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Mix design of UHPFRC and its response to projectile impact

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ABSTRACT

The aim of this paper is to describe mix design of Ultra High Performance Fiber Reinforced Concrete (UHPFRC) and its response to deformable and non-deformable projectile impact. UHPFRC represents a class of cementitious composite in which stress–strain response in tension undergoes strain hardening behaviour accompanied by multiple cracking, leading to a high strain prior to failure. The compressive strength of the resulting UHPFRC mixtures exceeded 130 MPa and direct tensile strength was in the range of 10 MPa. Several UHPFRC mixtures with different content of fibers were subjected to deformable projectile impact. It was found that specimens containing 2% of fibers by volume have optimal resistance against deformable projectile impact. Slabs containing 2% of fibers were further subjected to a non-deformable projectile impact. In addition, response of slabs made of traditional fiber reinforced concrete (FRC) is discussed. The magnitude of the damage was assessed based on the penetration depth, crater diameter and loss of mass.

1. Introduction

Increasing requirements for durability, safety and security of concrete structures push its development still further. 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 fiber reinforced concrete (UHPFRC) are ideal for applications where high compressive and tensile strength, small thickness and high energy absorption capacity are required. For instance, the utilization of high strength concrete allowed construction of many skyscrapers around the world. In addition, UHPFRC significantly improves blast resistance of cladding panels and walls while maintaining its standard thicknesses and appearance [1].

UHPFRC can be characterized as a composite containing large volume of steel fibers, 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 [3]. Typical strengths are 150–200 MPa in compression and 7–15 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 and smaller spalling and scabbing under impact loading. Improved resistance to impact loading in terms of penetration depth and crater diameter can be achieved through decreased water-to-cement ratio and increased concrete compressive strength. Addition of steel fibers to the mixture tends to reduce the crater diameter while it has no significant effect on penetration depth [8].

To prevent structural collapse and people's injuries (Fig. 1), high-rise structures from high strength materials must possess a much greater resistance to impact loading. It is well known that traditional fiber reinforced concrete (FRC) with normal strength matrix and aggregate size equivalent to the projectile diameter has large capacity to absorb energy [9]. However, several authors [6,7,10,11] suggest that UHPFRC has much greater capability to absorb energy both in quasi-static and dynamic loading.

This paper describes both formulation of UHPFRC mixture and measurement of its mechanical properties. In addition, resistance of UHPFRC to impact loading was determined using impact of deformable and non-deformable projectile on thin slabs. A steel-jacketed projectiles (both 8.04 g) were used with average muzzle velocity of 710 m/s. These types of projectiles are supposed to cover most of the load caused by small arms [12].

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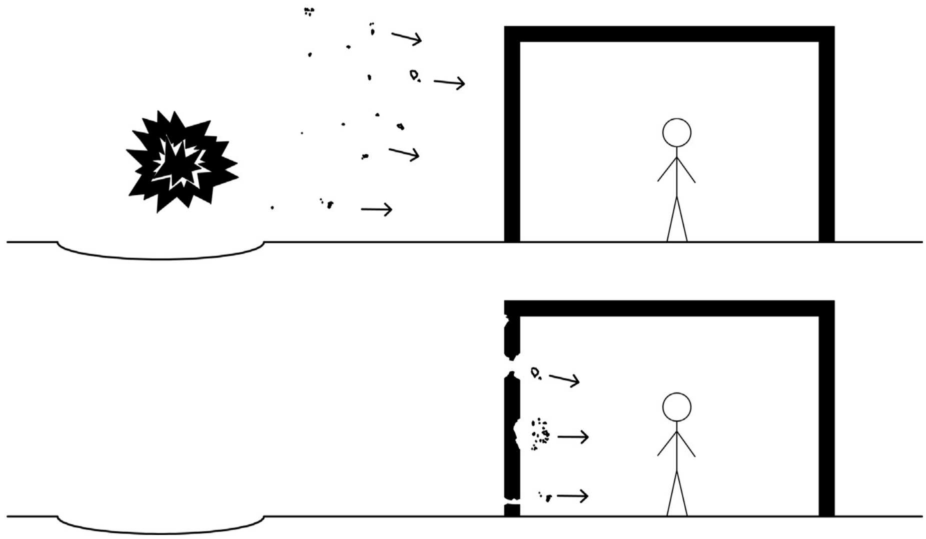

Fig. 1. Explosion-generated projectiles.

2. Mixture optimization

2.1. Mix design and sample preparation

During the mixing of UHPC, it is very important to achieve good workability, particle distribution and packing density. In comparison to normal strength concrete, UHPC contains more constituents and finer particles. Several researchers recommend [6,13,14] to mix all fine dry particles first before adding water and high-range water reducer (HRWR). It is because small particles tend to agglomerate and it is easier to break these chunks when the particles are dry. The specific mixing procedure was as follows: In the first step both types of aggregate (A) and silica fume (SF) were mixed for 5 min. In the second step cement (C) and glass powder (GP) were mixed for another 5 min. At the end of the procedure water and HRWR were added. The addition of HRWR was gradual. The mixture became fully workable after another 5 min.

In case of UHPFRC fibers were added gradually into the flowable mixture to avoid chunks formation during additional 5 min of mixing. The shear action of fibers helped to destroy any remaining agglomerates in the mixture, thus improving workability. The total mixing time was 15 min for UHPC mixtures and 20 min for UHPFRC. A horizontal, low rotation speed mixer with a capacity of 50 l was used to prepare the samples.

2.2. Cementitious matrix design and optimization

In the first phase of the research, several concrete mixtures without fibers were produced to find the best combination of constituents with respect to maximal compressive strength and workability. High particle packing density is a key property of ultra-high compressive strength of concrete. Therefore the mixture design was based on optimizing the particle packing density of S, SF, GP and C as well as alternating various sand fractions. In total 24 mixture designs were tested. Flexural strength was evaluated on 40 × 40 × 160 mm prisms and compressive strength was determined on the halves of these prisms following CSN EN 1015-11. Workability was tested according to CSN EN 1015-3 using standard flow-table test.

The first mixture was designed following the proportions of C:SF:GP recommended by Wille et al. [2] as 1:0.25:0.25 with a water-binder (w/b) ratio of 0.2. Subsequent changes in the most important parameters such as HRWR, water, amount of A, SF, and GP led to an optimized cementitious matrix in terms of compressive strength and workability. From the 24 tested mixtures, two best performing cementitious matrix compositions denoted as UHPC2 and UHPC3 are shown in Table 1 along with the first starting mixture (UHPC1). Table 1 also shows basic material properties of the selected mixtures. In the average spread row a diameter of paste spread measured after filling and removing the standard cone and impacting the table 15 times is compared.

2.3. Fiber addition

In the second step of the optimization process straight steel fibers were added up to 3% of volume in replacement of the equivalent volume of coarser sand to the best performing mixture i.e. UHPC3 and forming UHPFRC 3 mixtures. Straight fibers were used because it is known that they provide a good trade-off between tensile properties and workability of the composite [13]. The fibers were 13 mm long with a diameter of 0.15 mm and tensile strength of 2800 MPa. Mixture proportions can be found in Table 2. The second number after the type of matrix denotes the fiber content by volume. For instance UHPFRC 3-2 means mixture containing 2% of fibers which is based on the UHPC 3 matrix design. The mixing procedure was the same as for previous samples. For each mixture (UHPC 3, UHPFRC 3-1, UHPFRC 3-2, UHPFRC 3-3) three cylinders with a diameter of 100 mm and height of 200 mm, three dog-bone

Table 1
Design of mixtures without fibers.

Type of component	UHPC1	UHPC2	UHPC3
	Proportions by weight		
(C) Cement CEM I 52,5R	1	1	1
(SF) Silica fume	0.25	0.25	0.25
(GP) Glass powder	0.25	0.25	0.25
(W) Water	0.25	0.22	0.22
(HRWR): Sika SVC 20 Gold	0.050	–	0.031
(HRWR): Sika ViscoCrete 20He	–	–	0.019
(HRWR): Sika ViscoCrete 30He	–	0.025	–
(HRWR): Sika ViscoCrete 1035	–	0.025	–
(A) Fine sand 0.1/0.6 mm	0.42	0.42	0.42
(A) Fine sand 0.3/0.8 mm	1	1	1
(w/b) Water/binder ratio	0.2	0.176	0.176
Average spread (workability) [mm]	140	150	150
Avg. compr. strength [MPa]	110.0	132.2	141.9
Avg. flexural. strength [MPa]	17.6	20.8	22.1