

An Experimental Study on the Impact Performance of Ultra-High Performance Concrete (UHPC) Slabs with and without Steel Fibers under Projectile Loading

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ABSTRACT

This study investigates the impact performance of Ultra-High Performance Concrete (UHPC) slabs with and without steel fibers under high-velocity projectile loading. Thirteen concrete slabs, varying in thickness (30 mm, 50 mm, and 70 mm) and fiber content (0%, 1%, 2%, and 3%), were fabricated and tested using live ammunition fired from an AK-47 rifle. The experimental program evaluated the influence of fiber reinforcement and slab thickness on the penetration depth, crater dimensions, and failure modes. The results demonstrated that the UHPC slabs without fibers exhibited brittle failure similar to Normal Concrete (NC), particularly at lower thicknesses. The inclusion of steel fibers significantly improved the impact resistance, with an optimal performance observed at 2% and 3% fiber content. The increased slab thickness also enhanced performance, especially when combined with fiber reinforcement. The findings underscore the synergistic effect of steel fiber content and thickness in mitigating damage and preventing perforation under projectile impact, offering valuable insights for the design of protective concrete infrastructure.

Keywords-Ultra-High Performance Concrete (UHPC); steel fibers; impact resistance; projectile loading; slab thickness

I. INTRODUCTION

UHPC constitutes a promising material for protective structures due to its mechanical properties, including high compressive strength, enhanced durability, and superior energy absorption capacity [1-4]. These characteristics make UHPC particularly suitable for applications requiring resistance to extreme loading conditions.

Numerous studies have investigated the behavior of UHPC structures under blast loading [5-10], while others have focused on its performance in resisting projectile impacts [11-15]. Within the context of UHPC panels subjected to high-velocity loading, authors in [11] conducted an experimental study using 12 slabs ($300 \times 400 \times 50$ mm) made from NC, Fiber-Reinforced Concrete (FRC), UHPC without fibers, and Ultra-High-Performance Fiber-Reinforced Concrete (UHPRFC). Their objective was to examine the effect of the steel fiber content on the resistance to deformable projectile impacts and to identify the optimal fiber dosage. The results indicated that the plain UHPC specimens failed, while the inclusion of steel fibers significantly improved impact resistance. A volumetric fiber content of 2% was found to be optimal. However, the study did not investigate the influence of slab thickness on the impact performance. Based on this, in [12] numerical simulations were performed to evaluate the dynamic response of UHPRFC panels subjected to multiple bullet impacts. The study compared kinetic and internal energy absorption characteristics of the panels with those of high-strength concrete, offering further insights into the advantages of fiber-reinforced UHPC.

In [13], an experimental investigation was conducted on the penetration resistance of NC and UHPC panels subjected to projectile loading. Twelve panels, measuring 500×500 mm, with thicknesses of 100 and 200 mm, were cast and tested. All the UHPC panels incorporated 2% steel fiber by volume. The study measured parameters, such as the penetration depth, crater dimensions, mass loss, and failure modes. The results confirmed UHPC's superior performance in resisting high-velocity impacts compared to NC. In [14], both experimental and numerical studies were conducted on UHPC targets subjected to projectile velocities ranging from 216 to 340 m/s. The performance of UHPC was compared with that of granite targets. The findings demonstrated that UHPC provided better resistance by significantly reducing the crater diameters.

The literature review reveals that the experimental studies on the resistance of UHPC under high-velocity impacts remain limited. Furthermore, while the effects of fiber content and structural thickness have been investigated individually, their combined influence has not been extensively explored or quantified. To address this gap, the present study experimentally evaluates the impact performance of NC and UHPC slabs - with and without steel fibers, subjected to projectile loading. A total of 13 slabs were cast and tested, varying in fiber content (0%, 1%, 2%, and 3%) and thickness (30 mm, 50 mm, and 70 mm). The UHPC was produced using locally sourced materials from Vietnam. This research aims to elucidate the combined influence of fiber content and slab thickness on impact resistance, damage mitigation, and

perforation prevention. The findings are expected to offer valuable insights for designing UHPC-based protective infrastructure capable of withstanding high-velocity impacts.

II. EXPERIMENTAL PROGRAM

A total of thirteen slabs, as portrayed in Table I, each measuring 400×400 mm with varying thicknesses, were fabricated and tested under high-velocity impact loading to evaluate the effects of the fiber content and slab thickness on the impact resistance. The specimens were made using five different concrete mixes, including both NC and UHPC.

TABLE I. SPECIMEN PROPERTIES

Mix ID.	Slab ID.	Volumetric fiber content (%)	Slab thickness (mm)
NC	NC-T30	0	30
	NC-T50	0	50
	NC-T70	0	70
UHPC-F0	UHPC-F0-T30	0	30
	UHPC-F0-T50	0	50
UHPC-F1	UHPC-F1-T30	1	30
	UHPC-F1-T50	1	50
	UHPC-F1-T70	1	70
UHPC-F2	UHPC-F2-T30	2	30
	UHPC-F2-T50	2	50
UHPC-F3	UHPC-F3-T30	3	30
	UHPC-F3-T50	3	50
	UHPC-F3-T70	3	70

Steel fibers with a length of 13 mm, a diameter of 0.2 mm, and a tensile strength of 2750 MPa, as depicted in Figure 1, were incorporated at volumetric fractions of 0%, 1%, 2%, and 3%. Three slab thicknesses were considered: 30, 50, and 70 mm. Moreover, no steel mesh was used in any of the specimens, as previous studies have shown that steel mesh has a negligible effect on the perforation resistance of UHPC slabs subjected to high-velocity loading [11, 16].



Fig. 1. High-strength steel fibers used.

A. Material and Mix Proportions

Table II presents the detailed mix proportions for producing 1 m^3 of concrete for all five mixtures used in the experimental program. These include one NC mix and four UHPC mixes with varying steel fiber contents: 0% (UHPC-F0), 1% (UHPC-F1), 2% (UHPC-F2), and 3% (UHPC-F3) by volume.

The NC mix consists of cement, sand, crushed stone, and water, with no supplementary cementitious materials or admixtures. In contrast, all UHPC mixes excluded coarse

aggregates and incorporated high contents of cement, silica fume, and fly ash, along with a polycarboxylate-based superplasticizer to achieve the desired workability. Steel fibers were introduced at dosages of 0 kg/m³ (UHPC-F0), 78.5 kg/m³ (UHPC-F1), 157.0 kg/m³ (UHPC-F2), and 235.5 kg/m³ (UHPC-F3), corresponding to volumetric fiber contents of 0%, 1%, 2%, and 3%, respectively. As the fiber content increased from 0% to 3%, minor adjustments were made to the contents of other constituents, such as sand, cement, and water, to maintain a consistent workability and target performance.

TABLE II. MIX PROPORTION

Mix proportions for 1 m ³ concrete	NC	UHPC-F0	UHPC-F1	UHPC-F2	UHPC-F3
Sand (kg)	626	1130	1119	1108	1096
Cement (kg)	395	848	839	831	822
Crushed stone (kg)	1210	n.a	n.a	n.a	n.a
Fly ash (kg)	n.a	170	168	166	164
Silica fume (kg)	n.a	113	112	111	110
Polycarboxylate superplasticizer (kg)	n.a	37.7	37.3	36.9	36.5
Water (kg)	183	167	166	164	162
Steel fiber (kg)	n.a	0	78.5	157.0	235.5

The casting for all samples involved the same steps: Mixing the ingredients in a mixer (Figure 2(a)) and pouring the mixture into the formwork (Figure 2(b)).

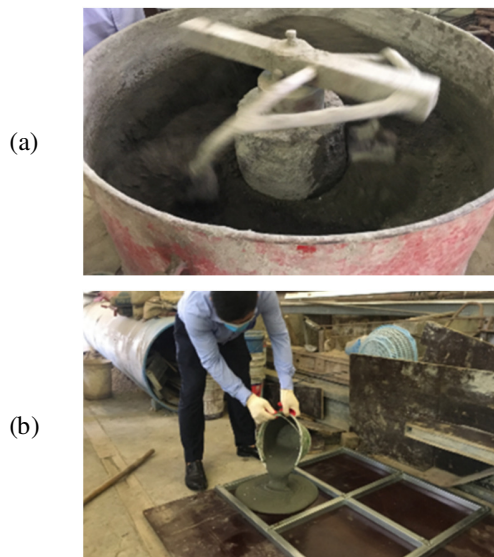


Fig. 2. Casting procedure.

B. Material Properties

Table III presents the key material properties of the concrete mixes, as determined through standard laboratory tests. The reported properties include compressive strength, elastic modulus, flexural strength, and density, with variations reflecting changes in fiber content across the different mixes. The compressive strength and elastic modulus for the NC mix were measured using 150 × 300 mm cylindrical specimens, while 100 × 200 mm cylinders were utilized for the UHPC mixes. The flexural strength was evaluated using prismatic specimens measuring 150 × 150 × 600 mm for the NC mix and 100 × 100 × 400 mm for the UHPC mixes.

TABLE III. MATERIAL PROPERTIES DEFINED BY TESTS

Mix proportions	NC	UHPC-F0	UHPC-F1	UHPC-F2	UHPC-F3
Volumetric fiber content (%)	0	0	1	2	3
Compressive strength (MPa)	30	120*	110	120	120
Elastic modulus (GPa)	30	-	40	48	48
Flexural strength (MPa)	3	-	9	15	16
Concrete density (kg/m ³)	-	2465	-	2573	2627

The NC mix, which contained no fibers, exhibited a compressive strength of 30 MPa, an elastic modulus of 30 GPa, and a flexural strength of 3 MPa. In contrast, the UHPC mixes demonstrated significantly enhanced mechanical properties. The UHPC-F0 mix (without fibers) was designed to achieve a compressive strength of 120 MPa, although the experimental results for the flexural strength and elastic modulus were not recorded.

As the fiber content increased from 1% to 3% (UHPC-F1 to UHPC-F3), there was a notable improvement in the flexural strength and elastic modulus, reflecting the reinforcing effect of steel fibers. Specifically, the flexural strength increased from 9 MPa for UHPC-F1 to 16 MPa for UHPC-F3, while the elastic modulus rose from 40 GPa to 48 GPa. These results highlight the beneficial impact of steel fiber incorporation on the mechanical performance of UHPC.

III. TEST SETUP

High-velocity impact tests were conducted on thirteen square concrete panels, each measuring 400 × 400 mm. The specimens were securely fixed within a vertical steel reaction frame, as depicted in Figure 3. Projectile loading was simulated using live ammunition fired from an AK-47 rifle positioned 20 m away from the target panels. The ammunition used was 7.62 × 39 mm, commonly referred to as M43 - a standard round widely used in AK-47 rifles. Each cartridge had a total length of 56 mm, with a casing length of 38 mm. The projectile had a diameter of 7.92 mm and a design velocity of 715 m/s.

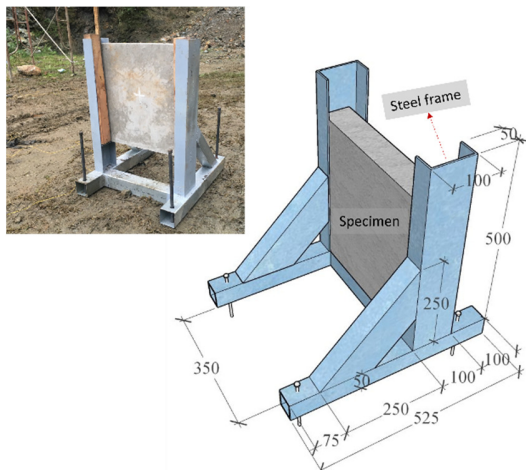


Fig. 3. Test setup.

IV. TEST RESULTS AND DISCUSSION

A. Structural Responses

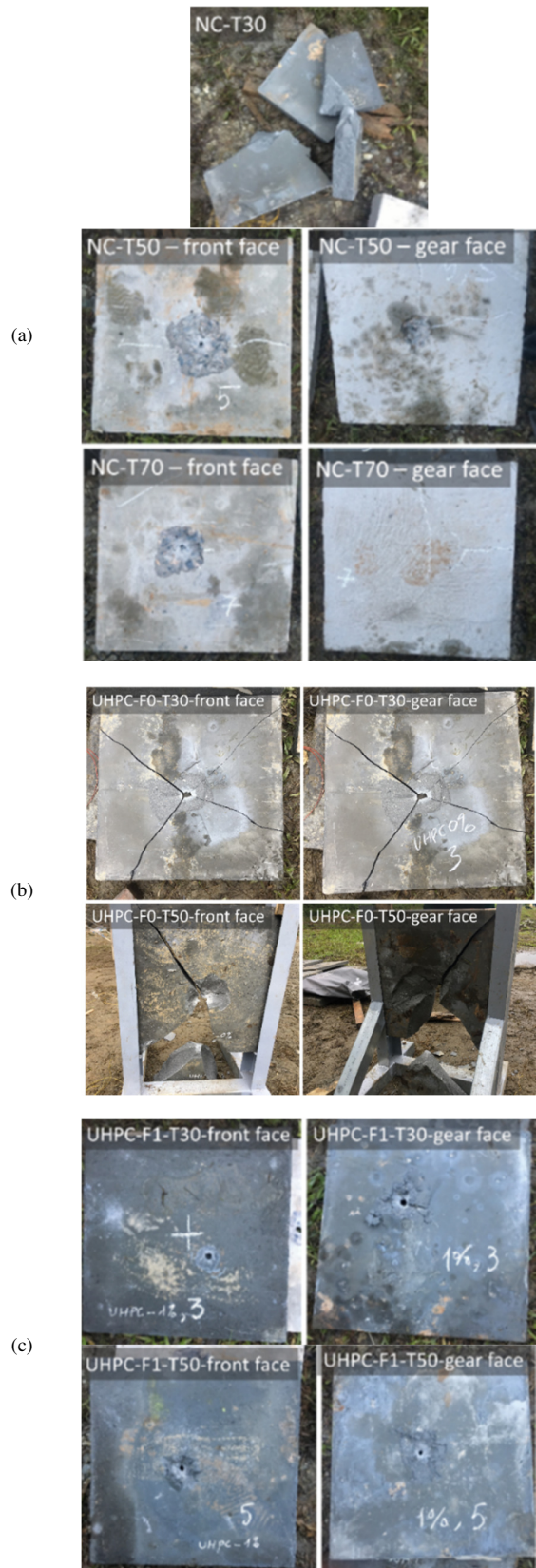
The 13 slabs were subjected to projectile loading to assess their impact resistance, resulting in a range of responses that reflect varying degrees of damage and failure. The level of damage is assessed based on crater diameter, penetration depth, and response type, as outlined in Table IV.

TABLE IV. TEST RESULTS

Slab ID.	Front crater diameter (mm)	Rear crater diameter (mm)	Penetration depth (mm)	Response type
NC-T30	n.a	n.a	30	P & S
NC-T50	122.5	71.6	50	P
NC-T70	82.0	0	-	PL
UHPC-F0-T30	133.3	135.0	30	P & S
UHPC-F0-T50	128.0	219.3	50	P & S
UHPC-F1-T30	48.1	90.1	30	P
UHPC-F1-T50	76.0	87.7	50	P
UHPC-F1-T70	110.1	0	-	UP
UHPC-F2-T30	52.0	81.0	30	P
UHPC-F2-T50	59.4	91.7*	-	UP
UHPC-F3-T30	48.8	84.7	30	P
UHPC-F3-T50	49.0	84.1*	-	UP
UHPC-F3-T70	91.4	0	-	UP

* scabbing instead scattering

The classification of the failure modes follows the convention established in [11, 16], where P denotes a complete penetration of the specimen by the projectile, S indicates the splitting failure, the Perforation Limit (PL) refers to cases in which the projectile was arrested within the specimen, and Un-Penetrated (UP) describes instances where the projectile caused localized damage, for example punching, but was rebounded without full penetration, as shown in Figure 4. The 13 slabs displayed a spectrum of behaviors, from severe damage (P and S) to robust resistance (PL and UP), depending on the material composition, fiber content and thickness. In addition, crater sizes are likely correlated with failure severity and specifically: The largest for P and S, moderate for PL, and the smallest for UP.



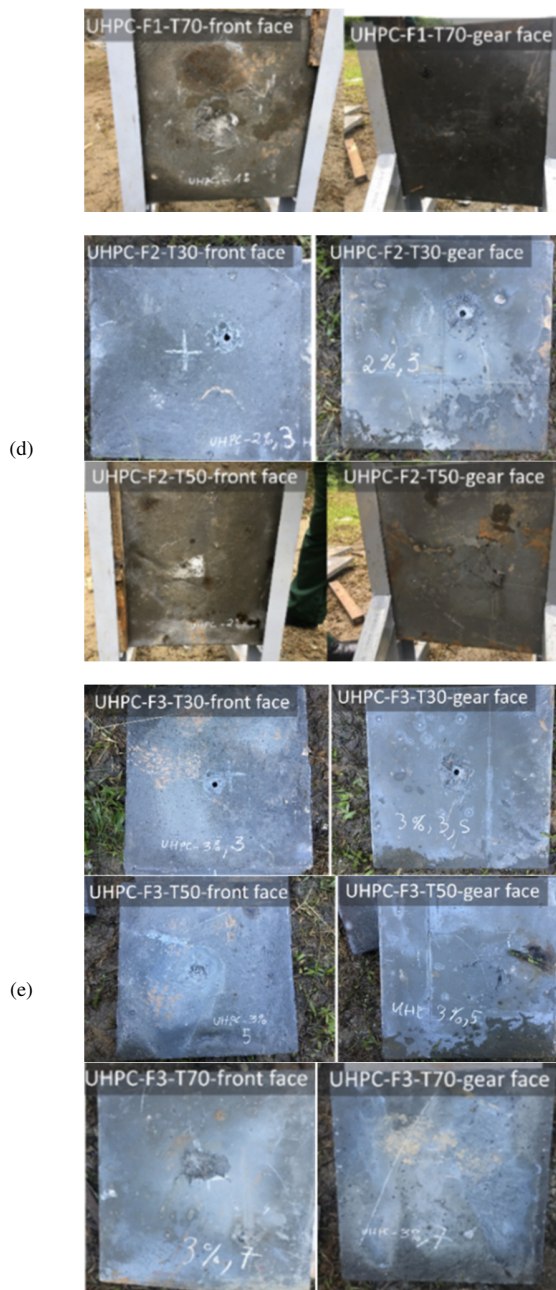


Fig. 4. Response of tested slabs: (a) NC, (b) UHPV – F0, (c) UHPV – F1, (d) UHPV – F2, (e) UHPV – F3.

NC and fiberless UHPC slabs at thickness of 30 and 50 mm showed poor impact resistance, failing via perforation and splitting with large craters. Adding fibers, especially at 2% and 3%, significantly improved performance, reducing the crater sizes and preventing perforation in 50 mm and 70 mm slabs. This is consistent with the findings in [11], where it is reported that fiber reinforcement improves UHPC's impact resistance. However, the current study extends these findings by quantifying the effect of slab thickness alongside the fiber content.

Test results show that the thickness was critical, with 70 mm slabs consistently outperforming the thinner ones. The UHPC-F3 series (3% fiber) demonstrated the best impact resistance, with minimal damage in thicker slabs, highlighting the synergistic effect of the high fiber content and adequate depth in mitigating the projectile impact.

For the majority of the tested slabs, excluding those with a thickness of 70 mm, where the projectile did not penetrate, and the NC-T50 specimen, the damage on the rear face, in terms of the crater diameter, was more pronounced than that on the front face. This phenomenon is attributed to the stress wave propagation mechanism during the impact. Upon striking the slab, the projectile generates a compressive wave at the front face. As this wave propagates through the material and reaches the rear face, it reflects as a tensile wave [3], leading to spalling and cratering on the rear side. Consequently, the damage zone on the rear face is typically larger in diameter than the initial impact area, as observed in the tests.

B. Comparison of NC and UHPC Slabs without Fibers

The test results indicate that both the NC and UHPC-F0 slabs exhibited brittle behavior, particularly in thinner specimens (30 mm). Both NC-T30 and UHPC-F0-T30 fractured into four pieces, demonstrating that neither material could withstand the impact at this thickness without experiencing severe damage. The UHPC-F0-T30 slab, despite being composed of ultra-high-performance concrete, exhibited a damage style similar to that of NC-T30, underscoring the limited benefit of UHPC at this thickness without fiber reinforcement. At a thickness of 50 mm, the NC-T50 slab avoided splitting, whereas UHPC-F0-T50 fractured into three pieces, further indicating that UHPC without fibers remains brittle under high-velocity impact loading. These results suggest that in the absence of steel fibers, the enhanced compressive strength of UHPC does not translate into improved impact resistance. A similar trend was observed in [11], where the lack of fiber reinforcement in UHPC also led to brittle failure under dynamic loading. This reinforces that the compressive strength alone is not sufficient for impact resistance, so fiber reinforcement is essential.

C. Effect of Fiber Content

To demonstrate the effect of the fiber content on the impact resistance of the tested slabs, the behavior of four UHPC slabs with a thickness of 50 mm and fiber contents ranging from 0% to 3% is compared, as displayed in Figure 5. It is noteworthy that for UHPC-F2-T50 and UHPC-F3-T50, scabbing was observed on the rear face instead of crater formation. Therefore, the rear-face crater dimensions for these slabs are not included in Figure 5.

The comparison shows that both front and rear crater diameters decreased as the fiber content increased, indicating an enhanced resistance to impact damage. The UHPC-F0-T50 slab, which contains 0% fiber content, exhibited the largest crater sizes, with a front crater diameter of approximately 120 mm and a rear crater diameter exceeding 200 mm. With the addition of 1% of fiber (UHPC-F1-T50), both crater diameters are noticeably reduced. The front crater shrinks to around 80 mm, and the rear crater is also substantially smaller,

highlighting the positive influence of fibers in mitigating the crack propagation and rear-face damage. Further increases in the fiber content to 2% and 3%, result in even smaller front crater diameters, with UHPC-F2-T50 and UHPC-F3-T50 measuring approximately 60 mm and 50 mm, respectively. The rear craters are entirely absent in these two specimens, indicating that the slabs were not perforated, and that the rear-face integrity was still preserved. These observations align with those in [4, 12], where the effectiveness of steel fibers in controlling crack propagation and enhancing dynamic strength was demonstrated.

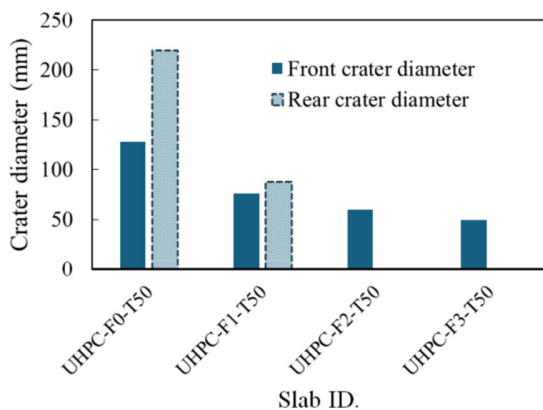


Fig. 5. Comparison of crater diameter between slabs with increasing fiber content in UHPC slabs.

Moreover, in terms of damage type, the test results outlined in Table IV and Figure 4, demonstrate that the fiber reinforcement significantly enhanced the impact resistance of UHPC panels. The panels without fibers produced using NC and UHPC-F0 mixes, exhibited severe damage. Both NC-T30 and UHPC-F0-T30 panels, with a thickness of 30 mm, experienced complete perforation and fractured into four pieces. Similarly, NC-T50 and UHPC-F0-T50 (50 mm thick) also perforated. However, panels reinforced with 1% of fiber content exhibited significant improvements. Although UHPC-F1-T30 and UHPC-F1-T50 still perforated, they were not broken. This indicates that even a low fiber content contributes to enhanced toughness.

Higher fiber contents provided further resistance improvements. Both UHPC-F2-T50 and UHPC-F3-T50 (50 mm thick) were free of perforation, although scabbing was observed on the rear side, indicating localized rear-face damage without full penetration. The UHPC-F3-T70 panel (70 mm thick) showed no perforation or rear-face cratering, reflecting minimal damage overall. However, thinner 30 mm panels (UHPC-F2-T30 and UHPC-F3-T30) still had perforation, suggesting that an increased fiber content alone is insufficient to prevent failure in thinner panels under the tested impact conditions.

D. Effect of Slab Thickness

The response of slabs under projectile loading demonstrated that slab thickness plays a crucial role in the impact resistance and damage behavior of both NC and UHPC panels. For NC panels, increasing the slab thickness led to improved

penetration resistance and reduced structural damage, as evidenced by the smaller crater diameters. In UHPC slabs without fiber reinforcement (0% fiber content), the UHPC-F0-T30 panel was perforated and split into four pieces, while the UHPC-F0-T50 panel was also perforated but split into only three pieces, indicating a slight improvement in resistance due to increased thickness.

For UHPC slabs with fiber contents ranging from 1% to 3%, all 30 mm thick panels were perforated but remained intact without splitting, indicating an improved structural integrity compared to both the NC and fiberless UHPC panels. At a thickness of 50 mm, the UHPC-F1-T50 panel was still perforated, while both UHPC-F2-T50 and UHPC-F3-T50 resisted full penetration, demonstrating the enhanced effectiveness of fiber reinforcement when combined with increased thickness.

At 70 mm thickness, the UHPC-F1-T70 and UHPC-F3-T70 panels had no perforation, reflecting a high level of resistance to impact loading. Overall, the test results confirm that increasing the slab thickness significantly enhances impact resistance, especially when used in conjunction with steel fiber reinforcement. The results of this study are consistent with those in [13, 14], where improved resistance with increased thickness was reported. However, these studies did not consider the combined variation in thickness and fiber content.

In general, the present study's results provide new insights by systematically examining how slab thickness interacts with fiber volume. For example, UHPC-F3-T70 showed negligible damage, indicating that the combination of high fiber content and increased thickness provides a synergistic effect. This combination is particularly effective in resisting high-velocity projectile impact.

V. CONCLUSIONS

This experimental study evaluated the resistance of Ultra-High Performance Concrete (UHPC) and Normal Concrete (NC) slabs with and without steel fibers subjected to high-velocity projectile loading. The findings led to the following conclusions:

- Steel fibers significantly improve impact resistance. UHPC slabs with fiber contents of 2% and 3% showed considerable enhancement in resisting projectile penetration, reducing the crater diameters, and preventing perforation, compared to both the NC and fiberless UHPC slabs.
- Fiberless UHPC behaves similarly to NC under impact. Despite its superior compressive strength, UHPC without fibers failed in a brittle manner under high-velocity impact, emphasizing the importance of fiber reinforcement in improving dynamic performance.
- The slab thickness plays a critical role. An increased thickness led to a better resistance against penetration and rear-face damage. The slabs with 70 mm thickness consistently outperformed those with 30 mm and 50 mm thickness.

- The best impact resistance was observed in 70 mm-thick UHPC slabs with 3% steel fibers, demonstrating a clear synergistic effect between material composition and geometry.

A novelty of this study lies in its systematic evaluation of the combined influence of steel fiber content and slab thickness on impact resistance. While previous research has explored these variables separately, this study's findings demonstrate a synergistic effect between material composition and structural geometry.

These insights provide practical guidance for optimizing UHPC-based protective systems, contributing new understanding to the field of high-performance concrete subjected to extreme dynamic loading.

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