

Penetration resistance of concrete reinforced by hybrid fibre subjected to multiple projectile impacts

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Abstract. Penetration resistance of steel-ultrahigh molecular weight polyethylene (S-UHMWPE) hybrid-fibre-reinforced concrete under multiple projectile impacts are investigated. In this paper, 16 sets of hybrids with various hybridizations were designed and prepared considering 0%-1.5% steel fibre volume and 0%-0.3% UHMWPE fibre volume. Each hybrid-fibre concrete target was stroke triple times sequentially under 12.7mm armor-piercing projectile. The projectile impact locations are among the middle of the target in equilateral triangle shape. After each penetration, depth of penetration (DOP) and crater area were investigated. Results show that hybrid-fibre concrete performs much better than steel or UHMWPE fibre reinforced concrete with less crater area and lower DOP for hybrid-fibre concrete combines the reinforcement and toughening effect of UHMWPE fibre on concrete's tensile strength and strengthening effect of steel fibre on concrete's compressive strength. Besides, the crater area caused by each impact decreased with the number of strikes increases.

Key words: steel fibre; hybrid-fibre-reinforced concrete; multiple impacts; penetration performance

1. Introduction

With the development of high-tech weapons, direct hits and multiple impacts have become the main ways to strike important targets, posing a serious threat to the safety of military engineering and equipment.

In order to improve the anti-penetration ability of engineering project, many scholars have focused on high-strength and high-performance concrete, carrying out researches on the anti-penetration problem of various fibre-reinforced concrete. For instance, steel fibre's effects on concrete had been researched by Ji C[1], Wu H[2], indicating that the penetration resistance of concrete increased as the volume of steel fibre rose and were affected by fibre's length and shape obviously. Zhang Y W[3,4] conducted experimental research on the mechanical properties and anti-penetration performance of ultrahigh molecular weight polyethylene (UHMWPE) fibre-reinforced concrete. Experimental results indicate that UHMWPE fibres as flexible fibres, though not readily apparent to the reinforcing effect of concrete's compressive strength, can significantly improve the tensile strength and toughness of concrete because of their high elastic strength. Besides, they can suppress the cracking damage of fibre concrete under impact penetration well thus can effectively improve the anti-penetration ability of concrete. Based on the study of single fibre -reinforced concrete, considering one fibre can exploit the potential mechanical properties of the other fibre during hybrid-fibre reinforced concrete, many



scholars studied the effect of hybrid fibre on penetration resistance of concrete. Investigations focused on concrete with steel fibres of different length and configurations[5];concrete incorporated with flexible and rigid fibres such as steel-polypropylene or polyvinyl alcohol fibres[6], steel-polypropylene or Kevlar fibres[7]. It was proved that hybrid fibre could exploit the advantages of different fibre's properties and characteristic parameters, which resulted in better anti-penetration ability than single fibre.

Despite various studies focusing on hybrid-fibre concrete anti single projectile impact, there are some studies investigated on concrete subjected to multiple impacts due to the needs to improve engineering project penetration resistance under multiple strikes. There are mainly two patterns of multiple impacts under studied. The first pattern demonstrates multiple projectile striking at the same place on target, like the multiple impacts experiments conducted by Gomeza[8],who hit semi-infinite reinforced concrete target with 6.4mm projectile and Lai J Z [9],who hit concrete target reinforced by hybrid fibres and corundum aggregates with 14.5mm projectile. The second pattern describes projectile impact locations distributed on target, like multiple impacts on UHMWPE fibre-reinforced concrete conducted by Xu M H [10] and experiments performed by Jun F[11] to study penetration resistance of multiple strikes on 12 sets hybridizations of hybrid-fibre-reinforced concrete.

Experimental results show that the second pattern will cause larger crater area than the first one. Besides, depth of penetration will increase as the latter projectile strike at the damage area of the previous projectile, however, it will not increase multiply.

This paper concentrated on multiple-impact performances of steel-UHMWPE hybrid-fibre-reinforced concrete based on the researches about multiple-strike penetration tests of concrete reinforced by UHMWPE fibre[10]16 sets of hybrids with various hybridizations were designed and prepared. Each target were stroke sequentially with projectile impact locations distributed in equilateral triangle like the experiments[10, 11]show, whereas target's damage appearance, crater area and DOP were under estimated and studied. Based on these results, effects of the number of impacts on the penetration damage and the influence of fibre ratio on penetration performances were studied. The results showed important theoretical guidance and reference significance to the development of high-strength fibre concrete and was beneficial to the application in the field of engineering project.

2. Materials and concrete production

The hybrid-fibre-reinforced concrete was designed according to C70 grade high strength concrete. The raw materials are as follows: Portland cement (P.I 42.5). Coarse aggregate, which contains continuous grading pebbles with particle size between 5 and 10mm. Fine aggregate, which is medium-sized river sand with mud content of 0.8%, it's fineness modulus is 2.5, the apparent density is 2.68g/cm³. Admixture is micro silica fume with SiO₂ content no less than 95%, specific surface area is 25000m²/kg, bulk density is 200-250 kg/m³, and particle diameter is 0.1-0.3 μm. For the sake of better performance, early strength and high efficiency naphthalene superplasticizer is added, which may contribute to the reduction of water up to 30%. The details of mix proportions are listed in Table 1.

Table1 Mixture proportions of plain concrete (kg/m³)

Water	Cement	Coarse aggregate	Sand	Fly ash	Superplasticizer
185	547	936	615	57.5	12

Researches[5] indicate when rigid and flexible fibres with two different properties are mixed in large content, flexible fibres are prone to agglomerate, which may lead to performance degradation. In order to ensure the uniform dispersion of fibres incorporated into concrete, the volume of UHMWPE fibre is limited within 0.3%[3], including 4 gradients of 0%, 0.1%, 0.2%, 0.3%; steel fibre is limited within 1.5%, including 4 gradients of 0%, 0.1%, 0.2%, 0.3%, the total hybridizations are 16 sets. UHMWPE fibre is twisted by ZTX99-400D fibre and steel fibre is short curved steel fibre, the geometric and mechanical properties information of these two fibres are listed in Table 2.

The production procedures of hybrid-fibre-reinforced concrete need to be controlled carefully to ensure good workability and particle distribution. The exact procedures are as follows. ①mix the dry cementitious materials like cement, flash ash, coarse aggregate, sand, steel fibre evenly ②add water

and superplasticizer along with UHMWPE fibre into the mixture carefully and mixed them for 5 min to ensure fibres are randomly distributed ③ add the remaining water, stir evenly, unload the mold, and tamper with a vibrator until the surface is flooded ④ cure the specimens at the temperature of $20^{\circ}\text{C}\pm 2^{\circ}\text{C}$ with humidity over 95%.

Table2 Fibre information

Fibre type	Diameter(μm)	Length(mm)	Density (g/cm^3)	Elastic modulus (GPa)	Tensile strength (MPa)	Fracture elongation (%)
Steel(Q195)	500	30	7.8	200	1300	2
UHMWPE	60	30	0.97	100	3000	2.8

In this paper, we use S_xP_y to represent each concrete target, where S represents steel fibre and P represents UHMWPE fibre and the subscript relates to the content of each fibre. For example, $S_{0.5}P_{0.2}$ represents hybrid-fibre-reinforced concrete with 0.5% steel fibre and 0.2% UHMWPE fibre.

3. Penetration tests of concrete targets

Penetration tests were completed at the Impact Penetration Laboratory of National University of Defense Technology. 12.7mm projectiles were fired to penetrate concrete targets, the mass of the projectile is 47.3-49g. The size of concrete target is $\Phi 400\text{mm}\times 250\text{mm}$, molded by 2mm steel plate where fibre concrete targets were cast. During penetration tests, concrete targets were constrained into the mold. Concrete targets are avoided from breaking apart and spreading out with the constraint of steel plate. The incident velocity of the projectile was measured by a dual-light curtain target and a six-channel electronic time-meter. The test velocity is 781_{-11}^{+9} m/s. Diagram of the test device is shown in Figure 1.

This paper use triple projectile strike distributed on the target to conduct multi-impact penetration experiments. According to the dispersion radius of projectile described in article[12] and the crater area in single penetration of hybrid-fibre-reinforced concrete, we set each projectile's locations' distance is $4D$, where D represents the diameter of projectile. The specific processes of positioning are as follows. Firstly, select the first hit point on the target surface. Secondly, take the first shot location as the center of circle with $R=4D$ and position the second hit location on the edge of circle. Afterwards, take the second shot location as the center of circle with $R=4D$ and position the third hit location on the point of intersection of the above two circles. The position of the three strike locations is shown in Figure 2.

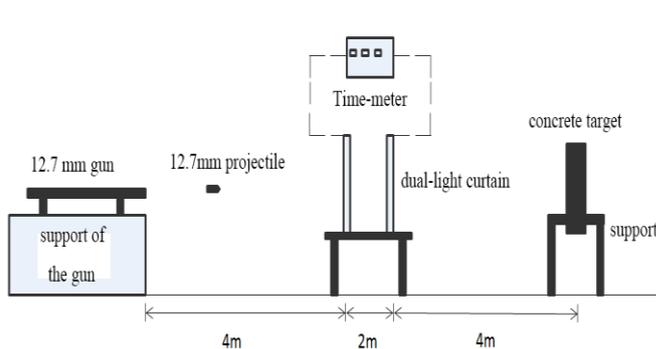


Figure1 Diagram of the test device

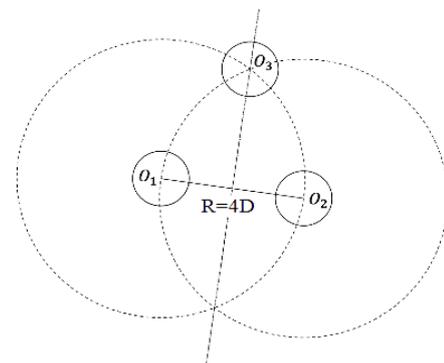


Figure2 Diagram of multiple-impact locations

During the experiments, the three strikes were carried out one by one. After each strike, the target damage and the size of damage crater area were recorded in time. After experiments, according to each penetration's trajectory, the ballistic profile was cut and the depth of each penetration was measured one by one.

4. Results and Analysis

4.1 Pattern of target damage

The diagrams of the pattern of 16 different hybridizations of concrete targets after 3 projectile impacts are shown in Figure 3. From the diagrams, we can find that:

- (1) After three strikes, those concrete targets reinforced by single fibre of steel fibre or UHMWPE fibre, outperformed 6-8 large cracks that adjoin to the outer edge of the concrete targets. Steel fibre can constrain the development of these large cracks as there are only small crackles left when the content of steel fibre reaches 1.5%. Unlike steel fibre, UHMWPE fibre shows much less constraint to the development of large cracks. Nevertheless, UHMWPE fibre show a preventive effect on the germination of the initial crack. Cracks and crackles of concrete targets reinforced by two mixed fibres are less than that of concrete targets reinforced by single fibre. Besides, the number of cracks or crackles decreased with the increase of fibre's content.

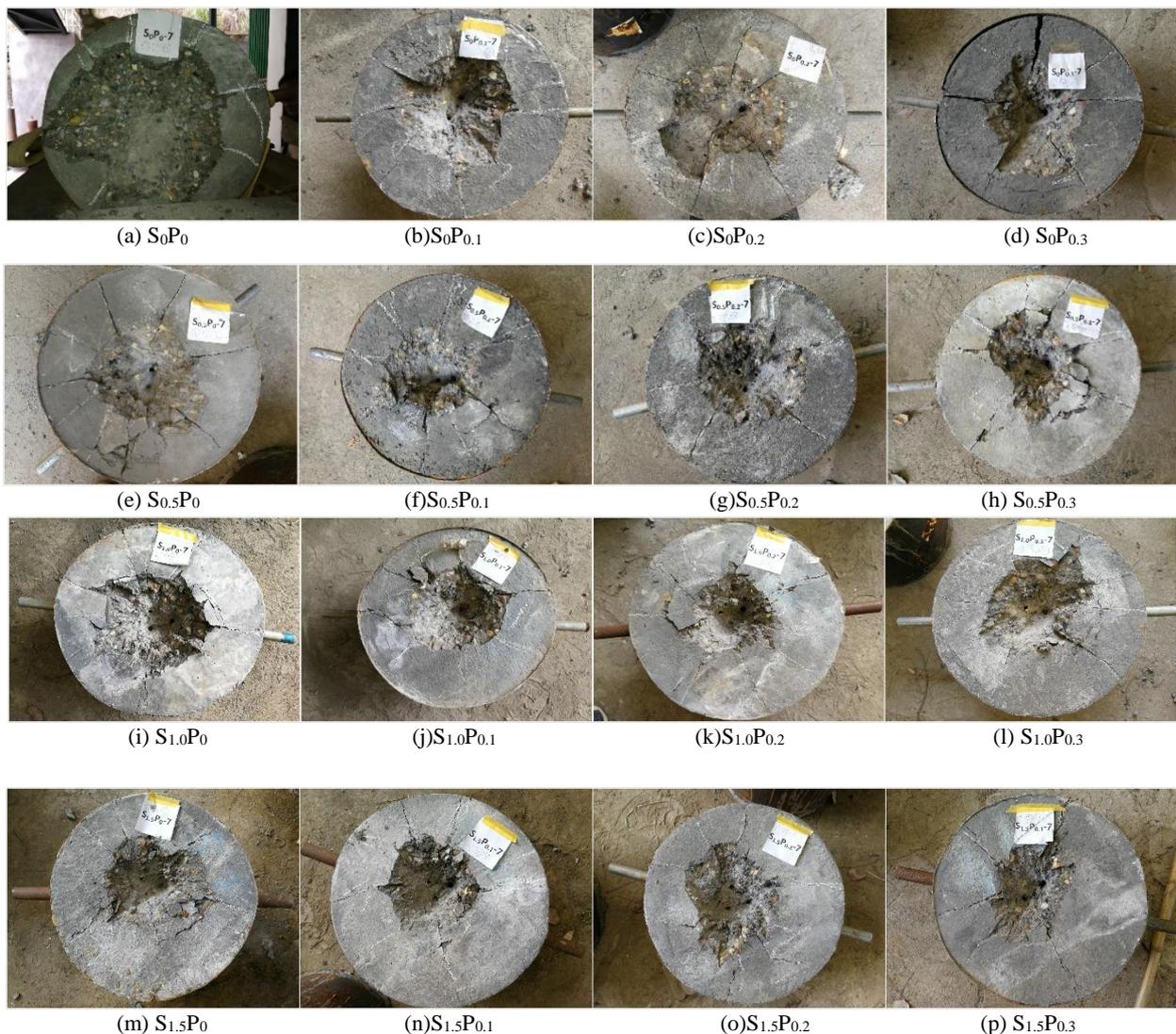


Figure3 Diagrams of the pattern of 16 concrete targets after triple projectile impacts

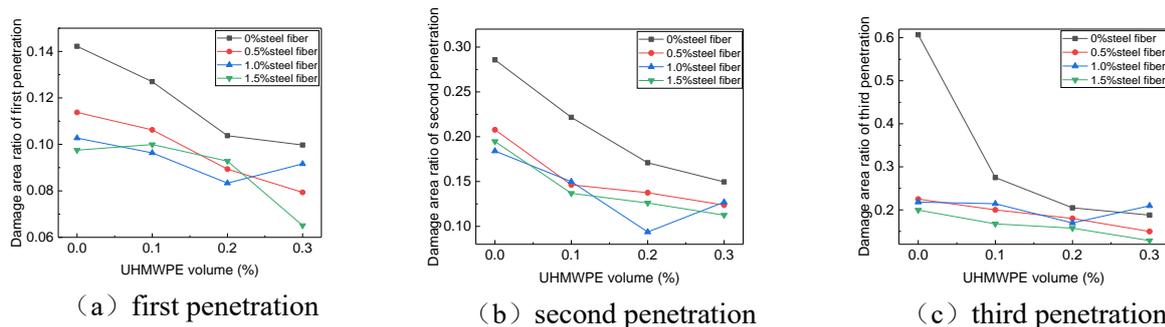
- (2) There are funnel crater areas on the front of each concrete target. Compared to the crater area covering up almost the whole front face of plain concrete target without fibre (S_0P_0), crater area on concrete target reinforced by single steel fibre or UHMWPE fibre or hybrid fibre becomes much smaller. Nevertheless, in the case of steel fibre or UHMWPE fibre, fibre mixing and increased dosage will further reduce the crater size.

4.2 Analysis of target damage

To analysis the effect of hybrid fibre in concrete target under multiple-impact, this paper assumes the crater area to be approximately oval. After each penetration, we measured the longest and shortest length of the crater area on the front face and set them as oval's long and short axis length d_{i1} and d_{i2} . The subscripts "1" and "2" indicate the long axis and the short axis respectively, i indicates the i -th impact. The crater area ratio r_i is defined to represent the ratio of the crater area to the whole target area after i -th impact:

$$r_i = \frac{\pi d_{i1} d_{i2} / 4}{\pi \bar{D}^2 / 4} = \frac{d_{i1} d_{i2}}{\bar{D}^2} \quad (1)$$

Where \bar{D} represents the diameter of target. Obviously, we can use r_i to judge the degree of local damage to the target.



(a) first penetration

(b) second penetration

(c) third penetration

Figure 4 Diagrams of the relationship between each target's damage crater area ratio and UHMWPE volume

Each target's damage crater area ratio varies from fibre content after each penetration, the relationship of them is demonstrated in Figure 4. The following phenomenon can be observed from these diagrams:

- (1) After single impact (first penetration), the crater area decreased with the increasement of fibre's content, which illustrated slighter damage crater of target. When adding single fibre of UHMWPE fibre, the damage area ratio decreased linearly with the increase of the dosage. Although the hybrid-fibre concrete had a little fluctuation due to the interaction of the two fibres, in general, the larger the content, the smaller the damage of the crater. In this experiment, the minimum crater area of hybrid-fibre concrete is $S_{1.5}P_{0.3}$, as small as 6.51%, equal to 45.8% of plain concrete's, 66.8% of concrete reinforced by single steel fibre, 65.3% of concrete reinforced by single UHMWPE fibre.
- (2) After multiple impacts, all hybridizations of concrete target's crater area increased to some extent. After second shot, the damage area ratio increased an average of 0.59 times by the first shot, that is, the additional damage of the second shot was about 59% of the first shot. On the basis of the second cumulative damage, the third issue has again increased damage by 38%. Notably the additional damage will gradually decrease with the increase of the number of strikes. The range of change of S_0P_0 exceeds the average value, mainly due to its large first strike crater, so that the subsequent strike locations are all located in the crater.

The relationship between penetration depth of hybrid-fibre concrete under the impact of three-shot projectiles and the fibre content is shown in Figure 5.

We can observe from these diagrams that:

- (1) After first penetration, the depth of penetration (DOP) decreased with the increasement of fibre's content. DOP decreased linearly with the increase of fibre content in concrete reinforced by single steel or UHMWPE fibre. The main influencing factor of the depth of penetration in hybrid-fibre concrete is the steel fibre content. In general, the depth of penetration decreases as the steel fibre content increases. In this experiment, the minimum depth of penetration of hybrid-fibre concrete is $S_{1.5}P_{0.1}$, as small as 118mm, equal to plain concrete's 75.6%, 93.6% of concrete reinforced by single steel fibre, 81.9% of concrete reinforced by single UHMWPE fibre. The depth of

penetration of $S_{1.5}P_{0.2}$ was abnormal. It may be caused by the concrete stirred uniformly, and the fibre agglomeration effect is obvious, resulting in an abnormal increase in concrete DOP.

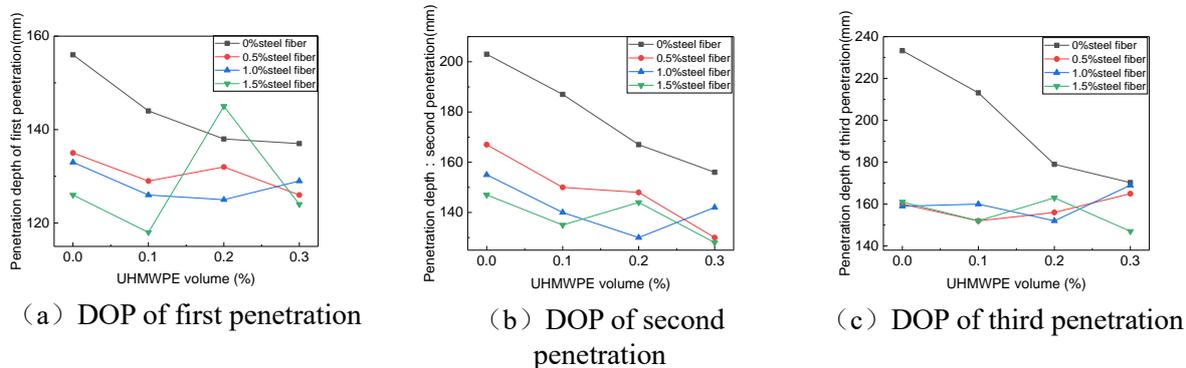


Figure 5 Diagrams of the relationship between each target's DOP and UHMWPE volume

- (2) After multiple shots, all concrete target's depth of penetration increased to some extent. Depth of penetration decreased more regularly on multiple-impact penetration compared to individual anomaly test data of single penetration. The depth of penetration of the second impact increases 16.7% averagely compared to the first impact, and the third increased 8.7% compared to the second. After the second and third penetration experiments, the minimum depth of concrete is $S_{1.5}P_{0.3}$, equal to 63.9% of plain concrete averagely, 90.5% of single steel fibre reinforced concrete and 85.5% of single UHMWPE fibre reinforced concrete.

5. Conclusions

From the triple-impact penetration experiments conducted on hybrid-fibre-reinforced concrete with steel fibre and UHMWPE fibre, pattern of target damage is compared. DOP and crater areas were examined after each penetration. The main conclusions are drawn as follows:

- (1) Hybrid-fibre concrete exploits the advantage of UHMWPE fibre in preventing initial crack germination and the effect of steel fibre on crack opening and expansion. Compared to plain concrete, concrete reinforced by single steel fibre or UHMWPE fibre had better penetration resistance with slighter crater damage and crack damage.
- (2) Under the multiple strike mode demonstrated in this paper, with the increase of the number of strikes, the crater damage area is gradually reduced. The DOP increases compared to the single strike, but the increasement mainly originates from the previous projectile impact.

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