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BEHAVIOR OF HYBRID STEEL FIBER REINFORCED HIGH STRENGTH CONCRETE

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High strength concrete has higher strength but lower ductility. Inclusion of single type of fibers into concrete has been proven to improve the behavior of concrete to a limited extent. However, recently it was found that the behavior of concrete can be improved more with the addition of hybrid fiber *i.e.*, a combination of different types of fiber. This paper presents the results of an experimental investigation on the behavior of Hybrid Steel Fibre Reinforced High Strength Concrete (HSFR-HSC). A total of eight cylinder specimens with 150 mm in diameter and 300 mm in height were cast and tested under uniaxial compression. Three different combinations of HSFR-HSC specimens and reference specimens without steel fibers were prepared. The first combination of HSFR-HSC included 1.5% Micro Steel (MS) fibers and 1% Deformed Steel (DS) fibers. The second combination included 1.5% MS fibers and 1.5% Hooked-end Steel (HS) fibers. The third combination included 1% DS fibers and 1.5% HS fibers. The experimental results showed that the addition of hybrid steel fibers improved the strength and ductility of high strength concrete compared to the reference specimens. The results also showed that the specimens reinforced with different hybrid steel fibers failed in a ductile manner, while the reference specimens failed in a brittle manner.

Keywords: High strength concrete, Micro steel fibers, Deformed steel fibers, Hooked-end steel fiber, Hybrid steel fibers.

1 INTRODUCTION

High Strength Concrete (HSC) possesses improved mechanical properties including higher compressive strength and higher durability compared to Normal Strength Concrete (NSC). However, HSC tends to be brittle and lacks plastic deformation capacity under high axial loadings (Sheikh *et al.* 2010). The inclusion of steel fiber into concrete was found to improve the mechanical properties of concrete including flexural toughness, tensile strength and resistance to crack propagations (Song and Hwang 2004, Thomas and Ramaswamy 2007, Yazici *et al.* 2007). The properties of concrete reinforced with a single type of fiber can be improved to a limited extent. However, recently it was found that combination of different types of fiber (Hybrid Fiber) can enhance the mechanical properties of concrete (Prisco *et al.* 2009).

Several studies investigated the behavior of concrete with the inclusion of a single type of steel fiber (Fanella and Naaman 1985, Ezeldin and Balaguru 1992, Nataraja *et al.* 1999, Mansur *et al.* 1999, Hadi 2007, Hadi 2009, Oliveira *et al.* 2010, Balanji *et al.*

2015). However, limited information is available about the behavior of the HFRC in the literature. Qian and Stroeven (2000) investigated the influence of fiber type (Polypropylene and Steel) and volume contents on the compressive strength and tensile strength of HFRC. Yao *et al.* (2003) observed the mechanical properties of HFRC in terms of compressive strength and splitting tensile strength. Chi *et al.* (2014) presented stress-strain behavior of Hybrid Fibre Reinforced Normal Strength Concrete (HFR-NSC). Most of these studies focused on the improvement of strength of HFRC. Only Chi *et al.* (2014) studied the stress-strain behavior of HFR-NSC. The complete stress-strain behavior of HSFR-HSC has not yet been adequately investigated.

As part of a research program aimed at investigating the strength and ductility capacity of steel fiber reinforced HSC columns, the objective of this study is to investigate the stress-strain behavior of HSFR-HSC under uniaxial compression. The parameters investigated in this study are the fiber type (Micro Steel, MS; Deformed Steel, DS; and Hooked-end Steel, HS), volume content and aspect ratio of the steel fibers.

2 EXPERIMENTAL PROGRAM

2.1 Material Details

A local supplier provided HSC with a compressive strength of 65 MPa. Eight cylinder specimens of 150 mm x 300 mm were cast and tested. Three different types of steel fibers *i.e.*, MS (6 mm in length, 0.2 mm in diameter and nominal tensile strength of 2600 MPa), DS (18 mm in length, 0.55 mm in diameter and nominal tensile strength of 800 MPa) and HS (35 mm in length, 0.75 mm in diameter and nominal tensile strength of 1225 MPa) were used. The specimens were divided into four groups. Two specimens were used in each group. Group R (Reference group) included plain HSC without steel fibers. Group MD included 2.5% hybrid steel fibers (1.5% of MS and 1% of DS). Group MH included 3% hybrid steel fibers (1.5% of MS and 1.5% of HS). Finally, Group DH included 2.5% hybrid steel fibers (1% DS and 1.5% of HS).

2.2 Casting, Curing and Testing

The HSC was placed directly from the concrete chute into the concrete mixer in order to add the steel fibers into the concrete. As per the design mix proportions, different steel fibers were mixed in a tray and then sprinkled into the concrete. The mix drum was filled to the correct height so the total volume for each group of the HSFR-HSC was 0.01 m^3. The mixer was switched on for 1.5 to 2 minutes until the fibers were uniformly mixed in the concrete. The slump of HSFR-HSC was measured by using a slump cone apparatus. The slump values ranged between 65 mm to 105 mm depending on the hybrid steel fibers type and volume content. Eight cylinder specimens were cast to study the behavior of HSFR-HSC. After casting, the specimens were covered with plastic sheet and cured for 24 hours at room temperature. Afterwards, the specimens were demolded and cured in a water tank until the day of testing.

After 28 days, all the cylindrical specimens were tested until failure in the 5000 kN Denison Universal Testing Machine at the University of Wollongong, Australia. Prior to testing, the specimens were capped with a hard plaster to ensure uniform loading faces. Both ends of the specimens were wrapped using Fibre Reinforced Polymer (FRP) sheet for a width of 35 mm in order to prevent premature failure. To measure the axial deformation at the middle half of the cylinder, Linear Variable Differential Transducer (LVDT) was used. Displacement controlled loads were applied at 0.5 mm/min. An electronic data acquisition system was used to record the load and the corresponding axial deformation. Figure 1 shows a specimen in the testing machine.

Figure 1. Test setup.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of Hybrid Steel Fibers

Eight cylindrical specimens were tested to study the stress-strain behavior of HSFR-HSC under uniaxial compression. The major parameters defining a stress-strain curve are peak stress (f'_{cf}) and strain corresponding to the peak stress (ε'_{cf}). The average values of the results of the two specimens in each group are shown in Table 1. The average peak stress (f'_{cf}) for Groups MD and DH were slightly lower than the average peak stress of Group R. However, the average peak stress for Group MH was higher by 8% than the average peak stress of Group R. It was also observed that the strain corresponding to the peak stress (ε'_{cf}) was increased with the inclusion of hybrid steel fibers into the HSC. The average strain corresponding to the peak stress was increased by 19%, 21%, and 48% for Groups MD, DH, and MH, respectively.

The complete stress-strain curves of the eight specimens are presented in Figure 2. Figure 2 clearly shows that the ascending branches of HSFR-HSC are slightly affected by the addition of different types of hybrid steel fibers. However, the descending branches of the HSFR-HSC are significantly influenced by the inclusion of different types of hybrid steel fibers. The slope of the descending branches of the stress-strain curve of Group MH was less steep than the slopes of Groups MD and DH. This is due to the high volume content of fiber in Group MH (3%) compared to the lower volume contents of fiber in both of Groups MD and DH (2.5%). In addition, MS fiber enhances the pre-peak stress by controlling the small cracks at an early stage. After the cracks became wider HS fiber reduced crack propagation by carrying loads and transferring them to other fibers. Thus, the ductility of Group MH increased. The slope of the descending branches for Group DH was less steep than the slope of Group MD. This is due to the high proportion of the longer steel fiber (1% of DS and 1.5% of HS) in Group DH. Consequently improvement was achieved in post-peak behavior for Group DH compared with Group MD.

The average of ductility of the HSFR-HSC was calculated and shown in Table 1. The ductility of the specimen was calculated as a ratio of the ultimate strain to the yield strain. It was observed that the ductility of the HSFR-HSC is increased with the inclusion of different types of hybrid steel fibers. The ductility was increased by 61%, 109% and 180% for Group MD, Group DH and Group MH respectively compared to the ductility of Group R.

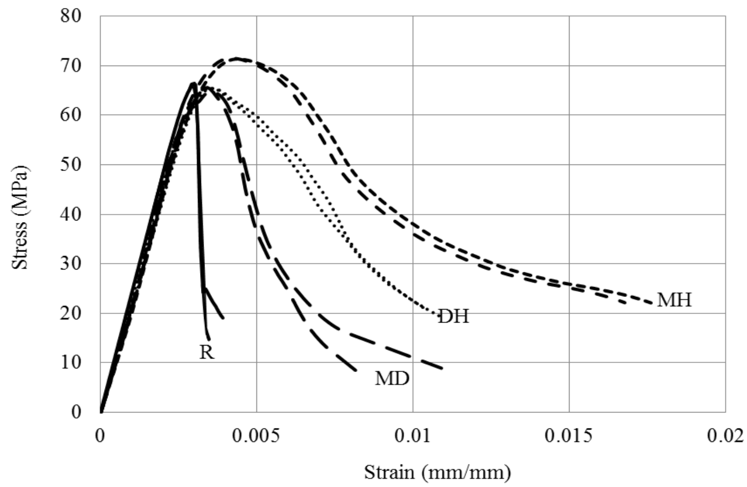

Figure 2. Stress-strain behavior of HSC with and without hybrid steel fibers.

Table 1. Average experimental results.

Group designation	Hybrid steel fibers volume content (V_f%)	Experimental results			
		f'_{cf} (MPa)	ε'_{cf} (mm/mm)	Ductility	Ductility relative to the Group R
R	0	66.3	0.0029	1.43	1
MD	3	65.2	0.00345	2.31	1.61
MH	2.5	71.4	0.0043	3.00	2.09
DH	2.5	65.4	0.0035	4.01	2.8

3.2 Failure Modes

The typical failure modes of the specimens are shown in Figure 3. The failure mode for Group R specimens was brittle. However, with the inclusion of different hybrid steel fibers into high strength concrete, the failure mode became a combination of shear failure and bugling of the specimens in the lateral direction. The failure mode of Group

MD specimens was due to the propagation of cracks parallel to the loading direction. This means that Group MD was effective in reducing early cracks propagation and contributes little to post peak behavior. The failure mode of Group MH specimens was due to shear failure and bugling of the specimens in the lateral direction. This means that Group MH was effective in reducing early cracks propagation and in improving the post peak behavior of the specimens. The failure mode of Group DH specimens was due to bugling of the specimens in the lateral direction. This behavior shows that Group DH was more effective in the post peak behavior and has less contribution to arresting early cracks propagation.

Figure 3. Typical failure modes.

4 CONCLUSION

In this study, a total of eight cylinder specimens of 150 mm x 300 mm were tested under uniaxial compression to investigate the behavior of different HSFR-HSC. The following conclusions can be drawn from the experimental results:

- The addition of hybrid steel fibers into HSC matrix changes the stress-strain behavior of HSC. The ascending branch of the stress-strain curve is slightly influenced, but the descending branch of the stress-strain curve is significantly influenced by the inclusion of hybrid steel fibers.
- The addition of hybrid steel fibers into HSC increases the average strain corresponding to the peak stress by 19%, 21% and 48% for Groups MD, DH, and MH, respectively. However, the average peak stresses of Groups MD and DH were slightly deceased, while the average peak stress was increased by 8% for Group MH compared to Group R.
- The inclusion of hybrid steel fibers into high strength concrete leads to significantly increase in the ductility of high strength concrete. The ductility was increased by 61%, 109% and 180% for Group MD, Group DH and Group MH, respectively compared to the ductility of Group R.
- The combination of the MS and HS fibers provides the highest enhancement in terms of strength and ductility compared to other combinations of the hybrid steel fibers and reference specimens without of fibers.

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