

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

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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

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 CO₂ emission for UHPFRC are the typical disadvantages that restrict its wider application. Hence, how to produce a “green” UHPFRC still needs further investigations.

As commonly known, for the production of a high strength or ultra-high strength concrete matrix, a large amount of binder (around 1000 kg/m³) is normally used [4, 5]. 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) have been used as partial cement replacements in UHPFRC [1, 6]. Moreover, some waste or recycled materials are included in the production of UHPFRC [7, 8]. 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, 9], 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/m³). However, from the literature, research on the design or

production of UHPFRC with an optimized particle packing is not sufficient. In most cases, the UHPFRC recipes are given directly, without any detailed explanation or theoretical support.

Additionally, in comparison with NSC, the application of UHPFRC is expected to improve the impact resistance capacity of construction and infrastructure under extreme mechanical or environmental loads, which should be mainly attributed to the contribution of fibres [10-12]. 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 [13]. Consequently, to achieve the goal of a “green” UHPFRC, it is also important to minimize the amounts of fibres applied in UHPFRC without sacrificing its superior performance.

To efficiently utilize fibres in UHPFRC, one of the promising methods is to appropriately blend several different types of fibres in one concrete matrix [14, 15]. Due to the fact that short fibres can bridge micro-cracks while long fibres are more efficient in preventing the development of macro-cracks, the mechanical properties of hybrid fibre reinforced concrete can be better than that with only one type of fibre [16]. 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 of 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” UHPHFC. The design of concrete mixtures is based on the aim to achieve a densely compacted cementitious matrix with relatively low binder amount, employing the modified Andreasen & Andersen particle packing model. The fracture mechanism of the UHPHFC under impact loading is analyzed, and the modeling of the energy absorption capacity of the UHPHFC 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; and 2) fibre length = 6 mm, fibre diameter = 0.16 mm.

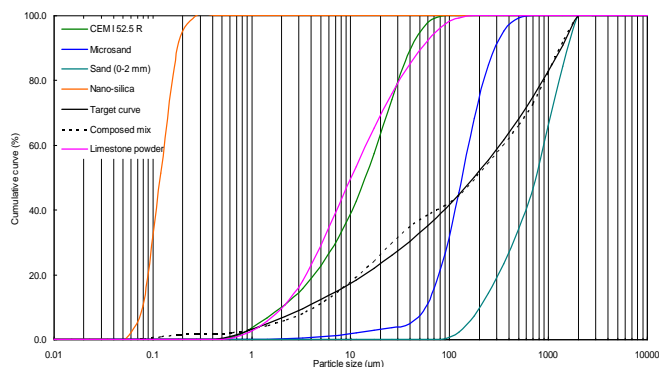


Fig. 1 Particle size distributions of the ingredients, the target curve and resulting integral grading curve of the mixture

2.2 Experimental Methodology

2.2.1 Mix Design of UHPHFC

In this study, the modified Andreasen and Andersen model is utilized to design all the concrete mixtures, which is shown as follows [17, 18]:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \quad (1)$$

where D is the particle size (μm), $P(D)$ is a fraction of the total solids being smaller than size D , D_{\max} is the maximum particle size (μm), D_{\min} is the minimum particle size (μm) and q is the distribution modulus.

Different types of concrete can be designed using Eq. (1) by applying different value of the distribution modulus q , as it determines the proportion between the fine and coarse particles in the mixture. In this study, considering that a large amount of fine particles are utilized to produce the UHPHFC, the value of q is fixed at 0.23, as recommended in [19].

In this research, the modified Andreasen and Andersen model (Eq. (1)) acts as a target function for the optimization of the composition of mixture of granular materials. The proportions of each individual material in the mix are adjusted until an optimum fit between the composed mix and the target curve is reached, using an optimization algorithm based on the Least Squares Method (LSM), as presented in Eq. (2) [20].

$$RSS = \sum_{i=1}^n (P_{mix}(D_i^{i+1}) - P_{tar}(D_i^{i+1}))^2 \quad (2)$$

where P_{mix} is the composed mix, and the P_{tar} is the target grading calculated from Eq. (1).

The UHPHFC mixtures developed based on the optimized particle packing model 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/m^3 of binders are used to produce the “green” UHPHFC. 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.

$$K_f = \frac{V_s}{V_s + V_l} \quad (3)$$

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

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

2.2.2 Selection of the Employed Mix Procedures

In this study, following the method shown in [3], the concrete matrix is well mixed with hybrid steel fibres. The mixing is always executed under laboratory conditions with dried and tempered aggregates and powder materials. The

room temperature while mixing and testing is constant at about 21 °C.

2.2.3 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.

2.2.4 Impact Test

In this study, the Charpy impact test is employed to test the energy absorption capacity of the UHPHFRC, referencing the ASTM E23 [21]. The working scheme of the used Charpy impact device is shown in Fig. 2, in which the maximum kinetic energy output is 147.1 J. According to [22], the configurations of the loading for the Charpy impact test are presented in Fig. 3, and the dimension of the specimen are 25.4 mm×25.4 mm×50.8 mm. After embedding the specimen, the pendulum is released from a height H_1 and swing through the specimen to a height H_2 , as shown in Fig. 2. Assuming negligible friction and aerodynamic drag, the energy absorbed by the specimen is equal to the height difference multiplied by the weight of the pendulum. During the testing, at least five specimens are tested for each batch.

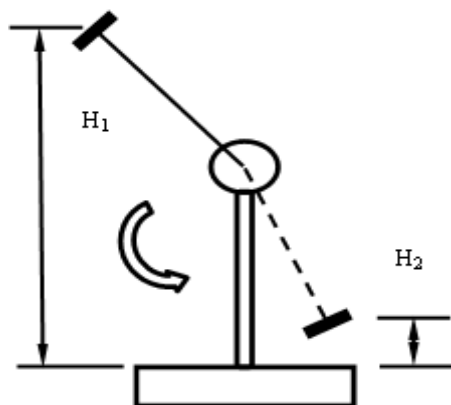


Fig.2 Working scheme of the used Charpy test device

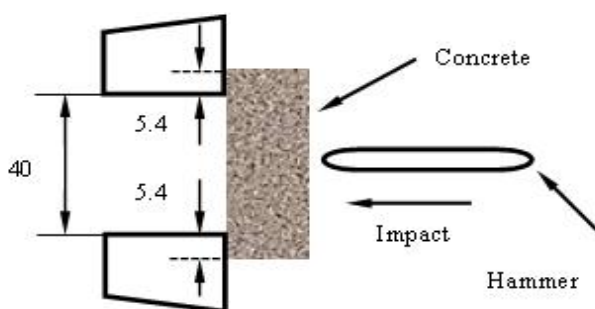


Fig.3 configuration of impact loading (units: mm)

3. RESULTS AND DISCUSSION

3.1 Bending Test Results

The stress-strain curves of the UHPHFRC samples at 28 days during the 3-point bending test are shown in Fig. 4. Similarly to the results shown in the literature [4-8], the addition of steel fibres (2% Vol.) can not only enhance the ultimate flexural strength, but also improves the energy absorption capacity of the designed UHPHFRC. This should be attributed to the fact that the additional steel fibres can bridge cracks and retard their propagation, which could change the fracture mode of concrete from brittle fracture to plastic fracture [16]. Moreover, 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. 4, 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. This can be explained by the following two reasons: 1) short fibres can bridge microcracks more efficiently, because they are very thin and their number in concrete is much higher than that of the long steel fibres, for the same fibre volume. Hence, when the micro-cracks are just generated in the specimen, the short steel fibres can effectively bridge the micro-cracks. As the micro-cracks grow and join into larger macro-cracks, the long steel fibres become more and more active in crack bridging, and the short fibres will then become less and less active, because they are being more and more pulled out, as the crack width increases [16]; 2) long fibres are always well oriented between the two imaginary borders, if casting of concrete in layers is applied (these borders may also be the walls of the moulds). With such positions, the long fibres form a kind of a barrier for short fibres, and limit their space for rotation. The short fibres will therefore be better oriented when combined together with long fibres than on their own [16]. Hence, more fibres distribute in the direction parallel to the force direction in the flexural test, and in turn the mechanical properties can be significantly improved.

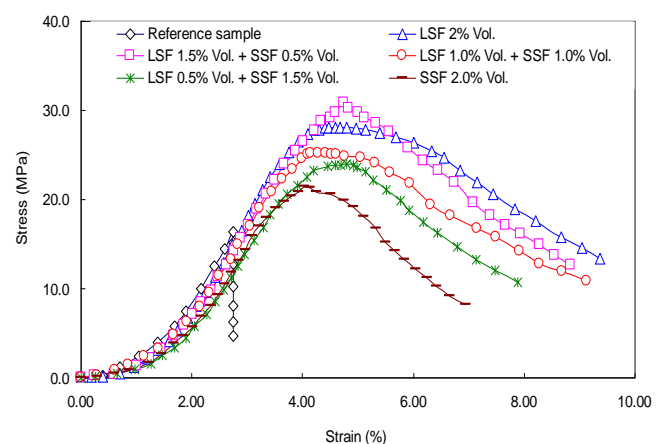


Fig.4 Stress - strain curve of UHPHFRC under flexural test after curing for 28 days

3.2 Dynamic Properties of the UHPHFRCC

Fig. 5 shows the fractions of the UHPHFRCC and reference samples after performing the impact test. It can be found from the experiments that the broken UHPHFRCC 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 UHPHFRCC 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 UHPHFRCC 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.

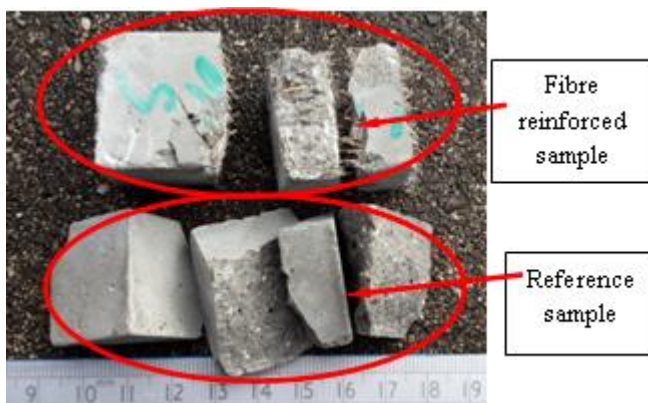


Fig. 5 Fractions of the samples (fibre reinforced and plain samples) after Charpy impact test

As commonly known, the fracture mechanism of concrete under high strain rate or external impact loading should be attributed to cracking, shearing and compaction, as shown in Fig. 6 [23]. It can be predicted that concrete will be broken along the forces direction, such as compaction, tension or confining pressures. However, the final cracks development in the whole concrete element depends on the basic properties of the concrete, the addition of fibres or steel reinforcement. Numerical and experimental investigation of Süper [24] on thick concrete plates seem to show that when the first diagonal crack occurs, still a very high portion of the initial kinetic energy is transferred from concrete to the reinforced steel, stirrups as well as longitudinal reinforcement. Hence, when the first crack occurs, the fibres can still bridge the crack and disperse the energy to other places in concrete. Once the fibres can not restrict the development of cracks, they will be pulled out, and the concrete will be damaged following the stress distribution on concrete during the impact (Fig. 6). In this study, after performing the Charpy test, it has been observed that each concrete sample is broken mainly into three pieces, according to the stress distribution. Nevertheless, for non-reinforced concrete, due to the fact that no fibres or reinforcements can restrict the cracks development, the cracks always grow along the weakest interface in the concrete, which causes that the broken fractions of the reference sample are small and irregular (as shown in Fig. 5).

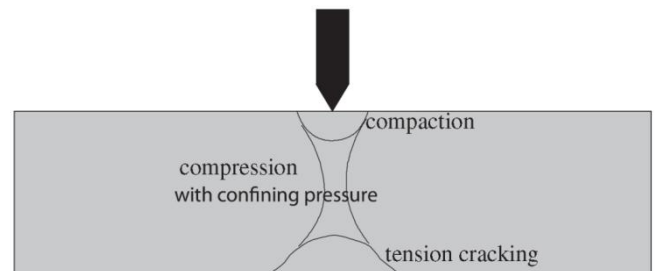


Fig.6 Schematic description of the mechanisms activated in concrete under impact loading [22]

To quantify the impact resistance capacity of concrete, the variation of the impact energy absorption of the UHPHFRCC with different hybrid fibre coefficient (K_f) is investigated, which is shown in Fig. 7. Note that with an increase of the value of the hybrid fibre coefficient, the impact energy absorption of the UHPHFRCC at 28 days decreases linearly. When the hybrid fibre coefficient increases from 0 to 1, the impact energy absorption of the UHPHFRCC reduces from about 69.1 J to around 28.4 J at 28 days. 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 UHPHFRCC. 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 UHPHFRCC. Actually, this phenomenon is in accordance with the results presented in Fig. 4, in which the sample with long steel fibres (1.5% Vol.) and short steel fibres (0.5% Vol.) shows the largest ultimate flexural strength but instable post-peak response. To clearly understand the mechanism of energy absorption process of the UHPHFRCC under impact loading, the theoretical analysis and modeling are needed, which is presented in the next section.

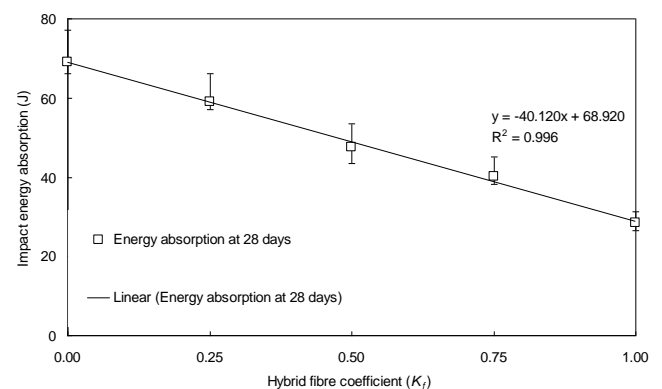


Fig.7 Variation of the absorbed impact energy of the UHPHFRCC with different hybrid fibre coefficients (K_f)

3.3 Modeling of the Energy Absorption Capacity of UHPHFRCC

As has already been mentioned, to evaluate the impact energy absorption of the UHPHFRCC 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 [25, 26], the fiber pullout process usually consists of three processes: 1) fiber/matrix working together; 2) fiber/matrix debonding; 3) fiber/matrix sliding. In this study, the fiber/matrix interfacial shear strength is assumed to be equal to equivalent shear bond strength. Hence, the total energy absorption of the sample during the impact testing can be simply expressed as follows [22]:

$$U = U_m V_m + N_f U_f \quad (4)$$

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_f is the number of fibers embedded in the broken cross section and U_f is the energy per fibre that is need to pull it out.

In this study, due to the fact that both the long and the short steel fibres are pulled out during the impact loading, the energy that is consumed in pulling out of long and short steel fibres should be considered individually. Assuming that the energies consumed in pulling long and short steel fibres are independent, Eq. (4) should be rewritten as follows:

$$U = U_m V_m + N_{f1} U_{f1} + N_{f2} U_{f2} \quad (5)$$

Where 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.

The fibre number can be presented as:

$$N_f = \frac{S_a V_f}{\pi r^2} = \frac{4 S_a V_f}{\pi d^2} \quad (6)$$

Where S_a is the area of the broken cross section of the tested UHPHFRC samples, V_f is the volumetric amount of fibres in concrete, r and d are the radius and diameter of used fibres, respectively.

Additionally, Chawla [27] 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 $\tau_i \pi d \cdot (k-x)$, where k is the fiber embedded length. When the fiber is further pulled out a distance dx , the work done by this force is $\tau_i \pi d \cdot (k-x) dx$. The total work U_f done in pulling out the fiber over the distance k can be obtained by integration as follows [22]:

$$U_f = \int_0^k \tau_i \pi d \cdot (k-x) dx = \frac{\tau_i \pi d k^2}{2} \quad (7)$$

Here, assuming that fibre can not be broken during the pulling out process, its pullout length can vary between a minimum of 0 and a maximum of $l/2$, where l is the fiber

length. Hence, integrating dk yields an average work of pullout per fiber, as follows [22]:

$$W_{fp} = \frac{1}{l/2} \int_0^{l/2} \frac{\tau_i \pi d k^2}{2} dk = \frac{\tau_i \pi d l^2}{24} \quad (8)$$

where W_{fp} is the average work of pullout per fibre. So,

$$U_f = W_{fp} = \frac{\tau_i \pi d l^2}{24} \quad (9)$$

Now, these equations of [22] are applied to the hybrid fibre reinforced concrete developed in this study. Substituting Eq. (9) and Eq. (6) into Eq. (5) gives:

$$U = U_m V_m + \frac{\tau_{i1} l_1^2 S_a V_{f1}}{6 d_1} + \frac{\tau_{i2} l_2^2 S_a V_{f2}}{6 d_2} \quad (10)$$

In the above modeling process of energy consumption of pulling fibres out, only a single broken cross section is considered per sample. In fact, as can be seen in Fig. 5, after the impact loading, UHPHFRC is typically broken into three pieces, which means there are two broken cross sections and more energy is consumed in pulling out fibres. Consequently, here, we have proposed a new equation that gives the impact energy dissipation of a hybrid fibre reinforced concrete under the Charpy test. Assuming that the hybrid steel fibres are homogeneously distributed within the specimen, Eq. (11) is modified as follows:

$$U_{\Delta} = U_m V_m + 2 \cdot \left(\frac{\tau_{i1} l_1^2 S_a V_{f1}}{6 d_1} + \frac{\tau_{i2} l_2^2 S_a V_{f2}}{6 d_2} \right) \quad (11)$$

Where U_{Δ} is the modified total energy absorbed by the UHPHFRC samples, l_1 and l_2 are the lengths of long and short steel fibres, d_1 and d_2 are the diameters of long and short steel fibres, V_{f1} and V_{f2} are the volumetric amounts of the long and steel fibres in UHPHFRC, respectively.

In order to calculate the total impact energy absorbed by the UHPHFRC from Eq. (11), it is necessary to obtain the interfacial bond strength between the concrete matrix and long or short steel fibres (τ_{i1} and τ_{i2}), which is defined as the friction between the fiber and the matrix [22]. The ultimate flexural stress in the mid span can be expressed as the summation of the flexural stresses of the matrix and the fibers. Hence, the interfacial bond strength can be obtained as follows [22, 26]:

$$\sigma = \frac{1}{2} \cdot V_f \cdot g \cdot \tau_i \cdot \left(\frac{L_f}{d_f} \right) + \sigma_m \cdot (1 - V_f) \quad (12)$$

Where σ is the flexural stress of the UHPHFRC, σ_m is the flexural stress of the reference sample with fibres, $g = 1.5$ [26].

Hence, based on the flexural stress test results (Fig. 4) and Eq. (11) and (12), the impact energy absorption of the UHPHFRCC can be calculated. The comparison between the experimental and modeling results are illustrated in Fig. 8. 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 UHPHFRCC 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.

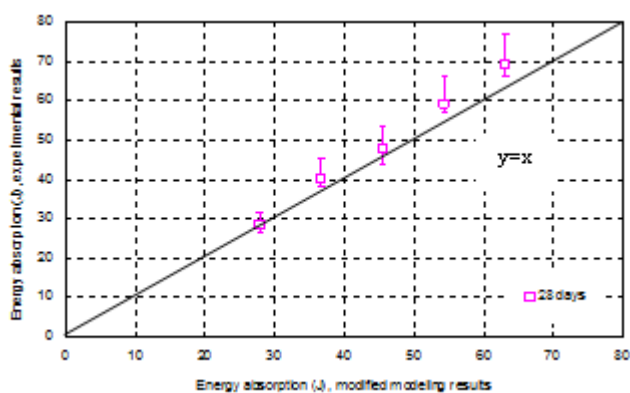


Fig.8 Comparison of the experimental and modeling results of the energy absorption of the UHPHFRCC during the impact loading

4. CONCLUSION

This article presents the analysis of the dynamic properties of a “green” Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRCC). The dynamic impact test results show that the long steel fibre plays a dominating role in improving the impact resistance capacity of the UHPHFRCC. With a constant total steel fibre amount, the addition of short fibres can cause a decrease of the impact resistance capacity of the UHPHFRCC. 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 UHPHFRCC 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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