Investigation of crack speed in ultra-high performance concrete (UHPC) under high speed loading rates

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Abstract: This study looks into the development of cracks and cracking speed in ultra-high performance concrete (UHPC). Pre-notched three-point bending specimens are tested. The main experimental parameters are the fiber volume fraction for UHPC and the rate of loading. Specimens are subjected to slow and high speed loading rates. Slow speed strain rates range from 0.025 to 1.0 1/s. High speed strain load rates range from 6.8 to 41.1 1/s. UHPCs are tested with steel fiber volume contents at 0.0%, 0.5% and 1.0% steel fibers by volume. Notch tip strain and crack speed are computed from the captured data, showing that crack speed increases asymptotically as the crack initiation strain rate increases.

Keywords: Ultra High Performance Concrete (UHPC), industrial by-products, flowability, V-funnel test, compressive strength

1. Introduction

Ultra High Performance Concrete (UHPC) is one of the most advanced cement based materials, which having numerous benefits over conventional concrete in terms of high strength (Wille et al. 2011), ductility (Pyo et al. 2015), impact resistance (Tran et al. 2016) and durability (Alkaysi et al. 2016). The mechanical benefits of UHPC can be achieved through optimized particle packing of various types of solid ingredients including silica fume and silica sands.

There are disagreements about fundamental aspects of the dynamic fracture process. For example, the observed maximum crack velocities in most materials are lower than the theoretically predicted crack speed (i.e. the Rayleigh wave speed). Gao (1993) proposed a wavy-crack model to explain the phenomenon of reduced apparent crack velocity by incorporating small deviations of the crack tip from its original crack path. Xie and Sanderson (1995) suggested that measured crack velocity cannot reach the Rayleigh wave speed because the dynamic stress intensity factor approaches zero when crack velocity is about half of the Rayleigh wave speed. Sharon and Fineberg (1999) insisted that intrinsic instabilities such as multiple-crack and micro-branching might explain the phenomenon that apparent maximum crack velocities in amorphous materials are far slower than their predicted values. However, they concluded that measured peak crack velocities approach the theoretical predictions by using instantaneous velocity rather than averaged velocity. The literature search suggests that there is still controversy over crack speed in solids under high speed of loading rates, and very limited information is available on crack propagation in UHPC.

The objective of this study is to characterize crack propagation in UHPC under high speed loading rates, and establish a relationship between crack speed and strain rate in UHPC. To achieve this, the recently developed impact testing system by the authors (Pyo and El-Tawil

2015) is modified to accommodate crack-propagation test specimens and exercised to enable the study.

2. Mix Design and Test Details

The materials used in UHPC mixtures are ordinary Portland cement (OPC), undensified silica fume, silica powder, silica sands, superplasticizer and high strength steel fibers with 0.2 mm of diameter and 19.5 mm long. . Table 2 shows three different UHPC mixtures used in this study. A Hobart type mixer was used to prepare the mixtures. Dried silica fume and fine aggregates were mixed first for five minutes. Silica powder and OPC were then mixed together for another five minutes. While the mixer was spinning, water and superplasticizer were gradually added into dry mixture. The dry mixture became fluid usually within five minutes after the fluids added. The mixtures were mixed another five minutes to allow the mixtures have adequate consistency. Lastly, the steel fibers, if any, were added by hands into the mixtures.

Table 1. Mix proportions by weight

Series	CS-0%	CS-0.5%	CS-1.0%
OPC	1.0	1.0	1.0
Silica Fume	0.25	0.25	0.25
Silica Powder	0.25	0.25	0.25
Water	0.22	0.22	0.22
Superplasticizer[§]	0.005	0.005	0.005
Sand I[†]	0.28	0.27	0.27
Sand II[‡]	1.10	1.09	1.07
Steel Fiber*	0	0.5	1.0

[§]Solid content
[†] Maximum grain size = 0.2 mm
[‡] Maximum grain size = 0.8 mm
*Volume fraction

A hydraulic servo-controlled actuator was used to test three point test of UHPC under relatively low loading rates. The impact testing system recently proposed by the authors (Pyo and El-Tawil 2015) is modified in this study to perform three-point bending test of UHPC under high rates of loading speed (se Figure 1). One of main advantages of the proposed impact testing system is that the loading rates can be easily adjusted simply by changing the size of the couplers. Figure 2 shows geometries of the three couplers used these experiments. The relationship between size of coupler and loading rates was discussed in Pyo and El-Tawil (2015). A high speed camera was used to capture images of UHPC specimens during fracture, and the Canny edge detection algorithm was adopted to calculate crack length from captured images. Details of the impact testing system, strain measurement process and associated calculations can be found in Pyo (2014).
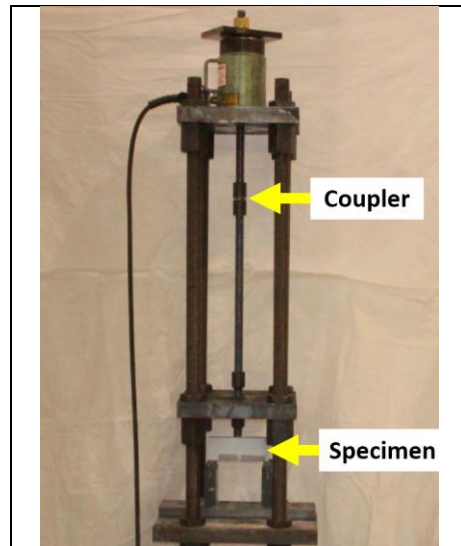
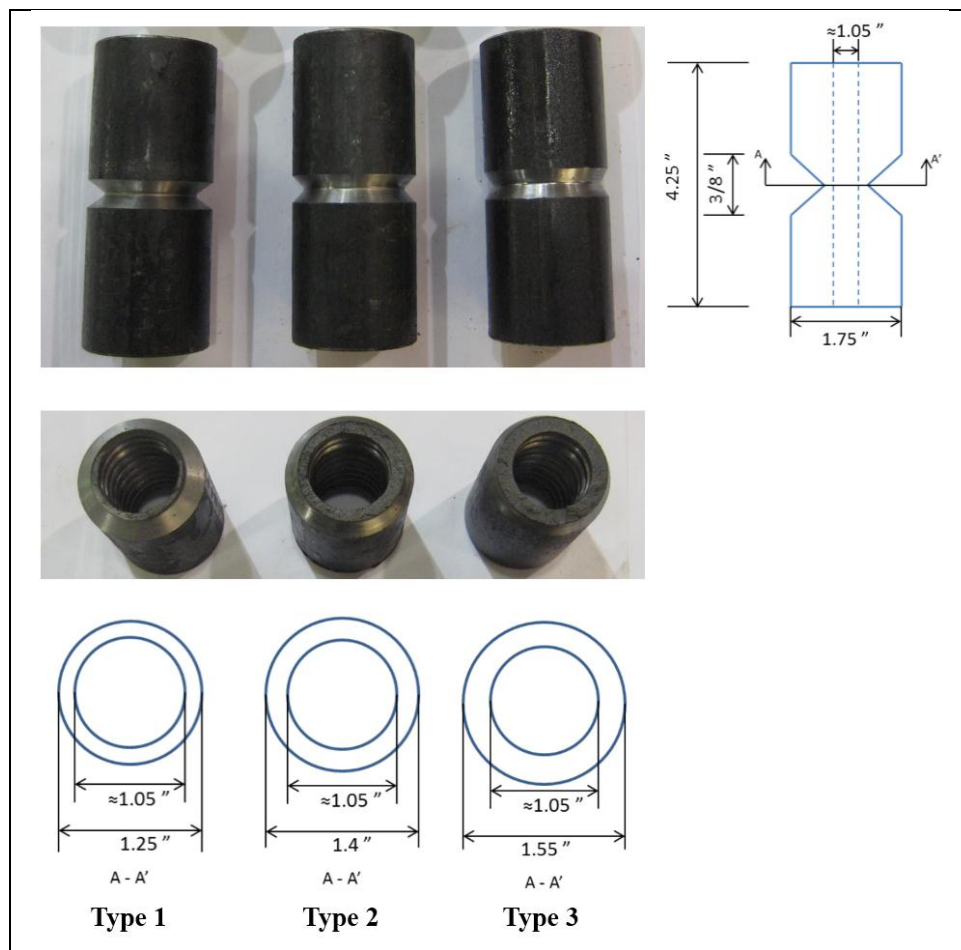**Figure 1. Impact testing system for measuring crack speed of UHPC**

Figure 2. Geometries of couplers used in the experiments

3. Results and Conclusions

Figure 3 summarizes experimental results from the series of tests using the hydraulic servo-controlled actuator (slow loading rate) and the modified impact testing system (fast loading rate). The achieved crack initiation strain rates are 0.025 to 1.0 1/s and 6.8 to 41.1 1/s using the hydraulic actuator and impact system, respectively. It can be seen from Figure 3 that the UHPC series with fiber reinforcement showed much lower crack speed than UHPC without fibers at the lower loading speeds, which indicates that steel fiber reinforcement play an important role in resisting crack opening at such speeds. In contrast, all UHPC series showed similar crack speeds at higher loading rates, suggesting that cracking is independent of fiber reinforcement at these higher loading rates.

It is found after carefully examining the crack surfaces of all UHPC specimens that there are no noticeable changes in the features of the crack surfaces as a function of crack speed. This is unlike brittle plastic, e.g. polymethylmethacrylate (PMMA) where the fracture surface is featureless up to a certain crack speed and appears jagged thereafter (Fineberg et al. 1991). Figures 4 and 5 show examples of CS-0.5% specimens after the three-point bending test for various loading rates. It is also revealed from the examination that single straight cracks developed predominantly in CS-0% specimens. In contrast, cracks followed an irregular path occur in CS-1.0% specimens, which is attributed to the effects of the fibers.

In the initial design stages of the experimental program, there was a desire to use Type 3 couplers (see Figure 2) to yield even greater impact speeds. Type 3 couplers have the greatest net area and therefore can lead to storage of the largest elastic energy. However, the use of Type 3 couplers caused the loading hammer to move so forcefully that it crushed the top half of specimens before notch tip cracking commenced, rendering the tests useless. Figure 5 shows an example of specimens with crushing damage due to the use of Type 3 couplers.
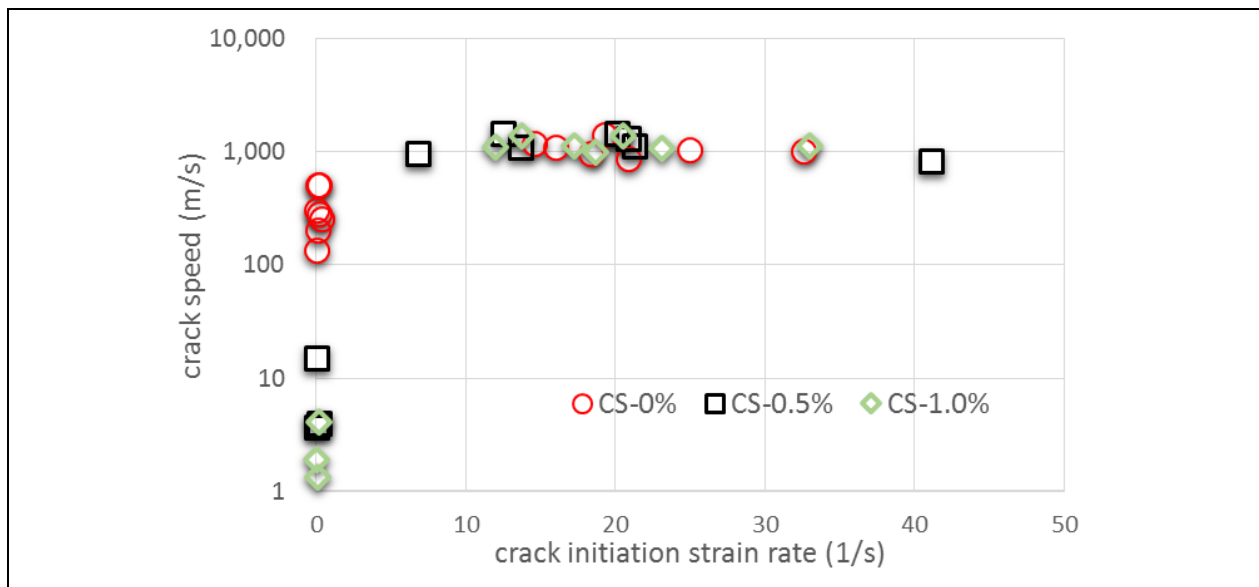

Figure 3. Summary of crack speed of UHPC

Figure 4. Examples of CS-0.5% specimen after testing using M-SEFIM with Type 1 coupler

Figure 5. Examples of CS-0.5% specimen with crushing failure test using M-SEFIM with Type 3 coupler

4. References

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5. Acknowledgements