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RESEARCH ARTICLE

Mechanical properties and impact resistance of concrete composites with hybrid steel fibers

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ABSTRACT The aim of this study is to develop concrete composites that are resistant to armor-piercing projectiles for defense structures. Different reinforcement configurations have been tested, such as short steel fibers, long steel fibers, and steel mesh reinforcement. Three different concrete mix designs were prepared as “Ultra High Performance (UHPFRC), High Performance (HPFRC) and Conventional (CFRC) Fiber Reinforced Concrete”. The content of hybrid steel fibers was approximately 5% in the UHPFRC and HPFRC mixtures, while the steel fiber content was approximately 2.5% in the CFRC mixture. In addition, a plain state of each mixture was produced. Mechanical properties of concrete were determined in experimental studies. In addition to the fracture energy and impact strength, two important indicators of ballistic performance of concrete are examined, which are the penetration depth and damage area. The results of the study show that the depth of penetration in UHPFRC was around 35% less than that in HPFRC. It was determined that the mixtures of UHPFRC and HPFRC containing 5% by volume of hybrid steel fibers showed superior performance (smaller crater diameter and the less projectile penetration depth) against armor-piercing projectiles in ballistic tests and could be used in defense structures.

KEYWORDS projectile impact, depth of penetration, fracture energy, crater diameter, UHPFRC

1 Introduction

Impact resistance is defined as the resistance of concrete to sudden repeated dynamic loads. High impact resistance is required in structures such as military buildings, water structures, landfill concrete constructions, railway sleepers, airport runways and structural elements exposed to explosives [1]. High Strength Concrete (HSC) has been used in military structures for a long time due to its superior strength properties. However, HSCs are brittle and energy absorption under impact is relatively low [2]. A protective material or structure is expected to have certain properties as strength, durability, and high energy absorption under impact [3,4]. To consider the ductility and impact resistance of HSCs, a certain amount of fiber is added to them [5–12]. It effectively reduces the crater diameter as the fibers can hold the concrete together and bridge cracks [13]. However, increasing the amount of steel fiber does not have a significant effect on the penetration depth of the projectile [14]. To reduce the penetration depth, it is necessary to increase both ductility and the compressive strength of the concrete [13]. Moreover, Clifton and Knab [15] stated that conventional reinforcement used in concrete had a significant effect on reducing the damage area caused by impact. To enhance the ballistic performance of concrete used in military structures, Ultra High Performance Fiber Reinforced Concrete (UHPFRC) can be used [16]. UHPFRCs have a much higher strength (compressive strength ⩾150 MPa), durability, and long-term stability performance compared to HSC. Liu [16] stated that due to the high cost of steel fibers, UHPFRC can reduce its cost in military and

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construction structures with alternatives and presented some studies in UHPFRC to replace the relatively low-cost steel mesh with steel fibers. In addition, Habel [17] used UHPFRC as an overlay material to increase the performance of reinforced concrete products and post-tensioned elements for projectile impact [17]. Costs can also be reduced by using UHPFRC as a coating material on the surface of the defense structures. On the other hand, studies are made with carbon, basalt, polymeric and natural fibers, alone or as hybrids in such concrete, in addition to steel fibers [18].

An important issue to consider for the ballistic performance of concrete under the effect of high-speed projectiles is that damage will not only be related to characteristics or dimensions of the material of the target. Factors such as mass, velocity, material properties and geometry of the projectile also affect the magnitude of the damage caused by the impact test [13]. In this context, there are many impact tests performed on test target material made of concrete with different characteristics and dimensions and using different weapons and projectiles. Using the data obtained from these tests, several empirical formulas have been developed for the effect of the impact load on the concrete. Moreover, a number of modeling programs based on the analysis method (finite element) for the dynamic behavior of concrete under impact are used in the tests [19,20]. In addition, some numerical modeling studies are performed to fully understand the failure mechanisms under impact loading [21].

Yu et al. [22] evaluated the fracture energy in the semi-static mode and high velocity projectiles on UHPFRC, by using high-speed projectile impact tests and bending tests, respectively. The results showed that the use of hybrid steel fiber increased the mechanical strength of UHPFRC, while hook-end steel fibers were more effective in increasing the fracture energy of UHPFRC, as expected. However, high-speed projectile impact tests showed that UHPFRC with hybrid steel fibers exhibits a higher energy absorption capacity and increases performance against scabbing, particularly on the rear surface of the target. As a result, it was found that the projectile effect occurred in a very short time (milliseconds) in contrast to the semi-static test and only regional damage occurred in the UHPFRC target. It is stated that the stress is distributed more homogeneously by using hybrid steel fibers, and the growth of the crack is prevented and consequently the damage area is effectively limited [22]. Máca et al. [23] showed that by using UHPFRC, the fibers do not have a significant effect on the penetration depth but play an important role in reducing the crater diameter. They also stated that optimum fiber content should be between 2% and 3% by volume with consideration for the strength, workability, and projectile resistance of UHPFRC [24]. Maalej et al. [25] similarly stated that the use of hybrid fibers in Engineered Cementitious Composite (ECC) panels increases the resistance against scabbing and spalling compared to normal concrete but has no effect on penetration depth [25]. The mechanical properties of concrete composites increase with steel fiber addition. Yu et al. [26] used particle packaging programs in their study for a denser internal structure and added short and long steel fibers to the mixture. As a result, they determined that by using long fibers, concrete with lower cement dosage and higher impact strength can be produced [26]. In addition to steel fibers, some synthetic fibers, basalt fibers and polyvinyl alcohol fibers can also be used in concrete to improve the impact resistance and other mechanical properties of concrete [27,28]. In the study conducted by Nam et al. [29], the impact resistances of Fiber Reinforced Concrete (FRC) composites and plain concrete were examined. Under the impact of the bullet, fragments of the flat concrete specimen were widely scattered. However, the fragments of their fiber-reinforced samples were dispersed in a much smaller area. They also showed that the fibers play an important role in controlling the local damage of FRCs [29]. In addition, more research is being carried out on new types of concrete composite with superior resistance to impact effects. The production of this composite consists of two stages. The first stage involves packing the fibers and coarse aggregate into the empty mold in a specific way. In the second stage, the gaps between them are filled by injecting cement mortar. Thus, composites with improved impact resistance can be obtained [30]. Haridharan et al. [31] carried out some studies on this new type of concrete with improved impact resistance. In their study, they laid Glass Fiber Mesh (GFM) and Textile Fiber Mesh (TFM) of different diameters between the steel fiber reinforced concrete layers. As a result, they stated that the GFM and TFM placed between the layers increase the impact resistance, but the most significant effect to impact resistance is attributed to the high strength 5D hooked-end steel fibers used in the concrete composite [31].

In addition, it is not sufficient to determine the compressive strength alone for the depth of penetration. Determination of the effective hardness index and modulus of elasticity are two other important parameters for the depth of penetration [32]. In addition, Li et al. [33] stated that steel fibers are indispensable in defensive concrete composites and that fibers play an important role in impact resistance in UHPFRC. In the study, two different types of steel fibers were used considering both the crack prevention and bullet penetration properties of the concrete. 13 mm steel fibers performed better than those with 30 mm hook ends [33].

The main aim of this study is to determine more clearly the relationship between the behavior of concrete under projectile impact and the mechanical properties of the concrete. It is known that improving the fracture energy and impact strength properties of concrete increases the resistance of concrete against the projectile impact. In literature, there are many studies on the impact strength of concrete against projectiles. However, the mechanism of action of the impact created by the projectile, unlike other impact tests, takes place in a much smaller area. The ballistic performance of the systems in which the concrete properties are improved at every point, (using short fibers in addition to long fibers) has not been adequately examined. In addition, there are also limited studies on the effects of using only mesh reinforcement without fiber on the ballistic performance of concrete. In this study, the performance of the systems containing long fibers, and the effect of the addition of short fibers and steel mesh reinforcement, was determined in detail. In order to determine the effect of increasing the fiber content, concrete containing 5% fiber by volume and 2.5% fiber was produced, and the effect on ballistic behavior parameters was investigated. The correlations between the mechanical strength and ballistic behavior in the projectile impact of concrete are also presented.

2 Experimental work

2.1 Materials and mix designs

The notations of the various concretes produced are as follows: U (ultra), H (high), P (performance), S (strength), F (fiber), R (reinforced), N (normal) and C (concrete). In this study, the first three different mix designs, UHPFRC, HPFRC, and CFRC, were prepared. The water/binder ratio of UHPFRC, HPFRC and CFRC were selected as 0.18, 0.24, and 0.37, respectively. Silica fume (SF) was used in the UHPFRC mixture and ground granulated blast furnace slag (GGBS) was used in the HPFRC mixture. In UHPFRC and HPFRC mixtures, two different types of steel fibers; 2.5% hooked-end steel fibers and 2.5% straight steel fibers, were used for a total volume 5% (400 kg/m^3). In CFRC mixture, 2.5% (200 kg/m^3) of steel fiber with a hooked-end type was used. Thus, three steel fiber reinforced concrete mixtures were produced in the study. The properties of the utilized fibers are presented in Table 1.

Furthermore, three plain versions of these mixtures having the same matrices without steel fiber were also produced. Compositions of all concrete mixtures are given in Table 2.

2.2 Specimen preparation

Aggregates, cement and mineral admixtures were blended first in dry condition. Then, water and superplasticizer were added into the mix. Finally, the steel fibers were added to the mixture. With the addition of high volume steel fibers, the flowability of the concrete decreased. For this reason, the concrete was poured into the steel moulds using a vibration table. All samples were demoulded within 24 hours and kept in a water tank at (20 ± 2) °C until 28 d of age. The testing of compressive strength, bending strength, splitting tensile strength, three-point bending test, and drop weight reduction test were conducted on all produced concrete series to determine impact resistance. The dimensions of the samples and the tests performed are presented in Table 3. At least four specimens for each mixture were prepared for the tests.

For the ballistic tests, concrete plates of 500 mm × 500 mm width and 80 mm thickness were produced from all concrete mixtures. All plates were prepared from NSC, CFRC, HSC, HPFRC, UHSC and UHPFRC mixtures and then they were reinforced with 3 mm diameter and 25 mm × 25 mm 3-layer steel wire meshes. The tensile strength of the wire mesh reinforcement is 500 MPa.

2.3 Fracture test

The bending test was carried out using beam samples of 100 mm × 100 mm × 500 mm as three point bending tests. For plain concrete, the displacement velocity in the middle of the beam sample was kept constant at 0.01 mm/min. In beams containing steel fiber, the test speed was carried out with a displacement velocity of 0.0175 mm/min until 0.5 mm deflection and then with a rate of 0.1 mm/min until 4 mm deflection. The load was applied using a test device with a capacity of 200 kN. Deviations were measured simultaneously with two Linear Variable Displacement Converters (LVDTs) and averaged over these measurements. The notch to depth ratios (a/D) of specimens were 0.40. The effective cross-section was reduced to 100 mm × 60 mm and the length of the support span was 400 mm. Crack stability for unreinforced concrete was achieved using the crack mouth opening displacement (CMOD) as a feedback variable.

Load-displacement curves were obtained for each beam, taking into account the displacements obtained from the beam mid-span. The fracture energy (G_F) of

Table 1 The properties of hooked-end and straight fibers

type of steel fiber	parameters			
	tensile strength (N/mm^2)	diameter d (mm)	length L (mm)	aspect ratio L/d
normal strength steel fiber (hooked-end)	1100	0.55	30	55
high strength steel fiber (straight)	2250	0.16	6	40

Table 2 Composition of normal, high and ultra high strength/performance concretes

materials	NSC/ CFRC	HSC/ HPFRC	UHSC/ UHPFRC
cement (kg/m^3)	500	800	1000
silica fume (kg/m^3)	–	–	250
GGBS (kg/m^3)	–	200	–
water (kg/m^3)	175	216	120
siliceous powder (0–0.5 mm) (kg/m^3)	–	–	330
siliceous sand (0.5–2 mm) (kg/m^3)	–	–	510
natural sand (0–4 mm) (kg/m^3)	515	568	–
crushed sand (0–5 mm) (kg/m^3)	480	568	–
crushed stone (5–12 mm) (kg/m^3)	820	–	–
superplasticizer (kg/m^3)	8.0	30.0	125
water/cement	0.36	0.30	0.22
water/binder	0.36	0.24	0.18
unit weight (kg/m^3)	2498/2698	2382/2782	2335/2735

Note: The amount of water from the superplasticizer admixture was taken into account in determining the water/cement and water/binder ratio. Unit weights are given as plain and steel fiber reinforced mixtures, respectively.

Table 3 Size of specimens and test types

test type	parameters	specimen	dimensions (mm)
compressive strength	f'_c (MPa)	cube	h100
splitting tensile strength	f_{spt} (MPa)	disc	Ø150, h60
flexural strength	f_{flex} (MPa), G_F(N/m)	beam	100 × 100 × 500
impact strength	I_R(kNmm)	disc	Ø150, h64

Notes: f'_c: compressive strength, f_{spt}: splitting tensile strength, f_{flex}: flexural strength, G_F: fracture energy, I_R: impact resistance

concrete was determined using the area under the load-displacement curve (W_0) with the help of the equation given below by RILEM [34]. In this study, since there were also plain concrete samples, a displacement of 4 mm was selected to calculate the fracture energies of UHPFRC, HPFRC, and CFRC.

$$G_F = \frac{W_0 + mg\dfrac{S}{L}\delta_s}{B(D-a)}. \tag{1}$$

In this equation, m, L, S, a, D, B are the mass, length, span, notch depth, depth, and width of the beam, respectively. W_0 is the area under the load displacement curve, g is the gravitational acceleration, and δ_s is the deflection of the beam specified for this study in 4 mm.

2.4 Impact test

Although there are various methods to determine the impact strength of concrete, one of the most preferred methods is the weight drop impact test. A schematic representation of the apparatus developed for this test is given in Fig. 1.

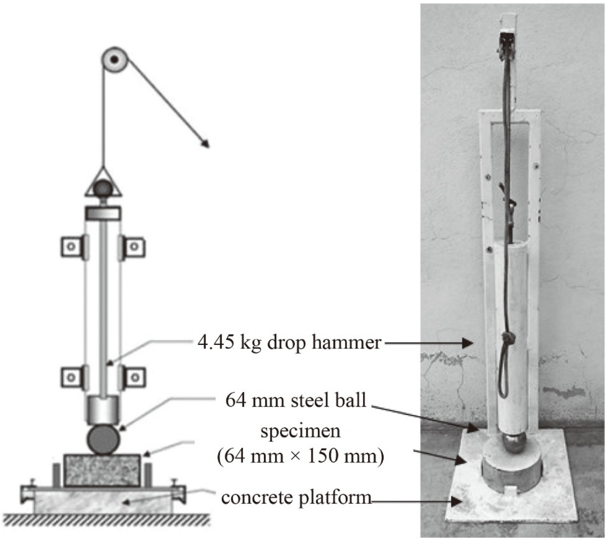

Fig. 1 Schematic representation of the drop weight impact test.

The principles of the drop weight impact test are given in detail in the ACI 544.2R standard [35]. According to the standard, the test is based on the principle of dropping a load of 44.5 N from a height of 457 mm on a steel ball with a diameter of 64 mm placed on a disk sample of 64 mm × 150 mm. Each time a drop occurs on the sample, impact energy of 20.36 N·m is absorbed. The hammer is dropped repeatedly until the sample fractured. The total number of impacts is determined as the impact energy of the sample.

2.5 Ballistic tests

For the ballistic tests, concrete plates of 500 mm × 500 mm width and 80 mm thickness were produced from all concrete mixtures. All tests were carried out using armor-piercing projectiles for the BR7 protection level [36]. The characteristics of the projectile used in the tests are 7.62 mm × 51 mm caliber, full copper jacket steel hard core and 810 to 830 m/s velocity range. Plates were tested on the same target plate in 3 shots with a distance of 120 mm between each shot point. The projectiles were fired at a distance of 10 meters from the target plate. When the projectile penetrated the rear surfaces of the plates, three shots were not required. All plates were prepared from NSC, CFRC, HSC, HPFRC, UHSC and UHPFRC mixtures and then they were reinforced with 3 mm diameter and 25 mm × 25 mm 3-layer steel wire meshes. Then high-velocity projectile impact tests were carried out on plates. After the projectile impact test, images of the plates were captured.

3 Experimental results

3.1 Mechanical, fracture, and impact test results

Test results for mechanical properties are given in Table 4.

Table 4 Fracture and strength properties of fiber reinforced and plain concrete

mix code	compressive strength, f_c' (MPa)		splitting tensile strength, f_{spt} (MPa)		flexural strength, f_{flex} (MPa)		fracture energy, G_F (N/m)		impact strength, I_R (N·m)	
	mean value	SD	mean value	SD	mean value	SD	mean value	SD	mean value	SD
NSC	51.3	2.1	5.7	0.3	5.8	0.2	68	10	41	–
CFRC	53.5	2.3	10.1	0.5	19.2	1.3	6642	521	9549	3255
HSC	84.8	3.2	6.8	0.2	8.1	0.5	70	13	81	–
HPFRC	116.9	2.9	13.1	0.7	26.6	2.1	9953	752	67840	21709
UHSC	105.6	3.5	8.2	0.6	11.2	0.9	82	11	102	–
UHPFRC	163.1	4.7	18.3	1.1	38.8	2.4	14463	1127	*	–

*Note: No cracks were observed in the drop weight impact test of UHPFRC specimens after 5000 blows. Therefore, the test was discontinued. (SD: Standard deviation)

It is shown that steel fiber reinforced concrete has higher bending strength, fracture energy, splitting tensile strength, and impact strength, than the plain concrete series, as expected. In addition, the compressive strength of HPFRC and UHPFRC mixtures containing hybrid steel fibers increased significantly compared to those of plain series of concrete, while the CFRC mixture containing hooked-end steel fibers had no significant change in compressive strength compared to the plain concrete.

The impact strength test results obtained using the weight-drop method are also presented in Table 4. When the results of the weight drop impact test according to the ACI 544 standard are examined, it is seen that test results have a large coefficient of variation and standard deviation, similar to previous literature studies [37]. However, it can easily be said that impact strength increased with increasing compressive strength of concrete. Although the variation of impact resistance test results was found large, fiber reinforced concrete in each case had a much higher impact strength than those of plain concretes. The increase in impact strength with introduction of fibers was more significant in UHSC, in fact no cracks were observed in the drop weight impact test of UHPFRC specimens after 5000 blows.

The compressive strength of the mixtures increased by 4% to 54% with steel fiber reinforcement, 1.8 to 2.2 times for bending strength, and 3.3 to 3.5 times for splitting tensile strength (Table 4). In addition, the impact strength and fracture energy of steel fiber reinforced concrete mixtures increased significantly compared to plain concrete. The fracture energy of steel fiber reinforced concrete mixtures increased 98 to 176 times, and the impact strength increased 233 to 1000 times. The addition of 30 mm steel fibers resulted in fracture energy and ductility significantly increased, compared to its plain mixture.

The addition of 6 mm straight short steel fibers resulted in the compressive strength of the concrete increase, thus fracture energy and impact strength were higher in concrete containing hybrid steel fibers. The highest fracture energy and impact resistance were achieved in the UHPFRC mixture. As in compressive strength, bending strength and impact strength properties, the highest values in fracture energy were obtained in UHPFRC concrete mixtures where steel fibers were hybrid. The load versus displacement curves of plain and steel fiber reinforced concretes are given in Fig. 2. The main effect of steel fibers in concrete can be seen when examining the behavior in post-cracking. Steel fibers prevent the cracks from progressing with the bridging effect after the first crack was formed. In addition, steel fibers significantly increased toughness, as pulling out the fibers from the matrix requires a remarkable amount of energy [38,39].

3.2 Ballistic test results

For the ballistic tests, concrete plates of 500 mm × 500 mm width and 80 mm thickness were produced from all concrete mixtures. Some tests were carried out to determine the impact strength of concrete slabs containing different types and ratios of steel fibers. Properties of the target plates such as fiber types and amounts and projectile impact test results including penetration depth and crater diameter are summarized in Table 5.

In projectile impact tests according to EN 1063 standard [36], the plates produced with NSC and CFRC mixtures did not perform adequately for the ballistic protection class BR7 (Ballistic Resistance). In the impact tests on NSC and CFRC plates, the armor-piercing projectiles perforated the plates. Similar to the NSC and

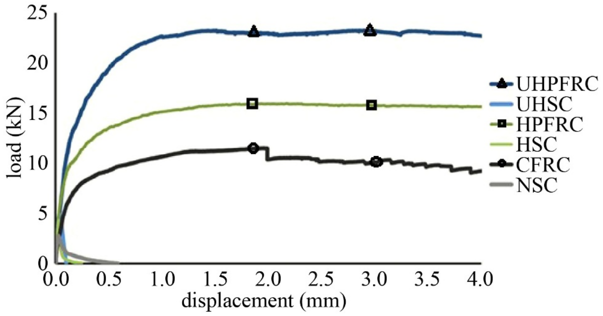

Fig. 2 A representative load versus displacement curves of tested concrete series.

Table 5 Properties of concrete plates and results of impact tests

mix code	fiber content (%)			plate thickness (mm)	penetration depth(mm)	crater diameter (mm)
	6 mm	30 mm	total			
NSC	0	0	0	80	80+	112
CFRC	0	2.5	2.5	80	80+	84
HSC	0	0	0	80	80+	133
HPFRC	2.5	2.5	5.0	80	42	59
UHSC	0	0	0	80	80+	137
UHPFRC	2.5	2.5	5.0	80	27	41

CFRC mixtures, HSC and UHSC specimens that did not contain steel fibers, had also passed armor-piercing projectiles onto the plate rear surface. However, by using hybrid steel fibers in HPFRC and UHPFRC mixtures, compressive strength, impact strength and fracture energy of these concretes were increased significantly. Mixtures of HPFRC and UHPFRC containing hybrid steel fibers exhibited superior ballistic behavior and no damage was observed on the rear surfaces of the plates produced with these concrete mixtures after impact tests. These concrete mixtures showed sufficient performance for the BR7 protection class.

After projectile impact tests, images of the NSC, CFRC, HSC, HPFRC, UHSC, and UHFRC plates were captured. As shown in Fig. 3, in the impact tests on NSC and CFRC plates, the armor-piercing projectiles perforated the plates. Due to the absence of steel fibers in the NSC plates, the damage to the front and rear surface of the plate was much greater. In CFRC plates, the damage to the front and rear surface of the plate was smaller. As a result, the ballistic performance of the NSC and CFRC plates did not provide the BR7 protection level.

As shown in Fig. 4, and the projectile impact tests on HSC and HPFRC plates, the armor-piercing projectiles were penetrating the rear surfaces of the HSC plate, while there was no perforation and cracking on the rear surfaces of HPFRC plate.

In the projectile impact tests on UHSC and UHPFRC plates, it was seen that armor-piercing projectiles were penetrating the rear surfaces of the UHSC plate, while there was no perforation and cracking on the rear surfaces of UHPFRC plate. Front and rear surfaces of UHSC and UHPFRC plates after projectile impact tests, are given in Fig. 5.

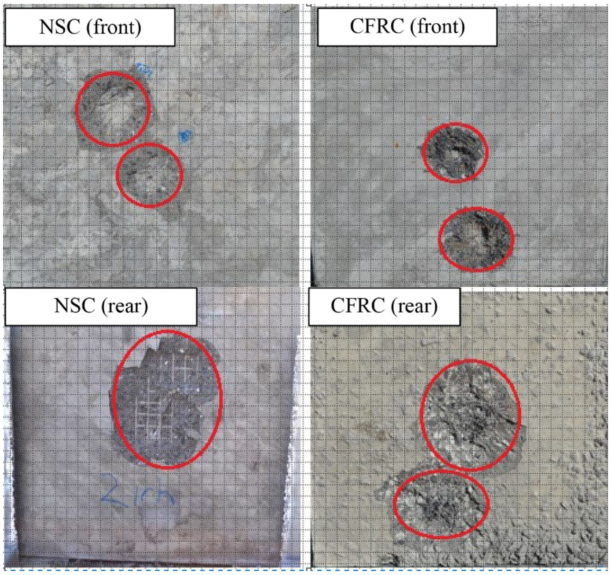

Fig. 3 Front and rear surfaces of NSC (left) and CFRC (right) plates after projectile impact tests.

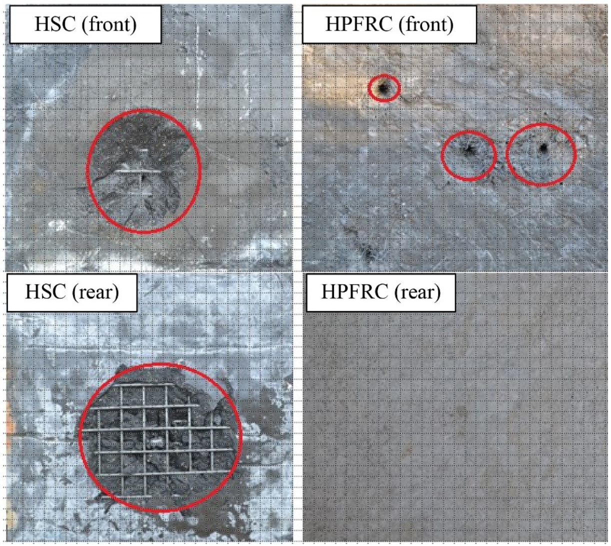

Fig. 4 Front and rear surfaces of HSC (left) and HPFRC (right) plates after projectile impact tests.

When the compressive strength, fracture energy, and impact strength test results are evaluated together with the crater diameter and projectile penetration depth parameters, there is a high relationship between the increase in the fracture energy and the decrease in the crater diameter ($R^2 > 0.95$). In addition, it was determined that there is a lower correlation between the fracture energy and penetration depth. Similarly, although a significant relationship ($R^2 > 0.90$) has been determined between impact strength and crater diameter, this relationship with penetration depth is weaker. Correlation

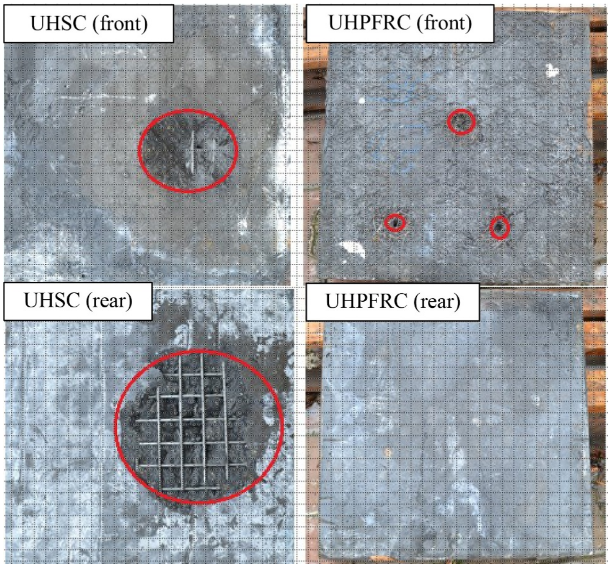

Fig. 5 Front and rear surfaces of UHSC (left) and UHPFRC (right) plates after projectile impact tests.

of compressive strength with crater diameter is lower ($R^2 < 0.35$). However, compressive strength shows a much better correlation ($R^2 > 0.97$) with projectile penetration depth.

4 Discussion

The fracture energy and impact strength values of the CFRC mixture were significantly higher than its plain concrete. However, the projectile impact tests of both culminated with failure. This result is due to the fact that there was a significant difference between the two experimental test methods and the projectile impact. Particularly in the bending test, the hooked-ended fibers have sufficient time to be pulled out. Hence, hooked-ended steel fibers were more effective than straight fibers in increasing fracture energy. However, short fibers were more effective in the impact of projectiles because they were homogeneously distributed throughout the concrete. Therefore, HPFRC and UHPFRC mixtures containing hybrid steel fibers showed sufficient performance under the impact of high velocity projectiles.

Unlike the bending tests in which the fracture energy is determined, the projectile impact effect occurs in a noticeably short time. This only creates a large impact in a local area. For this reason, although the fracture energy and impact strength increased significantly in the CFRC mixture where 30 mm fibers were used, this plate containing single type of fiber did not show sufficient performance against projectile impact tests. With the addition of 6 mm high strength short steel fibers, the homogeneity of the mixture is increased, and the development of crack growth can be effectively restricted in a local damage area.

When the mechanical properties of plain concrete (NSC, HSC, UHSC) are examined, it is seen that there is an improvement in all mechanical properties of HSC and UHSC compared to NSC. However, when examined together with fiber-containing mixtures, the changes among the plain concrete in properties such as impact resistance and fracture energy are negligible. With the addition of fiber to concrete, the fracture energy and impact strengths increased significantly. The ballistic performance (depth of penetration and crater diameter) of concrete composites is related to fracture energy and impact strength, as well as compressive strength. In the study, it was determined that the increase in the compressive strength of plain concrete alone did not affect the ballistic performance of the concretes and that all plain concrete showed insufficient ballistic performance without fiber addition. Even if the compressive strength of fiberless concretes is high, their ballistic performance is insufficient (the projectile perforated all the plain concretes).

As an important result of this study, crater dimensions in fiber reinforced concrete compared to those of plain concrete specimens indicated that fibers tend to reduce the extent of cracking and thereby minimized the damaged area. With the using of steel fibers, the area of the damaged region in all plates was reduced by 44% to 91%. In addition, it was observed that the depth of penetration in UHPFRC with a compressive strength of 163 MPa was around 35% less than that in HPFRC with a compressive strength of 104 MPa. Consequently, HPFRC and UHPFRC mixtures used the same steel type and amount of steel fiber, and it was determined that the UHPFRC plates containing SF were less damaged due to compact micro structure and higher compressive strength.

The CFRC mixture, which contains only 2.5% by volume of hooked-ended steel fiber, exhibited poor performance against armor-piercing projectile effects. Short cut straight high strength fibers had a significant impact on the improvement of ballistic performance. On the other hand, mesh reinforcement alone was not effective in achieving the ballistic performance when used in all plain plates without steel fibers. The reason for this situation is that the reinforcement is 25 mm × 25 mm mesh and the projectile size is 7.62 mm. The projectile creates a great effect in a small area in the spaces between the reinforcements and causes significant damage.

In this study, it has been determined that both HPFRC and UHPFRC have sufficient performance against armor-piercing projectile effects for BR7 class according to EN 1063 (1999) standard. When both concrete mixtures were compared, it was seen that ultra-high-performance concrete gave better results due to its higher compressive strength, bending strength, impact resistance, and fracture energy properties. It was shown that the crater diameter and penetration depth of the projectile were less in UHPFRC plate.

5 Conclusions

1) Hooked-end steel fibers significantly increased the impact strength and fracture energy, while straight high strength steel fibers increased the compressive strength of concrete.

2) UHPFRC and HPFRC mixtures containing 5% by volume of hybrid steel fibers showed superior performance against armor-piercing projectiles and can be used in defense structures. UHPFRC showed better ballistic performance than HPFRC in terms of crater diameter and projectile penetration depth parameters.

3) It was shown that the projectile impact occurs in a local area, and by using only steel mesh reinforcement or large steel fibers, intended ballistic performance could not be achieved despite a significant increase in impact strength and fracture energy. For superior ballistic performance, it has been determined that it is necessary to reinforce the concrete with high strength short steel fibers at every point homogeneously.

4) It has been determined that there are strong relationships between the mechanical properties of concrete composites such as compressive strength, impact strength, fracture energy, and the crater diameter and projectile penetration depth that occur in the projectile impact. There was an inverse correlation between mechanic properties (fracture energy and impact strength) and crater diameter. The crater diameter decreased significantly as the fracture energy and impact strength increased. However, this relationship did not exist with the depth of penetration. Projectile penetration depth was less affected by fracture energy and impact strength parameters. However, there was a very strong inverse relationship between the increase in compressive strength and the penetration depth. As a result, the best performance in projectile impact was obtained in the UHPFRC system, where the impact resistance, fracture energy and compressive strength were the highest, considering both the smaller crater diameter and less projectile penetration depth.

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