed that the need to protect government and military structures from improvised explosive devices or direct armed attack has never been greater. The most effective (passive) protection is sufficient stand-off distance followed by the material which can possess great resistance to impact loading. As former provision cannot be fulfilled at all sites, later provision can be provided by new hi-tech materials such as ultra-high performance fiber reinforced concrete (UHPFRC). UHPFRC has outstanding material characteristics such as self-consolidating workability, very high mechanical properties and low permeability which results in excellent environmental resistance [1]. In addition UHPFRC can significantly improve impact resistance of cladding panels and walls while maintaining its standard thicknesses and appearance [2]. To prevent structural collapse, perforation of the projectile and consequential people's injuries, building of strategic importance must possess a much greater resistance to impact loading. It is well known that conventional fiber reinforced concrete (FRC) has good capacity to absorb impact energy [3]. However, several authors suggested that UHPFRC has much greater capability to absorb energy [4-7] and smaller tendency to spalling and scabbing under impact loading.

1.1. Research significance

This paper contributes to the development of UHPFRC and its application in the field where high impact energy absorption capacity is required. Research described in this study is focused on the utilization of the very fine aggregate of maximal diameter size equal to 0.8 mm, very high binder content (1000 kg/m^3) and low water to binder ratio. This may results in the highly resistant concrete elements as cladding panels and walls while maintaining its slender design which do not induce the need for bigger weapons. Projectiles used in this study are chosen in order to simulate high-speed low-weight projectiles which could be formed by the industrial accidents or as an explosion generated fragments.

2. Materials

The UHPFRC mixture was developed from the commonly available components without using any special curing such as heat or pressure. In addition, the mixture was developed using standard laboratory equipment such as food-type and horizontal-pan mixers. High-strength straight fibers (2800 MPa) were used to construct UHPFRC slabs. Fibers were 13 mm long with diameter of 0.15 mm which determines the aspect ratio (l/d) to be 87. UHPFRC slabs were tested on deformable projectile impact in order to find an optimal fiber content. In this way slabs with different fiber content were constructed including 0% (UHPC), 1% (UHPFRC-1), 2% (UHPFRC-2) and 3% (UHPFRC-3) of fiber content (Table 1). Response type, crater diameter and penetration depth were the main factors of damage assessment.

Table 1. Mechanical properties of the mixtures used in this study

	UHPC	UHPFRC-1	UHPFRC-2	UHPFRC-3	NSC	FRC
Fiber content [%]	0	1	2	3	0	0.63
Compressive strength [MPa]	132	149	152	148	43	37
Modulus of elasticity [GPa]	41	45	56	52	36	30
Direct tensile strength [MPa]	6.6	7.8	9.9	10.9	-	-
Flexural strength [MPa]	14	-	30	-	6.2	7.1
Mid-span deflection [mm]	0.31	-	1.36	-	0.16	0.29

In addition, slabs made of Normal Strength Concrete (NSC) and Fiber Reinforced Concrete (FRC) were subjected to the deformable projectile impact as well. FRC slabs were constructed using maximal aggregate size of 8 mm and high tensile (2000 MPa) steel fibers that were 30 mm long with aspect ratio equal to 80. Fibers used for FRC mixture had hooked ends that are generally considered as best form of anchorage. The fiber content in FRC was designed to be 0.63% as the best range of steel fibers with hooked ends lies between 0.5% and 0.75% by volume [3]. Basic mechanical properties of the mixtures used in this study are listed in Table 1.

Compressive strength and modulus of elasticity were tested on cylinders with height of 200 mm and diameter of 100 mm. Flexural strength and corresponding mid-span deflection was determined on prisms 100x100x400 mm in three point bending configuration. Direct tensile strength was tested on dog-bone shaped specimen where the cross-section of the narrow part was 30×30 mm. Detail description of testing and development of the UHPFRC mixture used in this study is described in [8] and [9].

3. Projectile impact

Resistance to impact loading was performed on rectangular slabs with dimensions 300×400 mm and thickness of 50 mm. As the presence of reinforcing bars has negligible effect on perforation resistance of the slabs [10], no reinforcing bars were utilized to construct the specimens. Impact was simulated as a hit of deformable ogive-nose projectile. Distance to the slab was 20 meters and muzzle velocity was measured with a shooting chronograph located approximately 2 meters from the gun muzzle (Fig. 1-a). The weight of the projectile was 124 grains (8.04 g) (Fig. 1-b). The average muzzle velocity was 710 m/s with the average impact energy of 2026 J. In total 12 slabs were tested for impact loading.

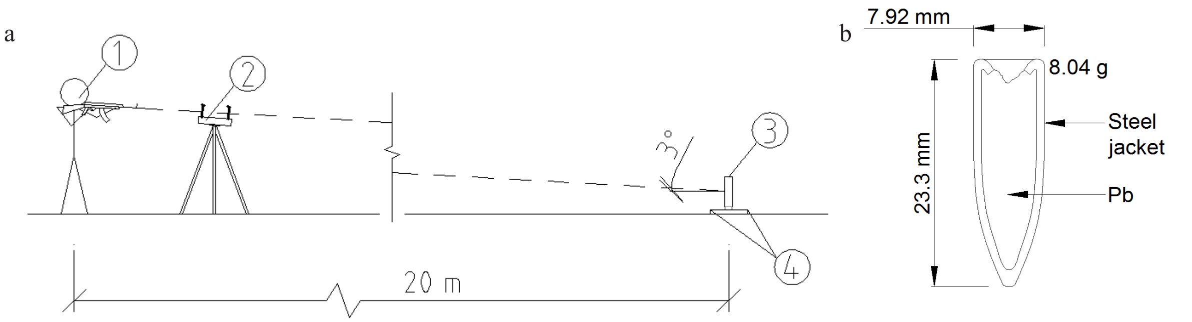

Fig. 1. (a) projectile impact test: 1-shooter, 2-shooting chronograph, 3-slab, 4-fixture for the slab; (b) deformable projectile

4. Results and discussion

The results of the impact tests including response type, crater diameter, penetration depth and mass loss are presented in the Table 2. Values listed in Table 2 were determined as an average value from two specimens. Response type was classified in accordance with the convention used in Vossoughi [11] as perforated - P (the projectile passed through the specimen entirely), perforation limit - PL (projectile was stuck), perforated and then bounced - PB (the projectile went through the slab and then bounced back) and unperforated - UP (panel was punched but the projectile bounced back). Projectile passed through the slab entirely in case of plain UHPC, NSC and FRC whereas all UHPFRC slabs remained unperforated.

Table 2. Response of 50 mm thick slabs to impact loading

	UHPC	UHPFRC-1	UHPFRC-2	UHPFRC-3	NSC	FRC
Fiber content [%]	0	1	2	3	0	0.63
Response type	P	UP	UP	UP	P	P
Crater diameter [mm]	148	85	74	73	74	65
Penetration depth [mm]	50+	20.5	20.0	19.0	50+	50+
Mass loss [g]	-	88	54	110	283	130

Perforation through the slab occurred in the case of UHPC specimen without fibers forming several macrocracks which split the slab into pieces. In case of UHPFRC slabs were not perforated and the projectile bounced back. The average penetration depth was reduced from 20.5 mm to 20.0 mm and 19.0 mm for UHPFRC slabs as the content of fibers increased from 1% to 2% and 3%, respectively. Therefore, it is evident that increasing the fiber content beyond 1% has only minor effect on penetration depth. The crater diameters in UHPFRC mixtures were 42-50% smaller than those in plain UHPC mixtures (i.e. 0% of fibers). The results showed, that the implementation of fibers reduced the crater diameter significantly, however increase of fiber content beyond 2% by volume had no further effect on crater diameter.

NSC specimen was perforated entirely and, in addition, vertical macrocrack propagated through the specimen splitting the slab into two pieces. FRC was perforated entirely as well, however, specimen remained unbroken performing roughly half mass loss compared to NSC.

5. Conclusions and further outlook

The experimental results revealed that the UHPC slabs are much more fragile than their NSC counterparts due to their higher compressive strength. Macrocracks propagated through the UHPC specimen under the projectile impact which caused that the slab split into several pieces.

Addition of high strength steel fibers to the mixture enhanced the impact behavior in terms of penetration depth compared to their plain concrete counterparts. However, any further increase of the fiber content beyond 1% had no significant effect on penetration depth of the projectile.

UHPFRC slabs tend to decrease the crater diameters by 42 to 50% than their plain UHPC counterparts. Nevertheless, further increase of fiber content beyond 2% had no effect on reducing the crater diameter, as diameter of the crater tends to remain constant within 2% and 3% of fiber content.

Based on the previous results it was found that the addition of high-strength fibers enhanced the resistance to impact loading. It was also found that the optimal amount of fiber content with respect to the mechanical properties and resistance to deformable projectile impact lies around 2% by volume.

It was verified that UHPFRC has much greater resistance to impact loading compared to conventional FRC also in terms of spalling and scabbing. The back side of the UHPFRC slabs remained compact, which decreased the mass loss significantly. 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.

Further refinement of fiber content to 0.5%, 1.5% and 2.5 % is needed to precise the optimal fiber content with respect to impact loading. Assessment of the residual energy of the projectile after non-deformable projectile perforation through the ultra-thin (40-45 mm) UHPFRC slab is also desirable.

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Appendix A. Pictures of the damage

Figures presented herein depict typical post-tests damage of the front and back side of the NSC, FRC, UHPC and UHPFRC-2 slabs, respectively. Concrete slabs were placed in the special fixture developed for the purpose of this study in order to prevent movement of the specimen during impact loading. The fixture was provided with four screws located in the corner of the specimen approximately 50 mm from the edges in order to simulate point supports.

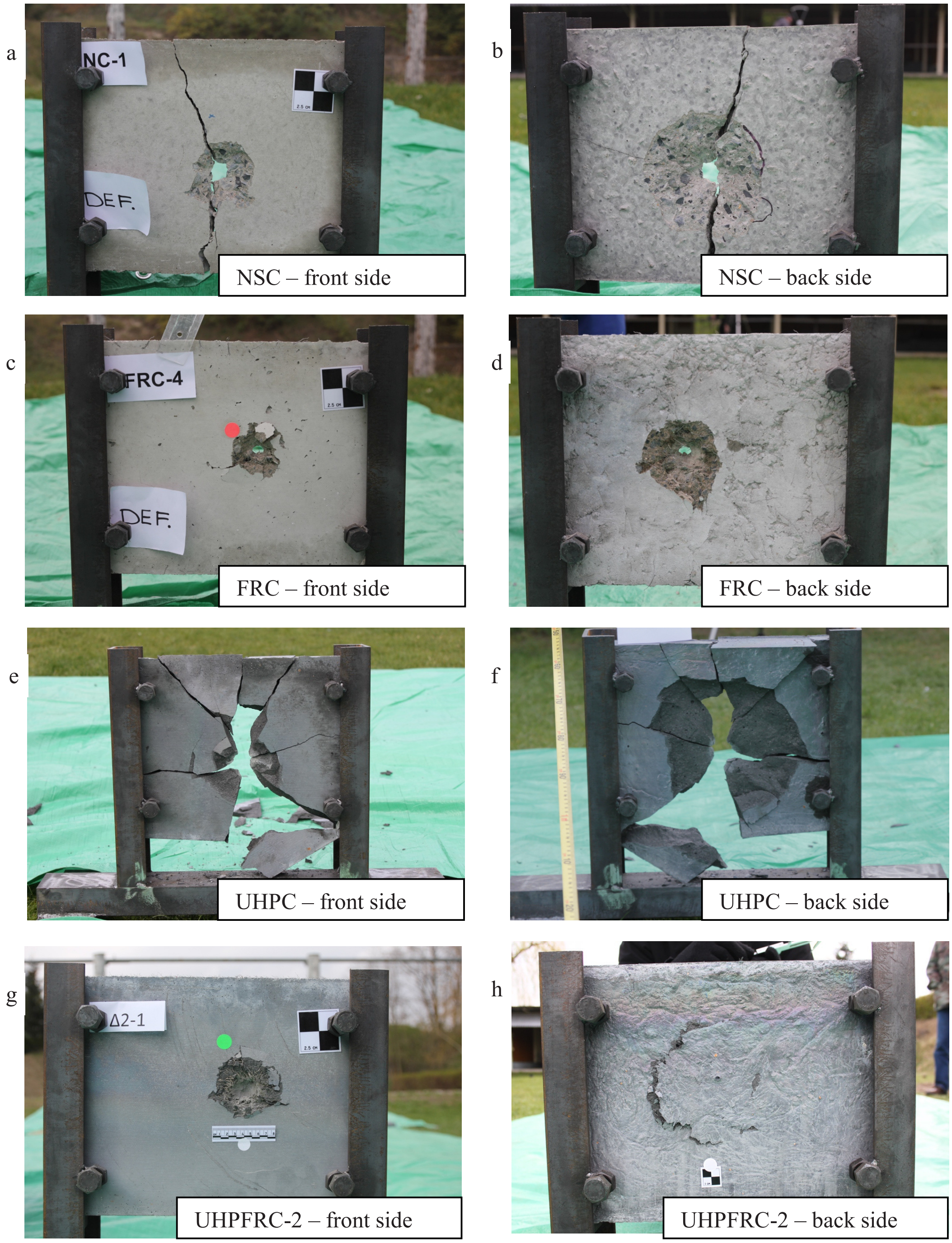

Fig. 2. Pictures of damage (a), (b), (c), (d), (e), (f), (g), (h)