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# Triaxial compressive behavior of UHPCC and applications in the projectile impact analyses

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## HIGHLIGHTS

- Optimal UHPCC for protective structures against projectile penetration was prepared.
- Triaxial compressive behavior of UHPCC with confining pressure up to 100 MPa was tested.
- Normalized peak axial strain increases linearly with the rising of confinement ratio.
- UHPCC under triaxial compression obey Willam-Warnke and Power-law failure criteria.
- Strength parameters of HJC constitutive model for HSC were confirmed and validated.

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## ABSTRACT

For the constructions of protective structures against potential projectile high-speed impact, the optimal ultra-high performance cement based composite (UHPCC) (straight steel fiber with the volumetric ratio of 2%, high-strength basalt aggregates with the size range of 5-10 mm, the designed uniaxial compressive strength of ~ 100 MPa) was prepared. By casting two batches of 50 mm × 100 mm cylindrical UHPCC specimens with the uniaxial compressive strengths of 95 MPa and 129 MPa, the triaxial compressive behavior of UHPCC under high confining pressure (up to 100 MPa) was experimentally studied. Based on the deviatoric stress-strain curves under various confining pressure, the failure criteria and toughness of UHPCC under triaxial compression were discussed. At last, the dominant strength parameters of Holmquist-Johnson-Cook constitutive model were confirmed based on the present and existing triaxial compression tests on high-strength concrete. The validity of which was verified based on eleven sets of projectile penetration or perforation tests on concrete-like targets with the uniaxial compressive strength ranged from 60 MPa to 157 MPa.



## 1. Introduction

Ultra-high performance cement based composite (UHPCC) is a relatively new type of composite material which possess very low water-to-binder ratio, high amount of high-range water reducer (HRWR), fine aggregates with the maximum size less than 1 mm and high-strength steel fibers with the diameter of 0.15–0.20 mm [1]. Compared with the newly developed engineered cementitious composites (ECC) [2], multi-scale cement composite (MSCC) [3], reactive powder concrete (RPC) [4] and slurry infiltrated fiber concrete (SIFCON) [5], the ordinary curing temperature and pressure preparation procedures, as well as the comprehensive prominent characteristics (e.g. high compressive strength and tensile strength, high fracture energy, self-consolidating workability and very low permeability), make UHPCC becoming the most prospective construction materials for both military and civil protective structures (fortifications, nuclear containment, defense shelter and etc.), which are designed to withstand the intentional or accidental impact and blast loadings caused by projectiles, fragments, aircrafts, explosives and etc. For above scenarios, the concrete material always undergoes multi-axial compressions with a high confinement, thus the investigations of triaxial compressive behavior of UHPCC are important and essential to provide valuable information (e.g. strength criteria, post-peak response) for the structural design and calibration/-validation of the constitutive model.

The existing works on the mechanical behavior of UHPCC were mainly concentrated on the uniaxial compressive or tensile properties [6–8], limited tests were carried out to investigate the triaxial

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compressive behavior of UHPCC with relatively high confinement ratio. In the present study, based on the previous works [9–14] on impact resistance of cement composites, the optimal UHPCC (straight steel fiber with the volumetric ratio of 2%, high-strength basalt aggregates with the size range of 5-10 mm, the designed uniaxial compressive strength of ~100 MPa) for protective structures against projectile high-speed impact was prepared under ordinary procedures. Triaxial compressive test on two batches of 50 mm × 100 mm cylindrical specimens with uniaxial compressive strength of 95 MPa and 129 MPa was conducted with the confinement ratio (the ratio of confining pressure to the uniaxial compressive strength) reached 0.84 and 0.78, respectively. The deviatoric stress-strain curves for various confinement pressure were derived, the failure criteria and toughness of UHPCC under triaxial compression were discussed. Finally, by using the present and existing triaxial compression tests data [15–19] on high-strength concrete, the dominant strength parameters of Holmquist-Johnson-Cook (HJC) constitutive model [20] were confirmed. Furthermore, aiming to verify the validity of the proposed model parameters, by utilizing the finite-element program LS-DYNA, the predicted projectile penetration depth and residual velocity were compared with the experimental data from eleven sets of projectile penetration or perforation tests on concrete and rock targets with the uniaxial compressive strength ranged from 67.5 MPa to 157 MPa.

## 2. A review of the existing works on triaxial behavior of concrete

The existing related works are mainly on normal-strength concrete (NSC) and high-strength concrete (HSC). Wang et al. [21] performed a series of triaxial compressive test on 100 mm cubic specimen, the unconfined compressive strength was around 10 MPa and the confinement ratio reached up to 3, the nearly linear relationship of normalized triaxial compressive strength and the confinement ratio was obtained. Sfer et al. [22] conducted the triaxial compressive test on 150 mm × 300 mm cylindrical specimens with the unconfined compressive strength was around 30 MPa and the confinement ratio varied within 0-2. It is observed that the failure envelope of which correlated well with the nonlinear Etse and Willam model [23]. Sirijaroonchai et al. [24] experimentally studied the influences of fiber types (high-strength hooked steel fiber, ultra high molecular weight polyethylene fiber), fiber volumetric fraction (1%–2%) and confining pressure (41 MPa and 52 MPa) on the passive triaxial behavior of high performance fiber reinforced cement composites with the unconfined compressive strength was ~50 MPa. It indicated that, for relatively high confined ratio, confining effect introduced by the fibers with various types and fractions became minor. Chern et al. [25] experimentally investigated the influences of steel fiber volumetric ratio (0–2%) and confinement pressure (0–70 MPa) on the triaxial strength of the NSC with the uniaxial compressive strength around 20 MPa. It was concluded that the addition of steel fibers has insignificant effect on the mechanical behavior of concrete at confining pressure up to 70 MPa.

Correspondingly, Lu and Hsu [15] compared the triaxial compressive stress-strain relations and failure criteria of HSC and steel fiber reinforced HSC (SFHSC), also found the slight reinforcing effect on the uniaxial and triaxial strengths of 100 mm × 150 mm cylindrical specimens. In which the unconfined compressive strengths of HSC and SFHSC were 67 MPa and 69 MPa, and the maximum confinement ratios were 0.74 and 1, respectively. Xie et al. [16] experimentally confirmed the three-parameter parabolic relationships between the confined pressure and the maximum as well as residual strengths of HSC containing silica fume specimens (55.5 mm × 110 mm cylinder), the variation ranges of unconfined compressive strengths and confinement ratio were 60.2–119 MPa and 0–0.504, respectively. Ansari and Li [26–28] experimentally studied the triaxial constitutive relationships of 100 mm × 200 mm and 75 mm × 150 mm cylindrical concrete specimens, with the uniaxial compressive strengths ranged from 47.7 MPa (maximum confinement ratio of 0.878) to 107.3 MPa (maximum confinement ratio of 0.7792). The less pronounced effect of confining pressure on the failure strength of HSC than NSC, and the distinct effect of confining pressure on the failure strain were found. Also the specimen size of HSC has slight effect on the triaxial compressive failure strength and failure surface. Furthermore, the empirical failure criterion based on Ottosen constitutive model [29] was established for HSC. Attard et al. [30] and Candappa et al. [31] investigated the stress-strain relationships of concrete specimen (100 mm × 200 mm cylinder) with the unconfined compressive strength ranges were 60 MPa–130 MPa and 41.9 MPa–103.3 MPa, respectively. The empirical model for full triaxial stress-strain relationship was developed and the parameters for Ottosen constitutive model [29] were suggested. By comprehensively assessing the validities of the existing nine empirical formulae for triaxial ultimate compressive strength of HSC, Girgin et al. [32] proposed a new relationship to predict the ultimate strength of concrete with the unconfined strength ranged from 60 MPa to 132 MPa. Sovják et al. [17] experimentally studied the triaxial cylinder (100 mm × 200 mm) and cubic ($100\ mm^3$) compressive strengths of ultra high performance concrete, the unconfined compressive strengths of which were 123 MPa and 148 MPa and the confined ratio increased up to 0.25 and 0.6, respectively.

Additionally, Imran et al. [33], Farnam et al. [18], Vu et al. [34] and Piotrowska et al. [35] have systematically studied the influences of moisture content, loading path, steel fiber volumes, size, shape and composition of coarse aggregate as well as the cement paste volume on the triaxial compressive behavior of concrete.

However, for the widely applications of UHPCC in the on-site constructions of protective structures against projectile impact, limited works were concentrated on the composition optimization based on the balances of anti-strike ability and costs, preparation of optimal UHPCC under ordinary procedure, triaxial compressive behavior of optimal UHPCC as well as its applications in the projectile penetration or perforation analyses. The present paper is aiming to fill in the above gaps.

## 3. Mixing optimization of UHPCC and triaxial compression test

### 3.1. Compositions

For the protective structures withstand the high-speed projectile impact, the resistance of concrete target depends mainly on the compressive strength of the target as well as the size and strength (hardness) of the coarse aggregate [9–11,36–38]. Therefore, adding the high-strength coarse aggregate into the matrix of the concrete, although the compressive strength of the concrete might be decreased to some extent, while the impact resistance of which would be enhanced for the existence of the coarse aggregate.

As for the target strength, Zhang et al. [9], Langberg and Markeset [10], Wu et al. [11] have experimentally found that the penetration depth of projectiles are no longer decreasing obviously when the compressive strength of the targets are larger than a certain value, the compressive strengths of 90 MPa–150 MPa were recommended for protective structures by comprehensive considerations on the protective efficiency and production costs. Besides, as for the shapes (straight, hooked, twisted) and volumetric fractions of steel fibers, Wu et al. [11], Máca et al. [12], Sovják et al. [13] and Peng et al. [14] have proposed that the straight steel fibers with