

MULTIPLE IMPACT PENETRATION OF ULTRA HIGH PERFORMANCE CEMENTITIOUS COMPOSITES

Jianzhong Lai (1), Yaoyong Zhu (1), Sheng Xu (1) and Xujia Guo (1)

(1) School of Mat. Sci. & Eng., Nanjing Univ. of Science and Technology, Nanjing, China

Abstract

Ultra high performance cementitious composites (UHPCC) with compressive strength of 120 MPa ~ 250 MPa were prepared using ordinary concrete moulding process and hot water curing. The behaviour of UHPCC with excellent static mechanical properties was researched under multiple impact penetration. The damage of UHPCC targets was analyzed on penetration. The empirical equation of penetration depth in relation to the target compressive strength was modified using the experimental data and the multiple penetration formula proposed by Gomez.

Résumé

Des composites cimentaires à ultra-hautes performances, de résistance en compression comprise entre 120 et 250 MPa, ont été préparés par un procédé courant de moulage de béton et une cure en eau chaude. On recherchait un comportement mécanique statique de très haut niveau pour ces composites sous l'effet de multiples impacts pénétrants. L'endommagement des cibles sous pénétration a été analysé. L'équation empirique reliant la profondeur de pénétration à la résistance en compression de la cible a été modifiée sur la base des résultats d'essais et de la formule proposée par Gomez pour les pénétrations répétées.

1. INTRODUCTION

Military protection engineering is facing great challenge with the development of modern weapons. How to improve the survival rate of military constructions has become an urgent problem recently. Concrete is the most important building material which plays an irreplaceable role in the military constructions and defensive constructions. Thus, a lot of researches have been carried out to evaluate the impact resistance ability of concrete structures. Reinforced concrete has got great development after decades of research. Experts have put forward many concrete penetration models and empirical formulae under different testing conditions. For instance, Forrestal et al proposed concrete penetration resistance model by use of the spherical cavity expansion theory and a semi-empirical and semi-analytic model on the basis of penetration tests [1-2]. Gomez *et al.* conducted a series of experiments on

multiple impact penetration into semi-infinite concrete and proposed an empirical equation to calculate the multiple penetration depth in relation to the modifying factor and shot number [3]. Chen XW et al carried out the mechanical design and research of the body structure of earth penetration weapon (EPW) based on EPW penetrating in concrete targets [4-5]. Wang MY et al studied mechanics characteristics, energy change and material failure mechanism in the process of penetration and put forward the scaling conversion of penetration and perforation. Moreover, they modified and supplemented the empirical formulae of penetration depth [6]. He X et al carried out series of experiments on projectile penetrating into concretes at high speed under different conditions using high velocity impact penetration device and discussed the penetration ability, stability, deformation and failure of missiles [7].

Experimental researches on the multiple penetration impact are less. The purpose of the paper is to study the fracture process and the penetration depth under multiple projectile impacts into ultra high performance cementitious composites (UHPCC). The multiple impact penetration depth can be predicted using the proposed penetration formula in the paper.

Six type of UHPCC with different mix proportions were subjected to multiple penetration in the paper. The penetration resistance performance was analyzed on the damage form and the penetration depth of different targets. The factors that affect the experimental results such as fibres dimensions, fibres volume fraction, coarse aggregates were taken into account. The target strength factor *S* was obtained by fitting the experimental data on the basis of the research of Gomez. Then the multiple penetration calculation equation of UHPCC was proposed using modified target strength factor by regression analysis.

2. EXPERIMENTAL METHOD

2.1 Raw materials and mix proportions

All the specimens are prepared by the following raw materials: Portland cement with its mortar compressive strength not less than 52.5 MPa on 28 days required in Chinese national standard GB175-2007; silica fume with specific surface area of 22,000 m²/kg; blast-furnace slag powder with specific surface area of 1000 m²/kg; polycarboxylate based superplasticizer with a water-reducing ratio of more than 40 %; natural sands with the maximum particle size of 2.5 mm and a fineness modulus of 2.6; basalt coarse aggregates with the maximum particle size of 16 mm; copper coated steel fibres with the length of 6 mm and 13 mm and the diameter of 0.2 mm. The mix proportions and static compressive strengths of the UHPCC are listed in Table 1. All the specimens were cured in 20°C water for 3 days and then in 95°C water for 24h.

Table 1: Mix proportions of UHPCC

Specimen	Binder			VSF/%	VDSF/%	G/b	S/b	W/b	SP/b	f/MPa
	Cement/%	SF/%	Slag/%							
M0	50	20	30	0	0	0	1.2	0.19	0.02	123.6
MSF3	50	20	30	3	0	0	1.2	0.19	0.02	231.6
MDSF3	50	20	30	0	3	0	1.2	0.19	0.02	201.4
MG1.2	50	20	30	0	0	0.6	0.6	0.19	0.02	150.7
MG1.2SF3	50	20	30	3	0	0.6	0.6	0.19	0.02	247.5
MG1.2DSF3	50	20	30	0	3	0.6	0.6	0.19	0.02	206.7

Note: SF: silica fume; VSF: the volume ratio of 13 mm steel fibres; VDSF: the volume ratio of 6mm steel fibres; G/b: the mass ratio of coarse basalt aggregates to binder; S/b: the mass ratio of sands to binder; W/b: the mass ratio of water to cement; SP/b: the mass ratio of superplasticizer to binder; *f*: static compressive strength of UHPCC (cured in 20°C water for 3 days then in 95°C water for 24h).

2.2 Experimental system of penetration

The impact penetration tests were conducted with a gun-target system (Fig. 1), which launched the projectiles vertically at the speed of about 800 m/s. The target body was constrained with steel sleeve. The size of cylindrical target is $\Phi 100 \times 100$ mm. The 7.62 mm standard bullet is used and it has lead shell and steel core. The mass of the bullet is 9.68 g and the diameter is 7.62 mm. The curvature radius of sharp conical nose of the bullet is 400 mm. The multiple impact penetration tests were carried out on a shooting range.

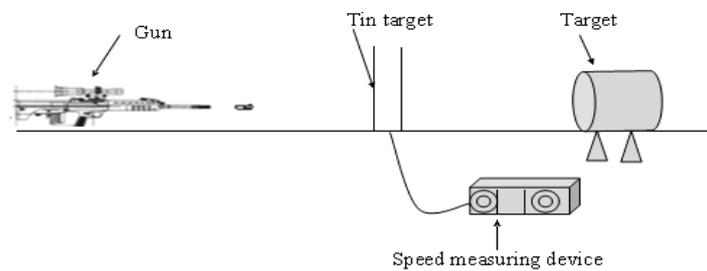


Figure 1: Set-up of penetration experiments

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Failure patterns of UHPCC subjected to penetration

Six different targets were shot respectively in the multiple penetration tests. Target damage patterns were different because different concrete targets had distinctive impact resistant abilities resting with the material compressive strength. Fig. 2 to Fig. 7 show the front and rear face damage of the each target after shooting.



(a) M0 (b) MSF3 (c) MDSF3 (d) MG1.2 (e) MG1.2SF3 (f) MG1.2DSF3

Figure 2: Damage in the front of the targets subjected to the first impact



(a) M0 (b) MSF3 (c) MDSF3 (d) MG1.2 (e) MG1.2SF3 (f) MG1.2DSF3

Figure 3: Damage in the back of the targets subjected to the first impact

Fig. 2 shows the first impact damage pattern in the front of targets. It is found that large area of spalling appeared in the target M0 and MG1.2 without steel fibres. In contrast, other targets just have different number of macroscopic cracks and different degree of surface damage. From Fig. 3, it is seen that almost all the targets remain intact in the back except for M0 and MG1.2 which have some small spalling or crack. Then the second shooting test was done and the damage pattern of the targets is shown in Fig. 4 and Fig. 5.

Target M0 was perforated after the second shooting and could not be subjected to the subsequent penetration test. The front damage of other targets was increased to some degree. There was a large area of spalling in the back of the target M0 and MG1.2. However, there were just some small cracks in the back of the target MG1.2SF3 and MG1.2DSF3 which contain steel fibres. The back of target MSF3 and MDSF3 still remained initial state. The third penetration experiment and the impact results are shown in the Fig. 6 and Fig. 7.



(a) M0 (b) MSF3 (c) MDSF3 (d) MG1.2 (e) MG1.2SF3 (f) MG1.2DSF3
 Figure 4: Damage in the front of the targets subjected to the second impact



(a) M0 (b) MSF3 (c) MDSF3 (d) MG1.2 (e) MG1.2SF3 (f) MG1.2DSF3
 Figure 5: Damage in the back of the targets subjected to the second impact



(a) MSF3 (b) MDSF3 (c) MG1.2 (d) MG1.2SF3 (e) MG1.2DSF3
 Figure 6: Damage in the front of the targets subjected to the third impact



(a) MSF3 (b) MDSF3 (c) MG1.2 (d) MG1.2SF3 (e) MG1.2DSF3
 Figure 7: Damage in the back of the targets subjected to the third impact

The target MG1.2 was perforated after the third shooting and serious damage was found in the front of other targets. There were various numbers of cracks in the back of the targets. Overall, the targets containing steel fibres have an obvious advantage in resisting the impact of the bullet. All targets can be fully resistant to first impact penetration as shown in the test results. The projectiles were inlaid in the targets with steel fibres and this phenomenon did not occur in the target MG1.2 with basalt aggregates. A large area of spalling was found in the front of target M0 and MG1.2 after the first impact penetration and the penetration depth of MG1.2 was smaller than that of M0.

After the first impact penetration, it is found that the area of surface spalling of target MSF3 containing 13 mm fibres is less than that of target MDSF3 containing 6 mm fibres. The area of front surface spalling of targets containing coarse aggregates including MG1.2SF3 and MG1.2DSF3 is less than that of targets without coarse aggregates including MSF3 and MDSF3. After the second impact penetration, all the targets were damaged more seriously. The area of front crater was enlarged and a small amount of cracks were found in the back of some targets. In particular, the target M0 was perforated by bullet impact and there was much spalling in the back.

The area of front crater expanded further and the micro-cracks in the back of targets were increased gradually after the third penetration. The target MG1.2 was perforated on the third impact and the back spalling of MG1.2 was most compared with other targets. There were just some small cracks on the back of the targets containing steel fibres. By comparison, larger macroscopic cracks were found on the back of the targets containing both steel fibres and coarse aggregates and part of these targets had been separated from the steel ring.

General speaking, the addition of steel fibres can make a beneficial effect on the anti-penetration property of UHPCC. The steel fibres with larger length to diameter ratio can increase the ability of anti-penetration on the basis of good concrete workability and homogeneity. The length to diameter ratio of steel fibres is an important influencing factor on the target strength. A larger length to diameter ratio can improve significantly the connecting force between the matrix and the fibres which can help to absorb the impact energy of the projectile. The longer steel fibres are difficult to be pulled out from the matrix and play a better role in transferring and bearing distributed loads on the projectile impact which greatly reduces the damage of concretes.

For targets with coarse aggregates, the bullet encountered greater resistance and hardly embedded into the target. This is mainly because the addition of basalt aggregates can obviously enhance the compressive strength of the target. It is seen that the moving path of bullets was deflected in the process of penetration. This phenomenon can reduce the target impact damage due to the alteration of bullet movement direction. The matrix damage gradually increased after multiple penetrations. Strong stress wave arrived to the back surface of the target and resulted in obvious cracks or large area of spalling. The target without fiber reinforcement can be perforated easily after multiple impacts.

3.2 Multiple penetration depth of UHPCC

The penetration depth of each target was measured after each impact and the data were shown in table 2. From Table 2, it is obviously seen that the multiple penetration resistance of target M0 is worst and fibre reinforcement can extremely improve the resistance of target to impact penetration. From two groups of data of target MSF3 and MDSF3, it can be seen that the different length of steel fibres influence the anti-penetration ability of targets with the

same volume fraction of steel fibres. According to the data, the bullet penetration depth of target MSF3 is decreased by 3.8 %, 6.9 %, 17.8 % respectively compared with that of target MDSF3 at the same number of impact.

Basalt coarse aggregates can significantly improve the penetration resistance of UHPCC by comparing two groups of experimental data of M0 and MG1.2. Target M0 was perforated completely after two shootings while target MG1.2 can withstand three shootings. It is found that the addition of steel fibres and coarse aggregates can greatly improve the material first anti-penetration ability from four groups of experimental results of MSF3, MG1.2SF3, MDSF3 and MG1.2DSF3. In the first penetration test, the target penetration depth is decreased by 52.9 % and 47.2 % with the addition of coarse aggregates when the fibre fraction and lengths are same. In the process of first penetration, high strength coarse aggregates have the effect of deviation which results in the reduction of penetration depth. But this effect is reduced gradually after multiple impacts because the damage in the target accumulates gradually after multiple impacts and the adhesion force between coarse aggregates and matrix is weakened.

Table 2: Penetration depth of UHPCC subjected to multiple impacts

Specimen	Penetration depth /mm		
	First impact	Second impact	Third impact
M0	54	77	--
MSF3	51	54	60
MDSF3	53	58	73
MG1.2	31	64	68
MG1.2SF3	24	43	60
MG1.2DSF3	28	33	63

4. MULTIPLE PENETRATION EQUATION OF UHPCC

On the basis of Forrestal's single impact penetration model, an empirical equation was developed by Gomez *et al.* to predict the multiple impact penetration depth of semi-infinite concrete target [3].

$$P = \frac{m}{2\pi a^2 \rho N} \ln \left(1 + \frac{N \rho V_1^2}{S f_c} \right) + 4a \quad (1)$$

Where, P is the penetration depth, a is the projectile radius, ρ is the target material density, m is the bullet quality, V1 is the bullet velocity, f_c is the unconfined compressive strength of the target material, S is the strength factor and it is a dimensionless parameter that modifies the compressive strength, N is given by

$$N = \frac{8\psi - 1}{24\psi^2} \quad (2)$$

N is a function of the Caliber Radius Head (CRH), $\psi = s/2a$, where s is the radius of the ogive-nose of the projectile and a is the projectile radius [3].

As shown in Fig. 8, the graphic expression of the relationship between S and concrete static compressive strength f_c was obtained using the equations developed by Gomez et al and the experimental data in this paper.

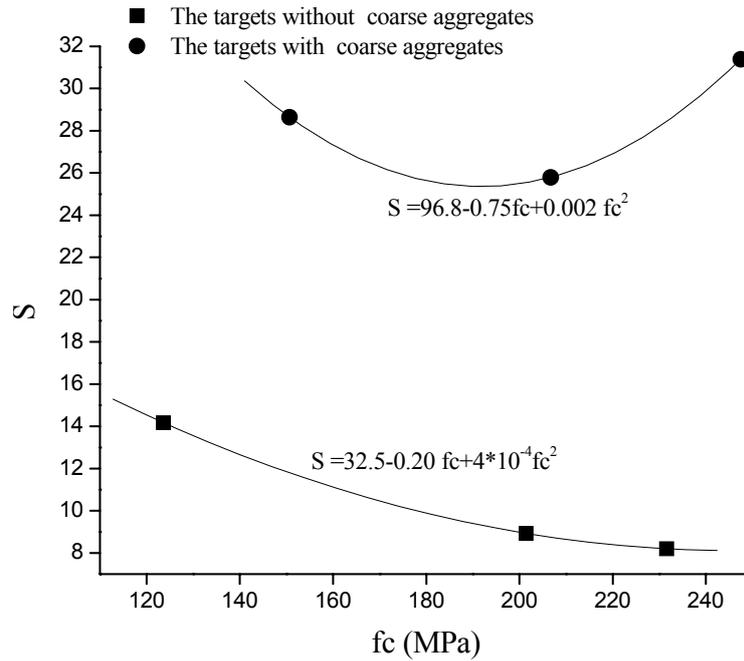


Figure 8: The relationship between S and f_c of UHPCC subjected to the first penetration

In Fig. 8, the strength factor S could be calculated when the concrete static compressive strength is given. Then the first penetration depth can be got using the Eq. (1). So how to get more accurate strength factor S is the most important step for the theoretical prediction of penetration depth. The strength factor formulae shown in Fig. 8 are proposed based on the equation given by Gomez and the penetration depth of UHPCC in this paper. It is seen that coarse aggregates have significant effect on the strength factor. Therefore two kinds of strength factor are discussed respectively for the targets with and without coarse aggregates and expressed by following two formulae:

$$S = 32.5 - 0.20 f_c + 4.0 \times 10^{-4} f_c^2 \quad (\text{Targets without coarse aggregates}) \quad (3)$$

$$S = 96.8 - 0.75 f_c + 0.002 f_c^2 \quad (\text{Targets containing coarse aggregates}) \quad (4)$$

With the increasing of penetration number, it is not suitable to judge the penetration ability by initial static compressive strength because the damage was found in the concrete target and its anti-penetration ability was decreased. Gomez *et al.* had put forward a modified formula as a function of shot number. They corrected the strength factor S which was equivalent to adjust the initial static compressive strength to a reasonable value. Based on Gomez's ideas, it is assume that:

$$S' = S \cdot (\alpha \times \ln(n) + 1) \quad (5)$$

Where, n is the impact number, α is the constant to be determined.

A stable value of α is found by non-linear regression analysis on the data of different targets. It is found that satisfying results are not easy to achieve if only S is modified. So it is important to correct the overall equation. In the experiments, different type of targets have different initial strength factor. Thus constant α is different. Eventually, the penetration depth equation of the targets without coarse aggregates is as follows:

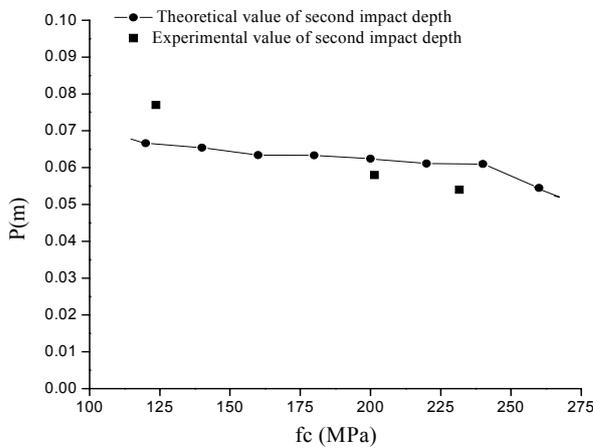
$$P = \frac{m}{2\pi a^2 \rho N} \ln \left(1 + \frac{N \rho V_1^2}{S' f_c} \right) + 4a \quad (6)$$

where, $S' = S(-0.26 \cdot \ln(n) + 1)$ (7)

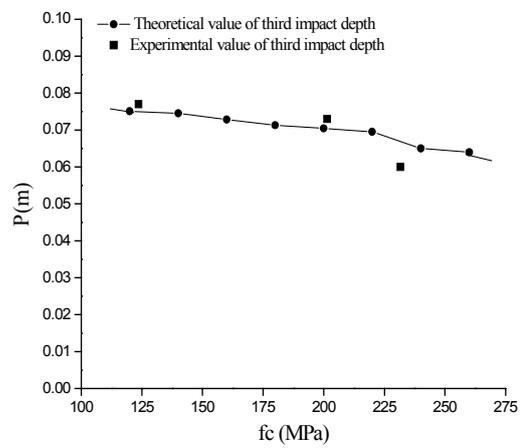
The penetration depth equation of the targets with coarse aggregates is as follows:

$$P = \frac{m}{2\pi a^2 \rho N} \ln \left(1 + \frac{N \rho V_1^2}{S' f_c} \right) + 6a \quad (8)$$

Where, $S' = S(-0.62 \cdot \ln(n) + 1)$ (9)

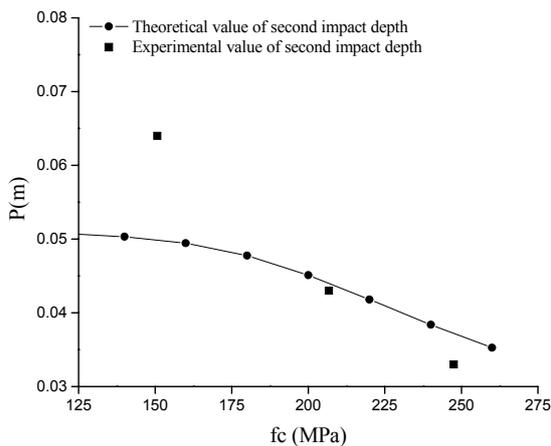


(a) the second penetration

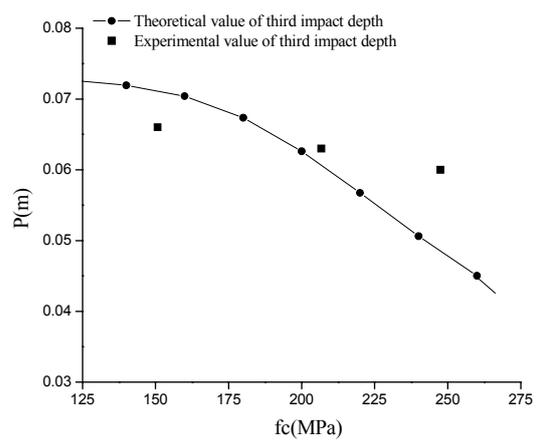


(b) the third penetration

Figure 9: Penetration depth versus static compressive strength of UHPCC without coarse aggregates



(a) the second penetration



(b) the third penetration

Figure 10: Penetration depth versus static compressive strength of UHPCC with coarse aggregates

The difference between the formula calculation value and the experimental value is shown in Fig. 9 and Fig. 10. It can be found from the comparing results that there is less difference between the formula calculation value and the experimental value for the targets without coarse aggregates, while there is more difference for the targets with coarse aggregates especially for the target with lower static compressive strength. The reason for this result is the uneven distribution of aggregates in the matrix and the non-uniform damage caused by multiple penetration. So the anti-penetration ability of the target is not corresponding very well with its static compressive strength. Another reason is the inevitable error in data measurement.

5. CONCLUSIONS

The penetration resistance of UHPCC can be greatly improved when steel fibres and coarse aggregates are added into the concrete matrix. Those two types of reinforcement have different enhancement mechanism. Coarse aggregates can generate a big force to resist the first penetration and make the project deflect so as to decrease the penetration depth. Steel fibres can increase the impact toughness of targets and decrease concrete cracks caused by stress wave. Longer steel fibres can improve penetration resistance more comparing with shorter steel fibres on the premise that steel fibres are well dispersed in concrete matrix.

The depth of penetration is related with the static compressive strength of UHPCC. The strength factor S of UHPCC is obtained on the base of Gomez's formula. The first penetration depth can be obtained using parameter S . The multiple penetration depth can also be calculated by modifying the parameter S to be suitable for repeated impact.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (No.51278249, 50808101), the China Postdoctoral Science Foundation (No.20080431100, 200902520), the NUST Excellence Plan "Zijin Star".

REFERENCES

- [1] Forrestal M J, Tzou D Y. A spherical cavity-expansion penetration model for concrete targets [J]. *International Journal of Solids and Structures*, 1997, 34(31-32): 4127-4146.
- [2] Forrestal M J, Altman B S, Cargile J D, et al. An empirical equation for Penetration depth of ogive-nose projectiles into concrete targets [J]. *International Journal of Impact Engineering*, 1994, 15(4): 395-405.
- [3] Gomez J T, Shukla A. Multiple impact penetration of semi-infinite concrete [J]. *International Journal of Impact Engineering*, 2001, 25(10): 965-979.
- [4] Chen Xiaowei. Mechanics of structural design of EPW (I): The penetration/perforation theory and the analysis on the cartridge of projectile [J]. *Explosion and Shock Waves*, 2005, 25(6): 499-505.
- [5] Chen Xiaowei, Jin Jianming. Mechanics of structural design of EPW (II): Analyses on the design of EPW projectiles, concrete targets and examples [J]. *Explosion and Shock Waves*, 2006, 26(1): 71-78.
- [6] Wang Mingyang, Zheng Daliang, Qian Qihu. The scaling problems of penetration and perforation for projectile into concrete media [J]. *Explosion and Shock Waves*, 2004, 24(2): 108-114.

- [7] He Xiang, Xu Xiangyun, Sun Guijuan. Experimental investigation on projectiles high-velocity penetration into concrete targets [J]. *Explosion and Shock Waves*, 2010, 30(1): 1-6.