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Impact resistance capacity of a green Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC): Experimental and modeling study

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Abstract

This article addresses the impact resistance capacity of a green Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC). The design of concrete mixtures is based on the aim to achieve a densely compacted cementitious matrix, employing the modified Andreasen & Andersen particle packing model. The modified Charpy test device is employed to test the energy absorption ability of the UHPHFRC under the external impact loading. The results show that the long steel fibres play a dominating role in improving the impact resistance capacity of the UHPHFRC. Additionally, the failure mechanism of the UHPHFRC under impact loading is analyzed and modeled. The proposed model can well predict the energy absorption ability of the UHPHFRC samples.

Keywords: *Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC), green concrete, impact resistance, modeling*

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1. INTRODUCTION

Ultra-high performance fibre-reinforced concrete (UHPFRC) is a relatively new building material, which has superior durability, ductility and strength in comparison with Normal Strength Concrete (NSC) and Fiber Reinforced Concrete (FRC) [1-3]. However, as sustainable development is currently a pressing global issue and various industries have strived to achieve energy savings, the high material cost, high energy consumption and CO_2 emission for UHPFRC are the typical disadvantages that restrict its wider application. Hence, how to produce a “green” UHPFRC still needs further investigations.

To reduce the binder amount and produce a cheaper and more environmental friendly UHPFRC, industrial by-products (such as ground granulated blast-furnace slag (GGBS), fly ash (FA) and silica fume (SF)) or waste materials are included in the production of UHPFRC [4, 5]. Another method to minimize the cost and environmental impact of UHPFRC is reduction of the cement amount without sacrificing the mechanical properties. According to the previous experiences and investigations of the authors [3, 6], by applying the modified Andreasen & Andersen particle packing model it is possible to produce a dense and homogeneous skeleton of UHPFRC with a relatively low binder amount (about 650 kg/m^3). However, from the aliterature, research on the design or production of UHPFRC with an optimized particle packing is not sufficient.

Additionally, in comparison with the NSC, the application of UHPFRC is expected to improve the impact resistance capacity of construction and infrastructure under extreme mechanical or environmental loads. Nevertheless, most of this research did not consider the cost of utilized fibres, while the cost of 1% volume content of fibres applied in UHPFRC is generally higher than that of matrix [7]. To efficiently utilize fibres in UHPFRC, one of the promising methods is to appropriately blend several different types of fibres in one concrete matrix [8, 9]. However, very little information is available about the dynamic load behavior of the UHPFRC incorporating hybrid fibres, which may be attributed to the variation and complexity of the influence from hybrid fibres.

Following the path opened by foregoing studies, the aim of this research is to assess at a laboratory scale the impact resistance of a “green” UHPHFRC. The fracture mechanism of the UHPHFRC under impact loading is analyzed, and the modeling of the energy absorption capacity of the UHPHFRC under impact loading is conducted.

2. MATERIALS AND METHODS

2.1 Materials

The cement used in this study is Ordinary Portland Cement (OPC) CEM I 52.5 R, provided by ENCI (The Netherlands). A polycarboxylic ether based superplasticizer is used to adjust the workability of concrete. Limestone powder is used as a filler to replace cement. A commercially available nano-silica in slurry (AkzoNobel, Sweden) is applied as the pozzolanic material. Two types of sand are used, one is normal sand in the fraction of 0-2 mm and the other one is a micro-sand with the fraction of 0-1 mm (Graniet-Import Benelux, the Netherlands). The particle size distributions of the used granular materials are shown in Fig. 1. Additionally, two types of straight steel fibres are utilized: 1) fibre length = 13 mm, fibre diameter = 0.2 mm; 2) fibre length = 6 mm, fibre diameter = 0.16 mm.

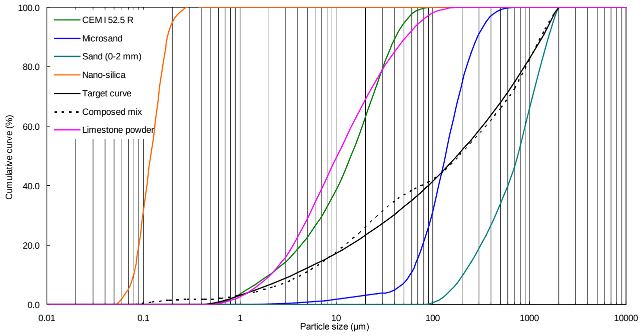

Fig. 1 Particle size distrubutions of the ingredients, the target curve and resulting integral grading curve of the mixture

2.2 Experimental methodology

2.2.1 Mix design of UHPHFRC

The UHPHFRC mixtures developed based on the modified Andreasen & Andersen particle packing model [10, 11], are listed in Table 1. The resulting integral grading curve of the composite mixes is shown in Fig. 1. In this study, only about 620 kg/m3 of binders are used to produce the "green" UHPHFRC. Additionally, steel fibres are added into the mixes in a total amount of 2.0% (Vol.), having different proportions of long and short steel fibres. Here, a new concept named "hybrid fibre coefficient" is proposed (Eq. (3)), representing the volumetric fraction of short steel fibres in the total fibre amount.

$$K_f = \frac{V_s}{V_s + V_l} \tag{1}$$

where K_f is the "hybrid fibre coefficient", V_s means the volumetric amount of short steel fibres in the concrete mixture, and V_l represents the volumetric amount of long steel fibre in concrete. Hence, the steel fibres are added into the concrete matrix at the hybrid fibre coefficient equal to 0, 0.25, 0.5, 0.75 and 1.0, respectively.

Table 1: Recipes of developed UHPHFRC matrix

C kg/m^3	LP kg/m^3	MS kg/m^3	NS kg/m^3	nS kg/m^3	W kg/m^3	SP kg/m^3
594.2	265.3	221.1	1061.2	24.8	176.9	44.2

(C: Cement, LP: Limestone powder, MS: Microsand, NS: Normal sand, nS: Nano-silica, W: Water, SP: Superplasticizer)

2.2.2 Bending test

The fresh UHPHFRC is cast into moulds with the size of 40 mm×40 mm×160 mm. The prisms are demolded approximately 24 h after casting and subsequently cured in water at about 21 ˚C. After curing for 28 days, the prism specimens are tested under three-point loading using a testing machine controlled by an external displacement transducer, such that the mid-span deflection rate of the prism specimen is held constant throughout the test. The specimen mid-span deflection rate is set to 0.01 mm/min, with a span of 100 mm.

2.2.3 Impact test

In this study, the Charpy impact test is employed to test the energy absorption capacity of the UHPHFRC, referencing the ASTM E23 [12]. According to [13], the dimension of the specimen is 25.4×25.4×50.8 mm. Assuming negligible friction and aerodynamic drag, the energy absorbed by the specimen was equal to the height difference multiplied by the weight of the pendulum. During the testing, at least five specimens are tested for each batch.

3. RESULTS AND DISCUSSION

3.1 Bending test results

The stress-strain curves of the UHPHFRC at 28 days during the 3-point bending test are shown in Fig. 2. It is important to notice that the flexural properties of the specimen strongly depend on the fractions of the long or short steel fibres in the total fibre amount. As can be seen in Fig. 2, the ultimate flexural strength of the concrete with long steel fibre (1.5% Vol.) and short steel fibre (0.5% Vol.) at 28 days is the largest, which is about 30.9 MPa. When only short steel fibres are utilized (2% Vol.), the ultimate flexural strength at 28 days reduce to around 21.5 MPa.

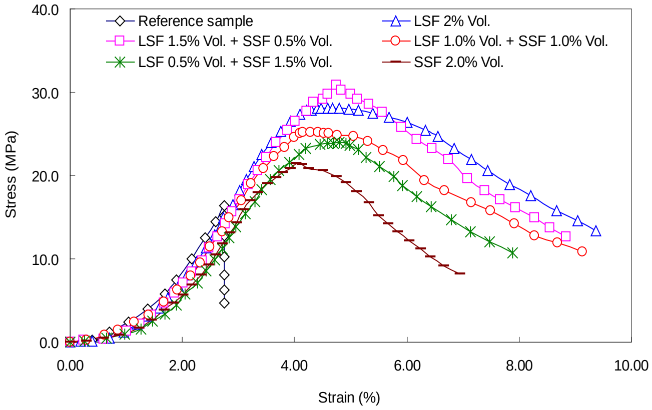

Fig.2 Stress - strain curve of UHPHFRC under flexural testafter curing for 28 days

3.2 Dynamic properties of the UHPHFRC

After performing impact test, the broken UHPHFRC samples are always composed of three cuboid-like fractions, while the broken fragments of reference samples are smaller and more irregular. Moreover, after the impact test on UHPHFRC samples, not only the concrete matrix is destroyed, all the embedded steel fibres around the rupture cross-section are pulled out, which implies that the impact energy absorption of the UHPHFRC specimen should mainly include two parts: the energy used to break the concrete matrix and the energy used to pull out the fibres embedded in the rupture cross-sections.

To quantify the impact resistance capacity of concrete, the variation of the impact energy absorption of the UHPHFRC with different hybrid fibre coefficient (K_f) is investigated, which is shown in Fig. 3. Note that with an increase of the value of the hybrid fibre coefficient, the impact energy absorption of the UHPHFRC at 28 days decreases linearly. Hence, based on the obtained experimental results, it can be concluded that the long steel fibre plays a dominant role in improving the impact resistance capacity of the UHPHFRC. With a constant total steel fibre amount, the increase of short fibres amount can cause a significant decrease of the impact resistance capacity of the UHPHFRC.

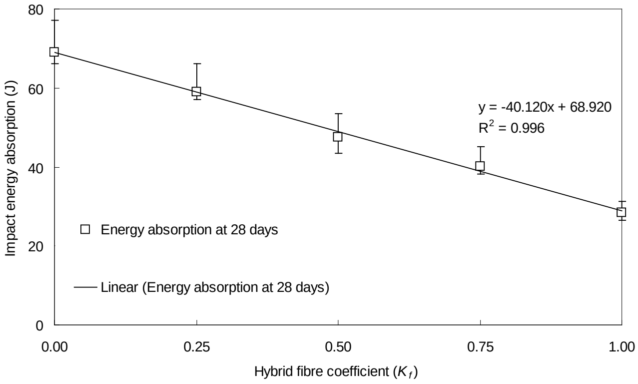

Fig.3 Variation of the absorbed impact energy of the UHPHFRC with different hybrid fibre coefficients (K_f)

3.3 Modeling of the energy absorption capacity of the UHPHFRC

As has already been mentioned, to evaluate the impact energy absorption of the UHPHFRC specimen, two parts should be mainly considered: the energy used to break the concrete matrix and the energy used to pull out the fibres embedded in the broken cross sections. According to the literature [13-15], the total energy absorption of the sample during the impact testing can be simply expressed as follows:

$$U = U_m V_m + N_{f1} U_{f1} + N_{f2} U_{f2} \qquad (2)$$

Where U is the total energy absorbed by the UHPHFRC samples, U_m is the crack energy absorbed by the reference sample without fibres, V_m is the volume fraction of the matrix, N_{f1} and N_{f2} are the number of long and short fibers embedded in the broken cross section, respectively, U_{f1} and U_{f2} represent the energy per long and short fibre that is needed to pull them out, respectively.

Additionally, Chawla [16] assumed that the fiber with a diameter d is pulled out through a distance x against an interfacial frictional shear stress (τ_i). Then the total force at that instant on the debonded fiber surface opposing the pullout is $\tau_i \pi d$ž$(k-x)$, where k is the fiber embedded length. When the fiber is further pulled out a distance dx, the work done by this force is $\tau_i \pi d$ž$(k-x)\,dx$. The total work U_f done in pulling out the fiber over the distance k can be obtained by integration as follows [13]:

$$U_f = W_{fp} = \frac{1}{l/2}\int_0^{l/2} \frac{\tau_i \pi d k^2}{2}\, dk = \frac{\tau_i \pi d l^2}{24} \qquad (2)$$

Hence, in this study, based on the equations above, a new equation is proposed to give the impact energy dissipation of a hybrid fibre reinforced concrete under the Charpy test:

$$U_{\mathrm{D}} = U_m V_m + 2 \times \left(\frac{\tau_{i1} l_1^2 S_a V_{f1}}{6 d_1} + \frac{\tau_{i2} l_2^2 S_a V_{f2}}{6 d_2} \right) \qquad (3)$$

The comparison between the experimental and modeling results are illustrated in Fig. 4. It is important to find that the modeling results are in good agreements with the experimental results, especially for the samples with lower energy absorption capacities. However, when the impact resistance ability of the UHPHFRC is relatively high, the modeling results slightly underestimate the experimental results. This could be attributed to the fact that the energy absorbed in the test device vibration or the friction between the sample and the device is ignored in the modeling process. Actually, when the impact resistance capacity of the concrete is relatively high, small vibrations of the Charpy device could be observed indeed, which means that some part of the energy is dissipated in the equipment.

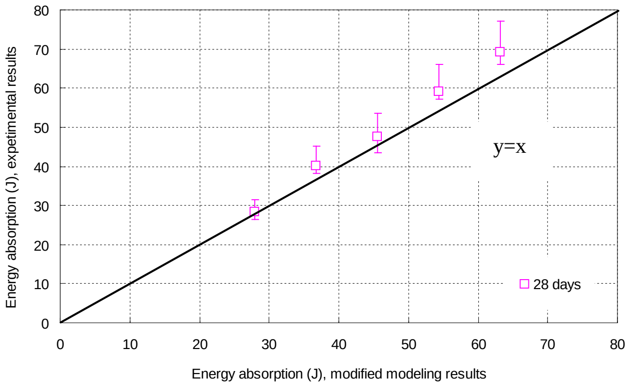

Fig.4 Comparison of the experimental and modeling results of the energy absorption of the UHPHFRC during the impact loading

CONCLUSIONS

This article presents the analysis of the dynamic properties of a "green" Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC). The dynamic impact test results show that the long steel fibre plays a dominating role in improving the impact resistance capacity of the UHPHFRC. With a constant total steel fibre amount, the addition of short fibres can cause a decrease of the impact resistance capacity of the UHPHFRC. Moreover, a new equation is proposed to compute the energy dissipated in the hybrid fibre reinforced concrete under Charpy test. The new model features a good correlation with the experimental results, especially for the samples with lower energy absorption capacity. When the impact resistance ability of the UHPHFRC is relatively high, the modeling results slightly underestimate the experimental results (about 9.3%), which could be attributed to the energy dissipated into the test device.

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