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Damage Mechanism of Ultra-high Performance Fiber Reinforced Concrete under Repeated Low-velocity Impact

Peipeng LI, Qingliang YU, Jos. BROUWERS

Abstract: In the present research, Ultra-high Performance Fiber Reinforced Concrete (UHPFRC) applying coarse basalt aggregate is designed by considering optimum mineral admixtures, particle packing theory and steel fiber reinforcement. The fresh behavior and mechanical properties including slump flow, fresh density, compressive strength, and tensile splitting strength are investigated. Then, the repeated low-velocity impact tests are carried out to UHPFRC beams by using a pendulum impact device and the post-impact behaviors are measured by using four-point bending tests. The results show that it is possible to design a UHPFRC with coarse aggregate which has a compressive strength higher than 150 MPa and excellent tensile property and impact resistance. The results also reveal the mechanism of fracture pattern and crack propagation. The post-impact flexural behavior indicates that the damage degree at the initial several impacts develops relatively slowly, which means that the UHPFRC can remain a good load capacity and energy absorption at the first several impact loading.

Keywords: UHPFRC, repeated low-velocity impact, crack development, energy dissipation, post-impact behavior

1 Introduction

As a relatively new building material fabricated since 1990s, Ultra-high Performance Fiber Reinforced Concrete has excellent mechanical strength, ductility, fatigue resistance and durability. Compared to the traditional concrete, UHPFRC has a superior energy absorption, which contributes to good resistance under impact loading. The excellent impact resistance of UHPFRC is greatly depending on the materials and design methods. Currently, various cementitious materials can be utilized to produce UHPFRC, such as cement, micro silica and fly ash etc. Previous researches have already shown that the micro-silica can improve UHPFRC’s strength, durability and interfacial transition zone (ITZ) due to the pozzolanic, filling and nucleation effects. As a non-pozzolanic mineral admixture, the limestone powder is mainly used as filler to partially replace cement. Recent researches indicate that particle surface of limestone powder is an active template for the nucleation and growth of cement hydration products. Somewhat soluble limestone powder contributes to form the carboaluminate hydration. It can improve the fluidity and microstructure of concrete, and has a positive effect on the generation of C-S-H gel. However, the optimum content of micro-silica and limestone powder in UHPFRC is still a studied manner.

To overcome the inherent weakness between coarse aggregate and cement matrix, and eliminate stress concentration at the contact points between those aggregates, most of UHPFRCs are designed by using only fine aggregates or refined aggregate. But concrete containing appropriate type and content of coarse aggregate can possesses some advantages for impact resistance. Peng et al suggested to use coarse basalt aggregate to improve the penetration impact resistance. Tai et al. presents that the at higher loading rates (impact loading), the cracks form quickly and can propagate through the aggregates, consequently increasing the impact resistance. But there is lack of literature to describe whether the basalt aggregate can also contribute to the low or middle velocity impact resistance, especially in UHPFRC.

Currently, limited researches on the impact resistance of UHPFRC usually focus on impact number, energy dissipation, and fracture pattern and crack development. There is a lack of investigation to present the damage development and post-impact behavior of UHPFRC. But the damage degree and post-impact property are very critical parameters to evaluate the safety state and residual bearing capacity of components or structures after impact loading or natural disaster.

Hence, in this study UHPFRC with coarse basalt aggregate was designed by using optimum mineral admixtures, particle packing theory and steel fiber. Both fresh behaviors and mechanical strengths were measured to describe its

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performance. The damage mechanism of UHPFRC under repeated low-velocity impact was investigated by using a designed pendulum device and four-point bending test. The impact responses such as crack development, fracture pattern, energy dissipation were analyzed and discussed, as well as the post-impact flexural behavior.

2 Experimental

2.1 Materials

The raw materials used in this study are Portland Cement CEM I 52.5 R (OPC), micro-silica (mS), limestone powder (LP), sand 0-2 (S), basalts aggregate (BA), water (W), PCE-type superplasticizers (SP) and steel fiber (SF) (length = 13 mm, diameter = 0.2 mm, tensile strength = 1100 MPa). The specific densities of those ingredients are measured by a gas pycnometer method (AccuPyc 1340 II Pycnometer) and the results are shown in Table 1. The particle size distributions of the used materials are measured by the sieve and laser diffraction analyses (Malvern Mastersizer 2000®), as shown in Figure 1.

<table>
<thead>
<tr>
<th>Materials</th>
<th>OPC</th>
<th>mS</th>
<th>LP</th>
<th>S</th>
<th>BA 1-3</th>
<th>BA 2-5</th>
<th>BA 5-8</th>
<th>W</th>
<th>SP</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific density (g/cm³)</td>
<td>3.15</td>
<td>2.32</td>
<td>2.71</td>
<td>2.72</td>
<td>3.05</td>
<td>1.00</td>
<td>1.07</td>
<td>7.85</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 1](image.png)  
**Fig.1** The particle size distribution of raw materials

2.2 Mix design of mixture

The powder content of UHPFRC usually ranges from about 900 kg/m³ to 1200 kg/m³ [18]. However, the powder volume fraction in UHPFRC containing coarse aggregate can be lower than that in UHPFRC without coarse aggregate [19]. Hence, the total powder content is chosen at 900 kg/m³ in this study. The fresh and hardened properties of UHPFRC are greatly depending on the active and non-active mineral admixtures. The micro-silica is used at 5% by the weight of total powder, while limestone powder is fixed at 20% by the weight of total powder. The proportion of the mineral admixtures is chosen based on previous research by considering the fluidity and mechanical strength. The water-to-powder ratio is fixed at 0.23 and the dosage of superplasticizer is 1.3% by the weight of powder to obtain a good workability. The fractions of the basalt aggregates are calculated by using the modified Andreasen and Andersen model \( q = 0.22 \) [20]. The dosage of steel fiber is 2% by the replacement of total volume of mixtures, which has been proven to be an appropriate dosage for UHPFRC from literatures [15,21]. The recipe of UHPFRC is shown in table 2.

The mixing of UHPFRC lasted about 10 min by using a 50-liter pan mixer, following the procedure: dry mixing for 60 s with all powder and sand, adding 80% water mixing for 60 s, sequentially adding the remaining water with SP incorporated for another 90 s, then adding basalt aggregate and steel fiber at the 5th min and 7th min, respectively. The mixing process was conducted at room temperature of about 20 ± 1 °C.

<table>
<thead>
<tr>
<th>Materials</th>
<th>CEM (kg/m³)</th>
<th>mS (kg/m³)</th>
<th>LP (kg/m³)</th>
<th>S (kg/m³)</th>
<th>BA 1-3 (kg/m³)</th>
<th>BA 2-5 (kg/m³)</th>
<th>BA 5-8 (kg/m³)</th>
<th>W (kg/m³)</th>
<th>SP (kg/m³)</th>
<th>SF (Vol. replacement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>675</td>
<td>45</td>
<td>180</td>
<td>517.1</td>
<td>212.1</td>
<td>376.0</td>
<td>307.1</td>
<td>207</td>
<td>11.7</td>
<td>2%</td>
</tr>
</tbody>
</table>

2.3 Testing method

The spread flow of UHPFRC was measured by using a truncated conical mould (Abrams cone: height 300 mm, top diameter 100 mm, base diameter 200 mm), in accordance with EN 12350-8: 2007 [22]. Fresh concrete is filled in the mould and the cone is lifted straight upwards to allow the concrete flows freely without jolting. The spread flow is calculated by the average value of two perpendicular diameters. The flow test was conducted at room temperature of

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about 20 ± 1 °C. The fresh concrete was filled in a cylindrical container of known volume, and then its mass is determined to calculate the fresh density.

The fresh UHPFRC was casted into steel cubic moulds (100×100×100 mm³). All samples were covered with polyethylene film to prevent the moisture loss. They were demoulded approximately 24 h after casting and then cured in water under room temperature of 20 ± 1 °C. The compressive and tensile splitting strength of UHPFRC samples were measured, based on EN 12390-3: 2009 [21] and EN 12390-6: 2009 [22].

The fresh UHPFRC was casted into wooden moulds (150×150×700 mm³), which had the same curing condition to cubic specimens. After 28 days, those beams were carried out to do impact test. The beams were symmetrically hung with a span of 450 mm. The repeated low-velocity impact test was carried out by using a pendulum set-up, shown in Fig.2. The knife-edge hammer was released from a certain height and subsequently impacted on the hanging concrete beam perpendicularly at the lowest position. The velocities of hammer and specimen, before and after impact, are measured by the high-speed camera. The energy absorbed by UHPFRC beam during single impact is calculated as following:

\[
E = \frac{1}{2} M_h V_0^2 - \frac{1}{2} M_b V_r^2 - \frac{1}{2} M_s V_s^2
\]

where the \( E \) is the absorbed energy by beam during single impact (J); \( M_h \) and \( M_b \) are the masses of hammer and beam (kg), which are about 32 kg and 40 kg, respectively; \( V_0 \) and \( V_r \) are the velocities of hammer before and after impact (m/s); \( V_s \) is the velocity of concrete beam after impact (m/s). The impact is repeated several times till to a certain impact number or the complete failure of the specimen. The flexural behaviors of partially damaged beams after a certain impact number were subsequently measured, based on ASTM C 1609-12 [23]. The set-up and parameter calculations of four-point bending are shown in Fig. 3. Based on the load-deflection curve, the net deflection at First-Peak Load \( \delta_1 \), net deflection at Peak Load \( \delta_p \), net deflection of L/600 and L/150 can be determine, as well as the corresponding forces and strengths, and the area under the load vs. net deflection curve from 0 to L/150 \( \tau_{150}^{0} \).

![Fig.2 Pendulum impact test](image)

![Fig.3 Four-point bending test](image)

3 Results and discussion

3.1 Fresh behavior and static strength

The fresh behavior of the designed UHPFRC is shown in Table 3. The slump flow and fresh density of the designed UHPFRC are 695 mm (class of SF2 according to SCC [24]) and 2.579 g/cm³, respectively. The excellent slump flow results from PCE-type superplasticizer, high content replacement of cement by limestone powder and utilization of coarse aggregate. The PCE molecules are adsorbed onto particles and separated by opposing their attractive forces with

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steric and/or electrostatic forces, which then disperse the particle, release the free water and increase the fluidity [27,28]. The limestone powder increases the workability because of its relatively low surface area and smooth surface. Compared to finer aggregates, coarse aggregate has lower surface area, which alters the workability [19].

The 28-day static strength of UHPFRC is shown in Table 3 and the development of compressive strength is shown in Fig. 4. The compressive and tensile splitting strength of UHPFRC at 28 days are 154.6 MPa and 19.1 MPa, respectively. The compressive strength develops rapidly before the first 7 days and then grows slowly. The results indicates that it is possible to design UHPFRC with coarse aggregate [16,19], which has a good fresh and mechanical behaviors.

<table>
<thead>
<tr>
<th>slump flow (mm)</th>
<th>Fresh density (g/cm³)</th>
<th>28-day strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>695</td>
<td>2.578</td>
<td>compressive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>154.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tensile splitting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.1</td>
</tr>
</tbody>
</table>

Table 3 Fresh behavior and strength of UHPFRC

Fig.4 Compressive strength under different curing ages

3.2 Crack development

Fig. 5 and Fig. 6 show the development of crack width in the front surface and crack depth in the top surface. It should be pointed out that the UHPFRC beams were complete failure (break into two parts) after repeated impact of about 13 times. After 3 times impact, only micro crack can be observed. Macro visual crack can be detected after repeated impact of 6 times, after that it becomes wider and deeper very rapidly. At the initial several impacts, the crack resistance is mainly depending on the total matrix. When the macro crack occurs, the fiber bridge effect begins to work, and the crack resistance is highly depending on the bonding force between fiber and matrix. Based on the crack pattern, it can be concluded that the fracture of UHPFRC beam only generates in a limited local area, near to the position of maximum moment under impact loading.

Fig. 5 Crack width (front surface)

Fig. 6 Crack depth (top surface)
3.3 Energy dissipation

Fig. 7 shows the energy dissipation of UHPFRC beam under each impact, calculated by using Eq. 1. The absorbed energy under each impact increases continuously before the first 6 impacts which is about half of the total impact number. During this period, the damage degree is relatively low, and the beam has a relatively high stiffness. The impact is more like an elastic collision, which leads more gravitational potential energy of hammer to transfer into kinetic energy of beam. After several repeated impacts, the damage degree is accumulated, and the stiffness of the partial damaged beam degenerates continuously. More and more energy is dissipated by the deformation energy and fracture energy of concrete. However, with the further increase of damage degree, more and more fiber is pulled out and crack depth of the matrix develops deeper and deeper. The potential deformation energy and fracture energy decreases, which result in the decrease of energy dissipation of UHPFRC beam.

![Energy dissipation graph]

3.4 Post-impact flexural behavior

Fig. 8 shows the load deflection curves of UHPFRC beam without impact and with several repeated impact by using the four-point bending test. For the UHPFRC beam without impact, a linear stage and the first-peak load can be observed, which represent the elastic deformation range and limit of proportionality. While, for the partially damaged UHPFRC beam with 3 times impact, there is no elastic stage and limit of proportionality. It indicates that the damaged beam is always subjected to elastic-plastic deformation under bending load.

Fig. 9 shows the parameter calculations based on the force-deflection curve, including the peak strength $f_p$, residual strength at net deflection of L/600 $f_{L/600}$, residual strength at the net deflection of L/150 $f_{L/150}$, and the toughness $T_{150}$ (the area under the load vs. net deflection curve from 0 to L/150). Fig. 9 presents a similar decreasing tendency of the flexural strength and toughness. After 3 times repeated impact, those parameters decrease about 7.9%, 12.6%, 19.6%, 16.5%, respectively. The post-impact flexural behaviour indicates that the damage degree at the initial several impacts develops relatively slowly, which means that the UHPFRC can remain a good load capacity and energy absorption at the first several impact loading.

![Post-impact bending load-deflection curves](image1)

![Flexural strength and toughness](image2)

4 Conclusions

UHPFRC with coarse basalt aggregate was designed with optimum mineral admixtures and steel fiber. The slump flow test, mechanical test and pendulum impact test were carried out to assess its performance and reveal its damage mechanism under repeated low-velocity impact.
The slump flow and mechanical test results show that it is possible to design a self-compacting UHPFRC with coarse aggregate which possesses a compressive and tensile splitting strength of about 155 MPa and 19 MPa, respectively. The results of repeated low-velocity test indicate the good energy dissipation and impact resistance of the designed UHPFRC. The development of crack shows that only micro crack occurs after the initial several impacts, but propagates wider and deeper very rapidly after repeated impact of about 6 times. The UHPFRC beams completely break to two pieces after repeated impact of 13 times, and the fracture only generates within a limited local area near the position of maximum moment under impact loading. The post-impact flexural behavior indicates that the damage degree at the initial impact develops relatively slowly, which means that the UHPFRC can remain a good load capacity and energy absorption at the initial impact loading.

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References:


