Strength Properties of Multi-Scale Hybrid Fiber Reinforced concrete

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Abstract

Recently, hybrid fiber reinforced concrete (HFRC) has gained popularity for its superior mechanical properties. The fiber hybridization in HFRC means the addition of two or more than two fibers in a suitable way to take full benefits from each fiber. The growth of cracks in concrete is multi-scale process from micro to macro scale. Also, the restriction of cracks with one dimension and length of fibers is limited at their particular scale and have no or little effects at other scales. Therefore, it is logical to combine various types and sizes of fibers in concrete for achieving optimized strength properties. In this study, the compressive and flexural strength of concrete with incorporation of calcium carbonate whisker, basalt fiber and steel fiber are evaluated. The mix design ratio of PC and HFRC is 1:2:1.5 (cement: sand: aggregate) with water cement ratio of 0.4. The HFRC, HFRC1, HFRC2 and HFRC3 were prepared with 5% steel fiber and 5% calcium carbonate whisker having basalt fibers content of 0%, 2%, 4% and 6%, respectively. The compressive and flexural strength tests are performed in accordance with the relevant ASTM standard. It is revealed that the compressive and flexural strength of HFRC are improved by 14% and 46%, respectively when compared with that of plain concrete. It is recommended to optimize the length and content of basalt fiber in hybrid fiber reinforced concrete.

Keywords: Multi-scale fibers, steel fiber, basalt fiber, calcium carbonate whisker, strength.

1. INTRODUCTION:

The concrete brittleness and poor crack resistance can be controlled up to some extent by reinforcement of randomly distributed fibers. The cracks from micro- to macro level can be arrested by use of fibers reinforcement. The fibers help to resist the initiation and crack growth from micro- to macro level and provide bridging effect which ultimately enhances the strength and toughness (Banthia and Sappakittipakorn 2007). The single type of fiber in concrete as a reinforcement can only be effective up to limited extent. Nearly 45 years ago, Walton and Majumdar (1975) studied the use of combining organic and inorganic fibers to achieve higher toughness and strength. After that different type of hybrid fiber reinforced composites were developed using fiber hybridization. It has been observed that the performance of multiscale hybrid fibers reinforced concrete mixtures is superior to that of concrete mixtures reinforced with single-type of fibers due to positive interaction between them and this phenomenon is commonly known as "fiber synergy". The fibers in hybrid fiber reinforced concrete (HFRC) can be classified by their geometrical size i.e. micro and macro fibers (Sorelli et al. 2015). The HFRC having two or more types of fibers has been studied and shows higher compressive strength, tensile strength and energy dissipation capacity (Li et al. 2017). Also, the strength can be enhanced by using optimized content of different types of fibers.

Sivakumar and Santhanam (2007) combined the different hybrid fiber combination, i.e. steel-glass, steel-polyester and steel-polypropylene fibers to study the mechanical properties of HFRC. It was reported that addition of steel fiber improves the energy absorption mechanism, i.e. bridging effect while the glass, polyester and polypropylene fibers results in delaying the development of micro-cracks. The reason for improved mechanical properties was due to increased hybrid fibers which provide the bridging effect. Steel fibers can bridge macro cracks and restrict the crack propagation at large scale ultimately enhances the mechanical properties of concrete. The basalt fibers restrict the formation of cracks at meso level. Meanwhile, $CaCO_3$ whiskers can bridge micro cracks and prevent further crack propagation at micro scale (Cao et al. 2018). Yoo et al. (2017) reported that the restriction of cracks with one dimension and length of fibers is limited at their particular scale, but have no or little effects at other scales. Therefore, it is necessary to combine different types of fiber and still the research is needed form macro-scale to micro scale hybrid fibers at multi-level cracking. In this study, the strength parameters of HFRC with steel fibers and calcium carbonate whiskers having different contents of basalt fibers are investigated.

2. EXPERIMENTAL PROCEDURES:

2.1 Materials:

The raw materials include cement, fine aggregate, coarse aggregate, super plasticizer, calcium carbonate whisker, basalt fibers (BF) and steel fibers. Table 1 shows the chemical composition of calcium carbonate whisker. The steel, basalt fibers and $CaCO_3$ whisker are shown in Figure 1. The properties of different types of fibers are presented in Table 2.

Table 1: Chemical composition of $CaCO_3$ whisker (wt.%)

Chemical Composition	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CO_2**	**MgO**	**SO_3**
$CaCO_3$ Whisker	54.93	0.29	0.11	0.07	42.07	2.14	0.31

a. b. c.

Figure 1: Raw materials, a. $CaCO_3$ whiskers, b. basalt fibers, and c. steel fibers

Table 2: Properties of different types of fibers

Raw Ingredients	Size		Tensile strength
	Length	Diameter	
$CaCO_3$ whisker	20–30μm	0.5–2μm	3000-6000 MPa
Basalt fiber	12 mm	7~15 μm	3000-48000 MPa
Steel fiber	35 +10% mm	0.55 +10% mm	1345 +15% MPa

2.2 Mixing design:

The mix design ratio of plain concrete (PC) and HFRC is 1:2:1.5 (cement: sand: aggregate) with a water cement ratio of 0.4. The super plasticizer content of 1%, by cement mass, is added to all HFRCs. The mix design ratios of all concrete mixes are shown in Table 3. The mix design ratio is selected from the previous study (Khan et al. 2018). A layer procedure for the mixing of fiber reinforced concrete was adopted for the HFRC mix. Khan and Ali (2016) and Khan and Ali (2018) also reported this method for uniform mixing and to avoid balling effect.

Table 3: Mix design ratio of all concrete mixes

Mix Type	Steel fiber	$CaCO_3$ whisker	Basalt fiber	Super plasticizer
PC	-	-	-	-
HFRC	5%	5%	0%	1%
HFRC1	5%	5%	2%	1%
HFRC2	5%	5%	4%	1%
HFRC3	5%	5%	6%	1%

Note: The mix design ratio was 1:2:1.5:0.4 (cement: sand: aggregate: water).
All percentages are by cement mass.

2.3 Test Specimens:

After uniform mix, three cylinders of size 100 mm diameter and 200 mm height and three beam specimens of size 100 mm width, 100 mm depth and 400 mm length were cast from each batch. The fresh concrete mix was poured into the plastic moulds and then compaction was performed on vibrating table. After 24 hours, the cylinders and beams were demoulded and kept for 28 days in to the curing room. The ASTM standard C 192 was followed for making and preparation of specimens.

2.4 Testing:

The compressive strength (CS) and flexural strength (FS) tests were conducted in accordance with the ASTM standard C39 and C1609, respectively.

3. RESULTS:

3.1 Compressive strength:

Figure 2 shows the CS of PC and all HFRCs with standard deviation values of up to 10%. The CS of HFRC is increased to 22.4 MPa and then reduces up to 20 MPa at 6% BF content. For HFRC, the CS is enhanced with incorporation of 2% BF content and then reduced with increase in BF content to 6%. The reason for enhanced CS is the filler effect of calcium carbonate whisker and also the crack bridging effect of basalt and steel fibers. Also, the addition of higher content of fibers results in creation of air voids which ultimately reduces strength. The CS of HFRC is increased up to 14% than that of PC. Kizilkanat et al. (2015) also reported the increase CS with addition of basalt fiber. The calcium carbonate whisker improved the CS of cement based composites (Cao et al. 2014). The incorporation of steel fibers results in enhanced CS of concrete and is also reported by Song and Hwang (2004). In comparison with PC, the CS of all HFRCs is higher. The increasing trend in CS is observed up to the HFRC1.

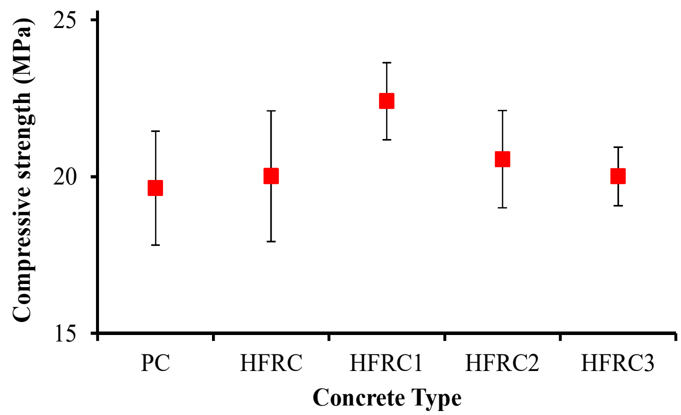

Figure 2: Compressive strength of all concrete types

3.2 Flexural strength:

The flexural strength with standard deviation values of PC and all HFRCs are shown in Figure 2. The FS is improved up to 46% with incorporation of up to 6% basalt fiber content. The multi-scale hybrid fibers crack arresting mechanism results in improved FS.

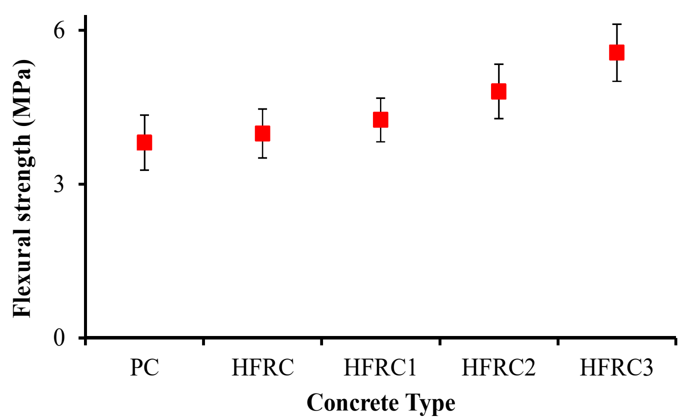

Figure 3: Flexural strength of all concrete types

The steel fibers, BF and calcium carbonate whiskers offered crack resistance at macro-, meso- and micro-level, respectively. Song and Hwang (2004) stated that the incorporation of steel fibers improves the flexural strength. The improvement in FS of concrete with inclusion of BF is also observed by Kizilkanat et al. (2015). The FS of all HFRCs are higher as compared to that of PC. It may be noted that as the content of basalt fiber increases the FS of HFRC increases. However, the HFRC3 showed the highest FS than that of PC and all other HFRCs. The standard deviation values of all concrete types are up to 14%.

4. DISCUSSION:

The fibers are surrounded by adhesive contact of paste which improves the strength of concrete from stress transfer mechanism between matrix and reinforced fibers as shown in Figure 4. Moreover, a part of tensile stresses are taken by fibers generated due to applied loading, thus resist crack growth and help to retain compact microstructure. Also, the applied load is transferred to the fibers cement-matrix which also keeps the fibers together. The competence of a HFRC is dependent on the fiber-matrix interface and the capability to transfer stress from the matrix to the fiber. The tensile cracking of concrete is controlled and delayed through discontinuous randomly distributed multi-scale fibers throughout the cement paste. A slow controlled crack growth of the inherent unstable tensile cracks is due to the incorporation of multi-scale fibers during crack propagation at different levels. This slow crack growth property of fibers delays the initiation of shears and flexural cracks and ultimately improves the strength.

a. b.

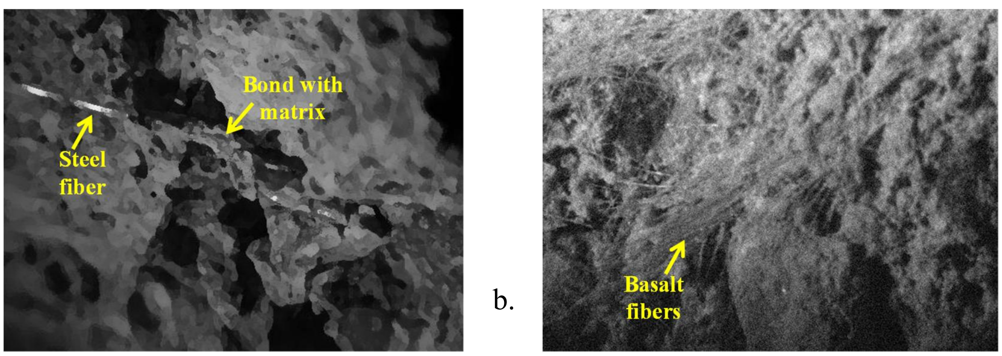

Figure 4: Fiber bridging during crack propagation, a. steel fiber, b. basalt fiber

5. CONCLUSIONS:

Following conclusions are made:

- The compressive strength of hybrid fiber reinforced concrete having 2% basalt fiber content is enhanced up to 6%, when compared with that of plain concrete.
- Compared to plain concrete, an increment of 46% is observed in flexural strength of hybrid fiber reinforced concrete with 6% basalt fiber content.
- The positive synergy of hybrid fibers can be observed from improved strength properties of concrete.
- The increased strength shows that the multi-scale hybrid fiber can resist the cracking and control the initiation of cracks at multi-level.

Based on above results, the multi-scale hybrid fibers showed the satisfactory performance. Therefore, further studies should be carried out on optimization of basalt fiber length and content in HFRC.

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REFERENCES:

ASTM C39/C39M-17, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017, www.astm.org

ASTM C192/C192M (2016). Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken, PA. www.astm.org.

ASTM C1609/1609M (2012). Standard Test Method for Flexural Performance of Fiber-reinforced Concrete (using Beam with Third-point Loading), American Society for Testing and Materials, West Conshohocken, PA. www.astm.org.

Banthia, N. and Sappakittipakorn, M., 2007. Toughness enhancement in steel fiber reinforced concrete through fiber hybridization. Cement and Concrete Research, 37(9), pp.1366-1372.

Cao, M., Zhang, C. and Lv, H., 2014. Mechanical response and shrinkage performance of cementitious composites with a new fiber hybridization. Construction and Building Materials, 57, pp.45-52.

Cao, M., Li, L. and Khan, M., 2018. Effect of hybrid fibers, calcium carbonate whisker and coarse sand on mechanical properties of cement-based composites. Materiales de Construcción, 68(330), p.156.

Khan, M. and Ali, M., 2016. Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks. Construction and Building Materials, 125, pp.800-808.

Khan, M. and Ali, M., 2018. Effect of super plasticizer on the properties of medium strength concrete prepared with coconut fiber. Construction and Building Materials, 182, pp.703-715.

Khan, M. Cao, M. Ali M., 2018. Hybrid fiber reinforced concrete for the application of bridge deck. 3rd FRC International Workshop Fibre Reinforced Concrete: from Design to Structural Applications, Desenzano, Lake Garda, Italy, June 27-30, Paper # 53.

Kizilkanat, A.B., Kabay, N., Akyüncü, V., Chowdhury, S. and Akça, A.H., 2015. Mechanical properties and fracture behavior of basalt and glass fiber reinforced concrete: An experimental study. Construction and Building Materials, 100, pp.218-224.

Li, Z.X., Li, C.H., Shi, Y.D. and Zhou, X.J., 2017. Experimental investigation on mechanical properties of Hybrid Fibre Reinforced Concrete. Construction and Building Materials, 157, pp.930-942.

Sivakumar, A. and Santhanam, M., 2007. Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres. Cement and Concrete Composites, 29(8), pp.603-608.

Song, P.S. and Hwang, S., 2004. Mechanical properties of high-strength steel fiber-reinforced concrete. Construction and Building Materials, 18(9), pp.669-673.

Sorelli, L.G., Meda, A. and Plizzari, G.A., 2005. Bending and uniaxial tensile tests on concrete reinforced with hybrid steel fibers. Journal of materials in civil engineering, 17(5), pp.519-527.

Walton, P.L. and Majumdar, A.J., 1975. Cement-based composites with mixtures of different types of fibres. Composites, 6(5), pp.209-216.

Yoo, D.Y., Kim, M.J., Kim, S.W. and Park, J.J., 2017. Development of cost effective ultra-high-performance fiber-reinforced concrete using single and hybrid steel fibers. Construction and Building Materials, 150, pp.383-394.