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Influence of $CaCO_3$ whiskers, steel fibers and basalt fibers hybridization on flexural toughness of concrete

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ABSTRACT

Nowadays, hybrid fiber reinforced concrete is developed with the combination of $CaCO_3$ whiskers, steel and basalt fibers due to their enhanced mechanical properties of structural applications. In this study, the effect of different basalt fiber contents on flexural strength of hybrid fiber reinforced concrete (HyFRC) is investigated. In addition to this, the energy absorbed (E), toughness indices (TI) up to specified point and residual strength factor (RSF) are also calculated according to the ASTM C1018. The steel fibers and $CaCO_3$ whiskers having contents of 5% each, by cement mass, are added. To prepare HyFRC, HyFRC1, HyFRC2, and HyFRC3, different basalt fiber content of 0%, 2.5%, 5% and 7.5%, respectively, are added. The increment in flexural strength of HyFRC up to 16% is observed. Future recommendations are to optimize basalt fiber length and content for mechanical properties of HyFRC.

Keywords: Hybrid fiber reinforced concrete; $CaCO_3$ whiskers; basalt fibers; structural applications; flexural toughness.

INTRODUCTION

Concrete is a universal construction material which is widely used due to its excellent strength, low cost and durability (Li et al. 2018). However, over decades, attempt has been made to enhance its deflection capacity, tensile strength and toughness (Nilforoush et al. 2017). To reduce the brittleness of plain concrete, fibers are added in concrete to improve its mechanical properties especially post cracking behaviour and tensile strength. Nearly 45 years ago, Walton and Majumdar (1975) studied the use of fibers in composites to achieve higher toughness and strength. Recently, many researchers have studied the flexural behaviour of fiber reinforced concrete (FRC) with enhanced flexural strength and toughness (Khan and Ali 2016, Khan and Ali 2018 and Khan and Ali 2018). The incorporation of fibers has low effect on first cracking properties, but mainly improves the post cracking behaviour of concrete (Yoo et al. 2013, Wu et al. 2016 and Choumanidis et al. 2016). Furthermore, many fiber factors, i.e. length, volume fraction, type and geometry affect the flexural properties of concrete (Li et al. 2018). The improvement in flexural strength and toughness is due to addition of different types of fibers, and it also enhances load carrying capacities and crack bridging (Lee et al. 2016, Lee et al. 2017 and Lee et al. 2017).

Recently, a new type of concrete known as hybrid fiber reinforced concrete (HyFRC) has gained popularity for its excellent performance and becomes a favorable construction material (Song et al. 2005, Huang et al. 2015, Chidambaram and Agarwal 2015, Huang et al. 2016, Yoo et al. 2017 and Chi et al. 2017). The fiber hybridization in HyFRC means the incorporation of two or more than two fibers in a suitable way to take full benefits from each fiber. These fibers have different properties, i.e. fiber diameter, length, type, elastic modulus and strength and so on (Song et al. 2005, Huang et al. 2015 and Huang et al. 2016). Large fibers (steel fibers) can bridge macro cracks and restrict the crack propagation at large scale ultimately enhances the flexural properties of concrete. The meso fibers, i.e. basalt fibers restrict the formation of cracks at meso level. Meanwhile, micro fibers ($CaCO_3$ whiskers) can bridge micro cracks and prevent further crack propagation at micro scale (Cao et al 2018 and Cao et al. 2018). As discussed above, the growth of cracks in concrete is multi-scale process from micro level to macro level. Also, 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 (Yoo et al. 2017). Therefore, it is logical to amalgamate different types and sizes of fibers in concrete for optimal flexural properties. The flexural behaviour of HyFRC with addition of various types of fibers and single type of fiber with different fiber lengths are studied by Kim et al. (2011), Rambo et al. (2014), Rashiddadash et al. (2014), Alberti et al. (2014), Banyhussan et al. (2016), Alberti et al. (2017), Yoo et al. (2017) and Yoo et al. (2017),. As discussed earlier, still the research is needed form macro-scale to micro scale hybrid fibers at multi-level cracking. Therefore, in this study, the flexural properties of HyFRC with steel, basalt and $CaCO_3$ whisker are emphasized and discussed.

EXPERIMENTAL INVESTIGATION

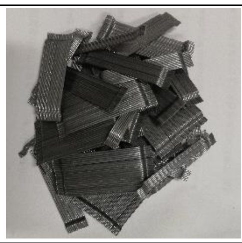
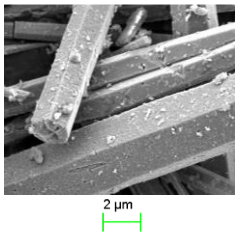
Material, Mixing and Casting

The raw materials include cement, fine aggregate, coarse aggregate, super plasticizer, 35 mm steel fibers, basalt fibers having length of 12 mm and $CaCO_3$ whisker of 20–30 μm. The properties of raw materials provided by manufacturer are shown in Table 1.

The mix design ratio of HyFRC is 1:2:2 (cement: sand: aggregate) with a water-cement ratio of 0.50. The steel fibers and $CaCO_3$ whiskers content of 5%, by cement mass, are added. The HyFRC, HyFRC1, HyFRC2 and HyFRC3 were prepared with steel fiber and $CaCO_3$ whisker having various basalt fibers content of 0%, 2.5%, 5% and 7.5%, respectively. The super plasticizer content of 1.1%, 1.2% and 1.3%, by cement mass, are added to HyFRC1, HyFRC2 and HyFRC3, respectively. A layer procedure for the mixing of fiber reinforced concrete was adopted for the HyFRC mix and this method is also reported by Ali and Chouw (2013), Khan and Ali (2016), Zia and Ali (2017), Khan and Ali (2018) and Khan and Ali (2018). The slump values for HyFRC, HyFRC1, HyFRC2 and HyFRC3 are 100 mm, 110 mm, 80 mm and 40 mm, respectively.

After uniform mix, 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 beams were demoulded and kept in to the curing room for 28 days. The ASTM standard C 192 was followed for making and preparation of specimens. A total of three beams were cast from each batch and labeled as HyFRC, HyFRC1, HyFRC2 and HyFRC3. The HyFRC denotes 5% content of steel fiber and $CaCO_3$ whisker; while 1, 2 and 3 represents the basalt fiber content of 2.5%, 5% and 7.5%, respectively.

Table 1. Properties of raw materials

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

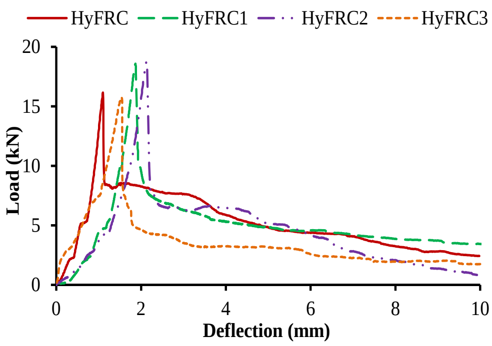
Test Method

The flexural strength test was conducted in accordance with the ASTM standard C 1609. The clear span was 300 mm. The deflection at peak load (Dp), energy absorbed (E), toughness indices (TI) and residual strength factor (RSF) of all HyFRC were calculated according to ASTM C1018. The Eδ, E3δ, E5.5δ and E10.5δ are the area under the curve up to first crack; 3 times first crack, 5.5 times first crack deflections and 10.5 times first crack deflections, respectively. The TI5, TI10 and TI20 are the ratio of E3δ/Eδ, E5.5δ/Eδ and E10.5δ/Eδ, respectively. The RSF5,10 and RSF10,20 denotes average level of strength retained after first crack; and is calculated by 20(TI10-TI5) and 10(TI20-TI10), respectively. Here, from the recorded load-deflection curves only the Eδ, E3δ, E5.5δ, TI5, TI10 and RSF5,10 can be calculated.

RESULTS AND DISCUSSIONS

The load-deflection curves and flexural strength of all HyFRC mixes are shown in Figure 1. From load-deflection curve, it can be seen that the HyFRC having steel fiber, basalt fiber and $CaCO_3$ whisker has maximum deflection at peak load than that of HyFRC (Steel fiber + $CaCO_3$ whisker). The reason may be the addition of basalt fiber in HyFRC1, HyFRC2 and HyFRC3 which results in more energy absorption capacity before the maximum load. Also, the incorporation of basalt fiber resist the cracking before peak load which ultimately result in higher deflection at maximum load as shown in Figure 1(a). The FS of HyFRC2 was higher than that of other HyFRC. The higher FS may be due to the positive hybrid effect between steel fiber, basalt fiber and $CaCO_3$ whisker which provide resistance against cracking. The reason for reduced FS of HyFRC3 can be the higher amount of basalt fibers which results in poor dispersion and heterogeneity of the mix. Also, the effectiveness of basalt fiber before peak load is superior as compared to that of after peak load. Furthermore, the HyFRC without basalt fiber showed steeper slope before and after maximum load than that of HyFRC with basalt fiber.

(a)



(b)

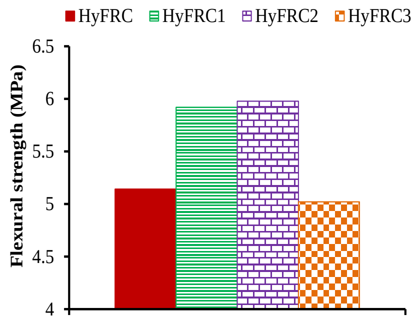


Figure 1. Flexural response of HyFRCs (a) Load-deflection curves; (b) flexural strength

The flexural strength, deflection at peak load, energies absorbed, toughness and residual strength factor of all HyFRC mixes are shown in Table 2. Compared with that of HyFRC, the energies absorbed by HyFRC2 were dramatically improved. The specimens consist of HyFRC had higher flexural toughness due to the less first crack load. As TI5 and TI10 were the ratios of E3δ/Eδ and E5.5δ/Eδ, respectively; so the minimum first crack load results in highest toughness. The first crack point was the point where the crack appeared initially on the side surface bottom of the beam. So, the first crack deflections were not same and also the toughness indices of TI5 and TI10 did not correspond to the similar deflections of various beams. Therefore, the TI for calculating the actual energies absorbed capabilities under typical service load is still a problem for structural members because different design codes of concrete structures reports the different deflections with respect to height or span of the members (Li et al. 2018). Banthia and Trottier (1995) reported that flexural toughness obtained from ASTM C1018 has some imperfection due to human judgment error. Also, the first crack point is observed occasionally and accurate location can’t be determined accurately. It is difficult to find first crack deflection in the load-deflection curve and this is also an issue in ASTM C1018 method (Jun Li et al. 2017). Therefore, if the first crack point is observed earlier than it results in higher energies absorbed and toughness. The HyFRC1, HyFRC2 and HyFRC3 had higher values at first crack point which ultimately results in less energies absorbed and toughness. However, the addition of basalt fiber in HyFRC showed positive synergy with steel fiber and $CaCO_3$ whisker ultimately the enhanced the flexural properties. The enhanced flexural behavior shows that HyFRC has the potential to be used for structural applications.

Table 2. Flexural strength (FS), deflection at peak load (Dp), energies absorbed (E), toughness index (TI) and residual strength factor (RSF) of all HyFRC mixes

Parameters	Concrete type			
	HyFRC	HyFRC1	HyFRC2	HyFRC3
FS (MPa)	5.14	5.92	5.98	5.02
Dp (mm)	1.09	1.84	2.05	1.49
Eδ (kN.mm)	5.65	7.50	8.92	8.85
E3δ (kN.mm)	24.29	31.63	36.49	23.16
E5.5δ (kN.mm)	39.77	50.28	47.00	33.03
TI5 (-)	4.56	4.48	4.35	2.78
TI10 (-)	7.47	7.12	5.60	3.96
RSF5,10 (-)	58.2	52.8	25.0	23.7

The comparison of flexural strength, deflection at peak load, energies absorbed, toughness index and residual strength factor of all HyFRC are shown in Figure 2. The FS of HyFRC1 and HyFRC2 are improved by 15% and 16%, respectively, as compared to that of HyFRC. The Dp of HyFRC is increased up to 188%. For HyFRC2, the Eδ, E3δ, E5.5δ are increased by 57%, 50% and 18%, respectively, than that of HyFRC. In contrast with HyFRC, there is reduction in TI and RSF of HyFRC2 up to 25% and 57%, respectively. The reason for improved flexural properties is due to the strong bridging effect and pull-out resistance of fibers caused by hybridization of multi-scale fibers at multi-level.

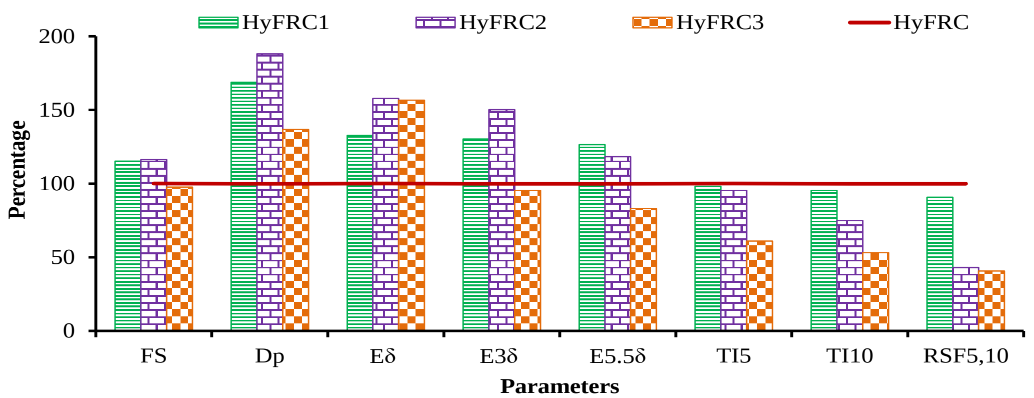


Figure 2. Comparison of flexural strength (FS), deflection at peak load (Dp), energies absorbed (E), toughness index (TI) and residual strength factor (RSF) of all HyFRC

CONCULSIONS

In this study, flexural behavior of hybrid fiber reinforced concrete (HyFRC) with inclusion of $CaCO_3$ whisker (5%), steel fibers (5%) and various basalt fiber contents (0%, 2.5%, 5%, and 7.5%, by cement mass) are investigated. Following conclusions are made:

- The flexural strength of HyFRC with basalt fibers is improved up to 16% than that of HyFRC without basalt fibers.
- The addition of basalt fibers in HyFRC enhances the flexural response of load-deflection curves and results in maximum deflection at peak load.
- The improved strength and energies absorbed of HyFRC incorporating basalt fibers show the positive synergy effect with steel fibers and $CaCO_3$ whisker.
- The HyFRC having 5% basalt fiber content, by cement mass, is suggested to be the optimum content based on better strength, maximum deflection at peak and energies absorbed for structural application.

The HyFRC with combination of steel fibers, basalt fibers and $CaCO_3$ whisker has satisfactory performance which is a positive indication for further studies. Therefore, it is recommended to study optimize the basalt fiber length and content in HyFRC for achieving overall best properties.

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