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Influences of nano-particles on dynamic strength of ultra-high performance concrete

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ABSTRACT

Known for its high strength, ductility and durability, ultra-high performance concrete (UHPC) is a topic of interest in recent years for scientists and civil engineers. Great potential application of UHPC has driven increasingly more investments and research into this industry. In recent studies, taken advantage of the nanotechnology, novel UHPC material with nano material addition was developed. Great static performance improvement was observed when compared with normal strength concrete. To obtain full understanding of material properties, especially dynamic performance, Split-Hopkinson Pressure Bar (SHPB) tests were conducted on this new concrete material. For comparison purpose, static properties from uniaxial compression and split tensile tests are obtained and discussed. In this paper, effects of nanomaterials on behaviour of UHPC are assessed through group comparison. Dynamic increase factor (DIF) values for both the dynamic compressive strength and tensile strength are generated. It is found that the strength of UHPC increases with the rising of strain rates and dosage of nano material influences UHPC dynamic properties. However, UHPC is noted to be less rate sensitive comparing with normal strength concrete. Microscopy analysis including Scanning Electron Microscope (SEM) Analysis, X-Ray Diffraction (XRD) Analysis and X-Ray Fluorescence (XRF) Analysis are conducted to understand the macroscopic failure phenomenon, element composition and concrete hydration process.

1. Introduction

Ultra-High Performance Concrete (UHPC), also known as reactive powder concrete (RPC), is a relatively new material formulated by combining Portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water, and steel or organic fibres. Compared with normal strength concrete material, UHPC is known for its high strength, high ductility and high durability. It allows construction of sustainable and economic buildings with extraordinary slim design. Its high strength and ductility makes it an ideal building material for bridge decks, storage halls, thin-wall shell structures, and highly loaded columns. Some pioneering applications of this material such as a hybrid (steel and UHPC) pedestrian bridge in Germany [1], a cable stayed bridge in Korea [2] and a series of pedestrian bridge in New Zealand [3] have impressed the world with its great capacity and potentiality. Although UHPC has been developed for decades, its performance and functions can still be further improved.

Fibre reinforcement is one of the most important composites of UHPC. The concept of using fibres is not new. In the ancient time, horse hairs were used in mortar and straw to construct mud bricks. Modern versions of concrete fibre were not widely used until 1960s when steel, glass and synthetic fibres took the stage. After mixing with fibrous material, material integrity increases. Some types of fibres like steel fibres produce great impact, abrasion and shatter resistance in concrete [4–6], thus reduce flexural, shear and spall damage which are quite common in normal strength concrete [7,8]. Steel fibres can also increase concrete flexural strength, provide better crack control and energy absorption capacity. As reported by Xu and Wille [9], the fracture energy of UHPC is influenced by fibre factor which is a function of the fibre volume fraction and slenderness. Comprehensive research on steel fibre reinforced concrete can be found in the open literature [10–13].

Recently, development of nanotechnology has attracted great scientific attention. It was observed that several phenomena including statistical mechanical effects and quantum mechanical

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effects become pronounced as size of the system decreases. Due to their ultra-fine size, addition of nanoscale particles results in significantly improved material properties without change of the material composition. As a consequence, researchers and engineers are exploring feasibility of re-engineering many existing materials like concrete by adding nanoscale particles into the matrix to get new and novel material which has unprecedented performance. Li et al. [14] investigated the properties of cement mortars blended with nanoparticles nano-SiO_2 or nano-Fe_2O_3 to explore their super mechanical and smart (temperature and strain sensing) potentials. Jo et al. [15] experimentally investigated properties of cement mortars with nano-SiO_2 addition. The experimental results showed that the compressive strengths of mortars with nano-SiO_2 particles were all higher than those of mortars containing silica fume at 7 and 28 days. They concluded that it was plausible to add nano-SiO_2 particles in order to make high-performance concrete. Qing et al. [16] made similar observations and they noticed that comparing with cement paste with silica fume addition, the cement paste mixed with nano-SiO_2 particles had obvious higher compressive strength, especially at early age. Nano-SiO_2 was believed to accelerate cement hydration process. Liu et al. [17] added nano-$CaCO_3$ (NC) into cement paste and the experimental results showed that NC had no effect on water requirement of normal consistency of cement. However, with the increase of NC content, its flowability decreased and setting time of fresh cement paste was shortened. Flexural strength as well as compressive strength increased with the addition of NC at the age of 7 days and 28 days. Nazari and his colleagues conducted series of experimental tests on different nanoscale additives mixed into concrete matrix [18–23]. Although their work had only been demonstrated in small samples, it was believed that if only it can scale up to larger quantities, it is possible to produce concrete four times stronger than the strongest existing commercial concrete mixes. Najigivi et al. [24] assessed workability and compressive of binary blended concretes mixed with different types of SiO_2 nanoparticles. It was concluded that SiO_2 nanoparticles played significant roles in mechanical properties of concrete by formation of additional calcium silicate hydrate gel during treatment, which played an important role in raising highly the compressive strength of binary blends.

Despite great advantages and potentials, concerns remain for wide utilization of nanoscale particles in structural construction. Firstly, toxicity and environmental impact of nanomaterials should be well addressed [25]. It is also well acknowledged that most of the nanoscale materials are expensive which limits their use with concrete in industry.

In recent research, a newly designed UHPC material with both steel fibre reinforcement and nano material addition was experimentally tested. The nano materials used in the concrete had been applied in industry for years because of their reasonable price. Static material tests such as uniaxial compression test and split tensile tests were conducted to get basic material properties of the newly developed UHPC. It was noted that the UHPC with nano-additives has much improved compressive strength as well as tensile strength which indicates good potential of utilizing such material in protective design against dynamic loads such as blast load, seismic load and impact load. However, it is commonly acknowledged that concrete material is sensitive to rate of loading. Both compressive strength and tensile strength of concrete increase with loading rate. Under this condition, it is imperative to conduct dynamic tests on the newly developed UHPC to obtain complete knowledge of material constitutive relationship including both the static and dynamic properties.

Conventional screw-driven or servo-hydraulic methods of material testing had been utilized in determining the material property at high strain rate. However, these methods may not be perfectly adequate as the strain rates in the test is limited and oscillations and emerging stress wave exist in the testing apparatus [26]. Such oscillations and stress waves impair the transducer load reading, thus making the data obtained more complex to interpret reliably. To overcome such limitations, testing method namely Split-Hopkinson Pressure Bar (SHPB) was developed [27] and extended [28,29]. SHPB method can be favourably used in both the dynamic compressive and tensile tests. In previous study concerning material dynamic performance, this method was widely adopted [30–32].

In the present study, SHPB test results of 94 UHPC samples including 41 compressive tests and 53 split tensile tests are summarized. Dynamic compressive strength and tensile strength of these samples are compared and discussed. Dynamic Increase Factors which are important describing the material under high loading rate are generated and plotted in charts, and the influences of different nano material additions and dosages on the dynamic properties of UHPC material are discussed. Furthermore, UHPC samples after SHPC tests are analysed under microscopy Scanning Electron Microscope (SEM) Analysis to explain the macro failure in micro scale. X-Ray Diffraction (XRD) Analysis and X-Ray Fluorescence (XRF) Analysis are carried out to further understand the failure element composition and strength development of this novel material.

2. UHPC composition

In the current research, nano materials including Nano-$CaCO_3$, Nano-SiO_2, Nano-TiO_2 and Nano-Al_2O_3 are added into the base mix of UHPC at the same weight fraction of 3%. All specimens in the current research are reinforced by micro steel fibre namely MF15. Micro steel fibre MF 15 has a diameter of 0.12 mm and a length of 15 mm, and its yielding strength is 4200 MPa.

Nano material in the current study was mixed at a constant weight dosage of 3%, and this amount of mixture was determined in order to achieve a balance of performance and cost-effectiveness. The addition of nano material affects material hydration process. When a small quantity of the nano-particles were uniformly dispersed in the cement paste, the nano-particles located in the cement will promote and accelerate cement hydration due to their high activity. However, when the nano-particles cannot be well dispersed, as in the case of extensive nano-particles content addition, these nano-particles will create weak zones. Consequently, the homogeneity of microstructure cannot be reached, and low strength will be expected. In a relevant study [16], it was reported that concrete strength increases with nano content up to 4 wt.% and then decreases. Considering high cost of nano materials, a weight dosage of 3% is made in the present study for all nano materials

Table 1
Mix proportions of different UHPC formula (unit: kg).

Constituents	Micro steel fibre MF15			
52.5 cement	750			
Silica fume	225			
Silica flour	190			
Sand	1030			
Superplasticizer	16			
Water	190			
Water/Cement	25.30%			
Steel fibre	191			
Nano-$CaCO_3$	63.1	–	–	–
Nano-SiO_2	–	63.1	–	–
Nano-Al_2O_3	–	–	63.1	–
Nano-TiO_2	–	–	–	63.1