International Journal of Impact Engineering 84 (2015) 1–12

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Repeated penetration and different depth explosion of ultra-high performance concrete

Jianzhong Lai*, Xujia Guo, Yaoyong Zhu

School of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

A R T I C L E I N F O

Article history:
Received 30 August 2014
Received in revised form
5 May 2015
Accepted 8 May 2015
Available online 19 May 2015

Keywords:
Ultra-high performance concrete
Penetration
Explosion
Damage
Finite element

A B S T R A C T

Ultra-high performance concrete (UHPC) was prepared and its dynamic behavior was researched under repeated penetration and different depth explosion using 14.5 mm bullets and TNT explosives. The penetration depth of UHPC was measured on different number of penetrations. The damage of UHPC was measured by the ultrasonic wave velocity method and the penetration process of UHPC was observed by the high-speed camera. The explosion damage of UHPC with TNT explosive embedded at different depths was measured and the explosion process was simulated by the finite element method. Results show that UHPC resistance to repeated penetration and different depth explosion is improved significantly by hybrid reinforcement of steel and basalt fibers. The second penetration depth of UHPC with basalt coarse aggregates is decreased and the damage of UHPC with basalt coarse aggregates is more than that of UHPC without basalt coarse aggregates. The mass and the placing depth of explosive have important effects on the damage of UHPC.

1. Introduction

Underground works will suffer attacks by the precision guided penetration weapons. So it is an urgent problem to improve the resistant ability of protective structures against repeated impact and different depth explosion. Forrestal and Tzou [1] proposed a concrete penetration resistance model by using the spherical cavity expansion theory and the predictions from the model are in good agreement with penetration depth data from experiments. Gomez and Shukla [2] 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. Almansa and Canovas [3] proposed a model to predict the thickness needed to avoid perforation or scabbing and to obtain the residual velocity by researching the behavior of normal and steel fiber reinforced concretes under impact of small projectiles. Teng et al. [4] proposed a simplified model to perform finite element analyses on reinforced concrete subjected to impact and the computational results using this model were very close to the test data. Almusallam et al. [5] researched the effectiveness of hybrid fibers in improving the impact resistance of concrete slabs. The test results showed that the hybrid fibers in the concrete led to smaller crater volumes and reduced the spalling and scabbing damage. Tabatabaei et al. [6] conducted a series of tests to compare the blast resistance of panels constructed with either conventional reinforced concrete (RC) or long carbon fiber reinforced concrete (LCFRC). Results showed that the addition of long carbon fibers significantly increased the concrete's blast resistance and significantly reduced the degree of cracking associated with the concrete panels. Zhou et al. [7] used a dynamic plastic damage model for concrete material to estimate the responses of both an ordinary reinforced concrete slab and a high strength steel fiber concrete slab subjected to blast loading. Comparison of numerical results with the experimental results showed that the present model gave reliable prediction of blast pressure and damage from the first blast but could not give an accurate estimation of blast pressure on the slab from a second blast.

Ultra-high performance concrete (UHPC) has ultra-high strength, high toughness and high durability. Therefore, it is an ideal selection for building protective structure. Yu et al. [8] designed an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) with a relatively low binder amount by utilizing the improved packing model. The maximum compressive and flexural strengths at 28 days of the obtained UHPFRC were about 150 MPa and 30 MPa respectively. Wang et al. [9] assessed the

---

* Corresponding author. Tel.: +86 13770574619.
E-mail address: jzh-lai@163.com (J. Lai).

http://dx.doi.org/10.1016/j.ijimpeng.2015.05.006
0734-743X/

durability of UHPFRC after accelerated aging using gas permeability under varying confinement and the UHPFRC properties were compared to those of standard mortar and ordinary concrete. Habel et al. [10] studied the development of the mechanical properties for UHPFRC between 3 and 365 days. Results showed that the rate of development of mechanical properties was highest for the secant modulus, followed by the compressive and then the tensile strength. Oertel et al. [11] compared the effects of different silica types on the hydration in ultra-high performance concrete. Results indicated that silica fume and pyrogenic silica accelerated alite hydration by increasing the surface for nucleation of C-S-H phases. Tuan et al. [12] studied the effect of rice husk ash (RHA) on the hydration and microstructure development of UHPC. The results showed that the addition of RHA increased the degree of cement hydration in UHPC at later ages and refined the pore structure of UHPC and reduced the $Ca(OH)_2$ content. Kang and Kim [13] investigated the effect of the fiber orientation distribution on the tensile behavior of Ultra High Performance Fiber Reinforced Cementitious Composites (UHPFRCC). Results showed that the effect was very small on pre-cracking behavior, but was significant on post-cracking behavior of UHPFRCC.

Protective structure built with UHPC has excellent ability against penetration, impact and explosion. Millard et al. [14] investigated the dynamic increase factor (DIF) under flexural and shear high-speed loading of ultra high performance fibre reinforced concrete. The results show that the DIF of the flexural tensile strength is rising from 1.0 at 1 s^{-1} but no DIF should be used to increase the shear strength at high loading rates. Maca et al. [15] researched the mix design of UHPFRC and its response to deformable and non-deformable projectile impact. The magnitude of the damage was assessed based on the penetration depth, crater diameter and loss of mass. Riedel et al. [16] conducted an experimental series on UHPC panels subjected to aircraft engine impact. The material's high compressive strength reduced the effect of the front side missile penetration without significant spalling. The mechanical effects of fibers reduce damage to the panel rear side and increase the ballistic limit velocity. Ellis et al. [17] investigated the behavior of UHPC panels subjected to planar waveforms with specific impulses between 0.77 and 2.05 MPa-ms and the experimental results were used to validate a multiscale model which accounts for structure and phenomena at two length scales. Yi et al. [18] performed blast tests on reinforced ultra-high strength concrete (UHSC) and reactive powder concrete (RPC) panels to evaluated their resistance to terrorist attacks or accidental impacts. The results showed that UHSC and RPC have better blast explosion resistance than normal strength concrete. Mao et al. [19] presented a numerical investigation on the performance of UHPFRC under blast loading with a concrete material model which takes into account the strain rate effect. The performance of the numerical models was verified by comparing simulation results to the data from corresponding full scale blast tests.

In this paper, UHPC was prepared by different fibers reinforcement and replacing cement with large amount of ultra-fine industrial waste powders. The resistance of UHPC subjected to repeated penetration and different depth explosion was researched using 14.5 mm bullets and TNT explosive. The penetration depth and damage of concrete targets were measured after impact of penetration and blast.

2. Materials and methods

The cylindrical targets of UHPC were 300 mm in the diameter and 300 mm in the length. The targets were cast inside cylindrical steel molds with the thickness of 1.6 mm. The mix proportions of UHPC are shown in Table 1. All the targets were prepared by the following raw materials: Portland cement, silica fume, blast-furnace slag powder, superplasticizer, natural sand, coarse aggregate and fibers. The mortar compressive strength is no less than 52.5 MPa on 28 d for the Portland cement according to the Chinese national standard GB175-2007. The specific surface areas of the silica fume and blast-furnace slag powder are 22000 m^2/kg and 1000 m^2/kg respectively. The water-reducing ratio of the polycarboxylate based superplasticizer is more than 40%. The maximum particle sizes of the natural sand and basalt coarse aggregate are 2.5 mm and 16 mm respectively. The fineness modulus of the natural sand is 2.6. The length and diameter of the copper coated steel fiber are 13 mm and 0.2 mm. The length and diameter of the basalt fiber are 20 mm and 17 μm.

The penetration experiments were carried out using the 14.5 mm standard bullets and the 14.5 mm gun. The bullets were shot into the targets perpendicularly. The mass, the diameter and the length of the bullet are 43 g, 14.8 mm and 52 mm respectively. The device of penetration is shown in Fig. 1 including the gun, tinfoil target, time-meter, high speed camera, concrete target and back plate.

The dimension of the targets for blast is same as that of the targets for penetration. A cylindrical hole with the size of $\Phi 38$ mm × 150 mm was prefabricated in the center of the target for placing different depth explosives as shown in Fig. 2. The cylindrical TNT explosive with the diameter of 37 mm was embedded inside the hole. The length of the cylindrical TNT explosive varied with the mass. Two kind of buried depth of TNT explosive are selected (150 mm and 50 mm) in order to analyze the influence of buried depth on the behavior of ultra-high performance concrete subjected to blasting. The dimension and mass of the TNT explosives for different targets are shown in Table 6 and 7.

Table 1
Mix proportions of UHPC.

Materials	Binder(wt%)			S/b	G/b	Sp/b	W/b	V_{SF}(%)	V_{BF}(%)	f_c (MPa)
	Cement	Silica fume	Slag							
M2	50	20	30	1.2	0	0.02	0.18	0	0	124
M2SF3	50	20	30	1.2	0	0.02	0.18	3	0	232
M2SF3BF1	50	20	30	1.2	0	0.02	0.18	3	1	234
GM2SF3	50	20	30	0.6	0.6	0.02	0.18	3	0	248
GM2SF3BF1	50	20	30	0.6	0.6	0.02	0.18	3	1	251

Note: S/b: the mass ratio of sands to binder, G/b: the mass ratio of coarse basalt aggregates to binder, Sp/b: the mass ratio of superplasticizer to binder, w/b: the mass ratio of water to binder, V_{SF}: the volume fraction of steel fibers, V_{BF}: the volume fraction of basalt fibers, f_c: static compressive strength of UHPC cured in 20 °C water for 3 d and then in 95 °C water for 24 h).