TENSILE BEHAVIOR AND DURABILITY OF HIGH PERFORMANCE FIBER REINFORCED CONCRETE

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Abstract

In response to demands for higher strength, higher performance and multi-functional construction materials for use in specialized structures, advanced concretes have been introduced. One of their features is high tensile strength. Among the advanced concretes, Ultra High Performance-Fiber Reinforced Concrete (UHP-FRC), introduced in the mid-1990s, is the most advanced. UHP-FRC can be generally defined by their superior compressive strength (over 150 MPa) and by the presence of fiber reinforcements to decrease brittleness and enhance tensile capacity. To characterize tensile behavior of UHP-FRC under wide range of strain rates, a hydraulic servo-controlled testing machine and a newly proposed impact testing system were used. Four strain rates ranging from quasi-static (\(\varepsilon = 0.00001 \text{ s}^{-1}\)) to seismic (\(\varepsilon = 0.1 \text{ s}^{-1}\)), and strain rates ranging from 90 to 146 \(\text{s}^{-1}\), respectively, were achieved using two testing systems. All UHP-FRC cases tested in this experimental program show remarkable strain sensitivity. A preliminary research on durability test is also carried out to evaluate long term behavior of high performance fiber reinforced concrete.

1. INTRODUCTION

There are increasing demands on blast resistance structural members for important infrastructures such as nuclear plants, safety shelters and military facilities due to the increase of terrorist threat. Even though the numbers of high-rise buildings and important industrial complexes keep increasing world widely, limited research has been carried out on blast resistance of structural members [1].

Traditionally, civil engineers have used thicker structural members to enhance structural safety for the blast resistance purpose. Since the thicker members degrade their original functionalities as structural members, it is essential to develop advanced construction materials to build efficient blast resistance structures. Especially, it is revealed by many researchers that fiber reinforced high performance concrete such as HPFRCC (high performance fiber reinforced cementitious composite) [2, 3] and UHP-FRC (ultra high performance fiber reinforced concrete) [4, 5] are very promising materials for blast resistance.
In the present paper, blast resistance of UHP-FRC was experimentally evaluated using a hydraulic servo-controlled testing machine and a newly proposed impact testing systems developed by Pyo and El-Tawil [5]. Both testing system were used to characterize tensile behavior of UHP-FRC specimens under wide range of strain rate. Characterization of tensile behavior of advanced concrete materials is essential for evaluating blast resistance because structural members with high strength concrete usually fail by reflected tensile stress wave reflected at free ends of structural members, although the high strength concrete could endure compressive impact stress wave. A spall version of split Hopkinson pressure bar (SHPB) is a good example of such phenomenon [6].

Four strain rates ranging from quasi-static ($\dot{\varepsilon} = 0.0001 \text{ 1/s}$) to seismic ($\dot{\varepsilon} = 0.1 \text{ 1/s}$), and strain rates ranging from 90 to 146 $\text{1/s}$, respectively, were achieved using two testing system. Dog-bone shaped specimens were used to evaluate dynamic tensile behavior of UHP-FRC with different types and volume fractions of steel fiber. Furthermore, a preliminary experimental research on freeze-thaw test is carried out to evaluate long term behavior of HPFRCC.

Figure 1: Testing systems for UHP-FRC under tension
2. EXPERIMENTAL PROGRAM

2.1 Testing system

A series of targeted experimental program were conducted to investigate material characteristics of fiber reinforced high performance concrete under wide range of loading rate. A hydraulic servo-controlled testing machine and a newly proposed impact testing system developed by Pyo and El-Tawil [5] were used to evaluate dynamic tensile behavior of UHP-FRC (see Figure 1). Details of testing systems and experiments can be found in Pyo et al. [7] and Pyo and El-Tawil [5].

Figure 2 shows the freeze-thaw testing system and dynamic elastic modulus measurement system used in this study to evaluate durability of HPFRCC. In addition, the temperature regime used in this study for the freeze-thaw testing is shown in Figure 3.

![Figure 2: Freeze-thaw testing and dynamic elastic modulus measurement system for HPFRCC](image)

![Figure 3: Temperature regime for the freeze-thaw testing](image)
2.2 Materials and fabrication

Mix proportion of UHP-FRC and material properties of steel fibers used in this study can be found in Pyo et al. [7]. Dog-bone shaped specimens were prepared for tensile testing under lower strain rates. Specimens with similar geometry were prepared for higher strain rate testing as can be seen in Figure 4. All testing were conducted after at least 28 days of water curing without any special heating or pressure.

Table 1 lists the mix proportion of HPFRCC used for durability testing. Three different mixes were prepared to evaluate their effect of the replacement of cements with other binder materials in terms of durability. 100×100×400 mm$^3$ sized specimens were prepared for the freeze-thaw testing and 300 cycles of the testing were carried out.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Water</th>
<th>Sand</th>
<th>Cement</th>
<th>Silica Fume</th>
<th>Blast Furnace Slag</th>
<th>Superplasticizer</th>
<th>Methyl Cellulose</th>
<th>Defoaming agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>0.4</td>
<td>0.5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.005</td>
<td>0.0005</td>
<td>0.001</td>
</tr>
<tr>
<td>OPC-SF</td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
<td>0.1</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>OPC-Slag</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
<td>0.005</td>
<td>0.005</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Figure 4: UHP-FRC specimens under tension: (a) used at lower strain rate testing; (b) used at higher strain rate testing

3. TEST RESULTS AND DISCUSSIONS

Experimentally obtained dynamic increase factor (DIF), the ratio of dynamic to static responses in terms of post cracking strength, for UHP-FRC were plotted in Figure 5. Experimental results of UHPC [8] available in the literature are also plotted in the figure for the comparison purpose. It should be noted that Millon et al. [8] used a spall version of SHPB, an indirect tension testing, for high strain rate testing. On the other hand, the impact testing system used in this study is a direct tension testing system. As can be seen in Figure 5, the
trend of experimental results are similar with the results in the literature. Figure 6 shows experimentally obtained stress-strain curves of UHP-FRC at high strain rates for two different types of straight steel fibers used in this study. It can be concluded from the figures that UHP-FRC has high strain rate sensitivity, suggesting that UHP-FRC is a promising construction material for blast and impact application.

Experimental results on freeze-thaw testing of HPFRCC is shown in Figure 7. OPC and OPC-Slag cases show consistent results on freeze-thaw testing; meanwhile, OPC-SF shows significant loss of dynamic elastic modulus as freeze-thaw cycles increase. It is revealed from the experimental study that HPFRCC has strong resistance against freeze-thaw cycles. It is also suggested that 10% replacement of silica fume to cement lowers its freeze-thaw resistance because densified microstructures possibly hinder the transport of trapped water.
However, additional research has to be carried out to clarify the mechanisms of this phenomenon.

Figure 6: Experimentally obtained stress-strain curve at high strain rates: (a) series with S-0.2-25 fibers; (b) series with S-0.4-25 fibers
4. CONCLUSIONS

- A series of experimental study has been carried out to characterize the tensile behavior of UHP-FRC under wide range of loading rate.
- Similar specimen geometries were used to evaluate dynamic tensile characteristics of UHP-FRC under broad strain rates, ranging from 0.0001 to 0.1 1/s and 90 to 146 1/s.
- All UHP-FRC cases tested in this experimental program show remarkable strain sensitivity.
- It is revealed from freeze-thaw resistance testing that HFFRCC has high durability.

ACKNOWLEDGEMENTS

The research described herein was sponsored by the National Science Foundation under Grant No. CMS 0928193 and the University of Michigan, Ann Arbor. This research was supported by a grant from a Construction Technology Research Project (Development of impact/blast resistant HPFRCC and evaluation technique thereof, 13SCIPS02) funded by the Ministry of Land, Infrastructure, and Transport, Republic of Korea. The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors. Some parts of the first author’s dissertation were revisited in this paper, and the first author would like to express his sincere appreciation to Dr. Sherif El-Tawil, who advised the dissertation.

REFERENCES


