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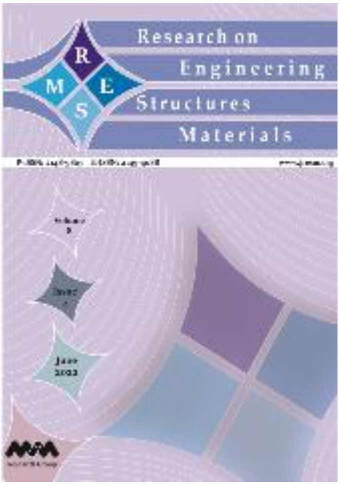

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Online Publication Date: 20 Sep 2022

URL: http://www.jresm.org/archive/resm2022.433me0515.html

DOI: http://dx.doi.org/10.17515/resm2022.433me0515

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Ojha PN, Singh P, Singh B, Singh A. Fracture behavior of hybrid fiber reinforced normal strength and high strength concrete: comparison with plain and steel fiber reinforced concrete. *Res. Eng. Struct. Mater*., 2023; 9(1): 243-262.

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Research Article

Fracture behavior of hybrid fiber reinforced normal strength and high strength concrete: comparison with plain and steel fiber reinforced concrete

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Article Info

Article history:

Received 15 May 2022
Revised 6 Aug 2022
Accepted 19 Sep 2022

Keywords:

HFRHSC;
Fracture;
Load-CMOD;
Three-point bend test

Abstract

The paper presents an experimental investigation on the fracture behavior of hybrid-fiber reinforced normal strength concrete (HFRC) and hybrid-fiber reinforced high strength concrete (HFRHSC). The hybrid fiber used in the study constitutes of 0.75% steel fiber and 0.25% polypropylene fiber, by volume of the concrete. A three-point bend test on a notched beam has been performed based on the recommendations of RILEM as well as literature. Fracture parameters like the fracture energy, stress intensity factor, energy release rate and characteristic length has been evaluated from the load-deflection and load-CMOD curves. These were compared with values for the plain and steel fiber reinforced concrete reported in literature for similar type of mixes. Result suggests that hybrid fiber improved the fracture performance in comparison to the steel fiber reinforcement in case of normal strength concrete. For higher strength concrete, replacing steel fiber by hybrid fibers caused marginal reduction in the fracture parameters. Compared to plain unreinforced concrete, the fracture behaviour irrespective of the strength improved by addition of the hybrid fibers.

1. Introduction

Innovations in the concrete mix design process and a better understanding of the materials have made it possible to design high strength concrete mixes with improved mechanical properties [1], [2]. However, one of the biggest limitations of high strength concrete is its post-peak brittleness. With increase in strength, concrete tends to suddenly fail without warning. The addition of steel fibres in high strength concrete leads to increase in the ultimate strain value and strain value at peak stress to sustain more deformation during loading, thereby avoiding sudden and brittle failure [3]. For enhancing the post-peak behavior [4], [5] and enabling the ductile failure of concrete, researchers have used different kinds of fiber reinforcement like Kevlar [6] and glass chopped fibers [7] but steel fibers are the most popular and are widely used [8]–[11]. The steel fiber used in the concrete helps in arresting the cracks [12]. It also solves the issue of the explosion of concrete at failure. A significant improvement in fracture parameters has been observed in past [12], [13] after the addition of a certain amount of steel fiber in the concrete mix. Some researchers tried to optimize the amount of steel fiber to be added to the concrete mix and reported it to be approximately 1% of the volume of concrete mix [14].

Apart from the post-peak brittleness, poor fire performance is also a serious concern for higher-strength concrete [15]. For improving the fire performance of the concrete, some special kind of fiber can be introduced in the concrete. Researchers [3], [16] have

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DOI: http://dx.doi.org/10.17515/resm2022.433me0515

suggested hybrid fibers [17]–[19] for improved safety in fire and an enhanced ductile failure simultaneously. At elevated temperatures, as encountered during a fire accident, high-strength concrete tends to explode. The reason for the explosion has been credited to the reduction in permeability [20] of the concrete due to denser packing. Due to dense packing of high-strength concrete blocks, the exit of pressurized water vapor gets created due to the rise in the temperature. To counter this phenomena, literature suggests [20] addition of materials in concrete that stay rigid at a lower temperature, but melt with the temperature rise, in an event of a fire accident. It is suggested that the melting point of the material should be much higher than the normal temperature of the environment, but should be sufficiently low to melt before the creation of pressurized steam at extreme temperatures. When the temperature of the concrete increases, the fiber is expected to melt, improving the permeability of the concrete and allowing steam to eject. Polypropylene is a suitable material for this purpose. It is a thermoplastic polymer which is a polymer of propylene. Its melting point varies between 130 degrees to 170 degrees Celsius. The solutions proposed above to tackle the issues give rise to two special classes of concrete – (i) Steel fiber reinforced concrete (SFRC) and (ii) Hybrid fiber reinforced concrete (HFRC). Similarly, two classes can be defined for high strength concrete (compressive strength more than 50 MPa) i.e., (i) Steel fiber reinforced high strength concrete and (SFRHSC) (ii) Hybrid fiber reinforced high strength concrete (HFRHSC).

The addition of steel fiber and polypropylene fiber alters the mechanical and fracture properties of the concrete. Mechanical properties like compressive strength and split tensile strength are evaluated using Indian Standard codes. RILEM recommendation (50-FMC [21]) specifies a method for determining the fracture energy (GF) of mortar and concrete by using stable three-point bend tests on notched beams. As per RILEM, the fracture energy is defined as the amount of energy required to create one-unit area of a crack. The area of a crack is defined as the projected area on a plane parallel to the main crack direction [21]. The fracture energy defined by RILEM is shape dependent, as it significantly increases with increase in the notch depth ratio of the specimen. It can be noted that the size dependence of the fracture energy estimated by RILEM is quite strong.

Past studies on hybrid fiber reinforced concrete have compared the fracture parameters of varying proportion of fibers in concrete mix. Xiangjun et al.,[22] have found maximum fracture performance with approximately 0.9% steel fiber and 0.1% Polypropylene fiber. Alwesabi et al. [14], also reported similar proportion of the fibers for the maximum fracture energy. Smarzewski, and Barnat-Hunek [23] in their investigation reported maximum compressive and split tensile strength for the mix with 0.75% of steel fiber and 0.25% of polypropylene fiber. Based on the findings an optimum choice of 0.25% PPF and 0.75% SF has been adopted in present study to compare it with 1% of steel fiber and the plane concrete mix without fiber. Some of the recent studies on the fracture behavior and crack propagation utilizes techniques like acoustic emission and digital image correlation. The fracture behavior of synthetic fiber reinforced concrete, steel fiber reinforced concrete and hybrid fiber reinforced concrete under flexural loading using Acoustic Emission (AE) technique was conducted by Bhosale, Rasheed, Prakash and Raju [24]. Study by Bhosale et al. highlights that steel fibers gave superior performance followed by hybrid and macro-synthetic fibers. Steel fibers also gives higher toughness than hybrid and macro-synthetic fibers for the fixed fiber dosage. Study also revealed that length of fracture process zone in longitudinal direction is longest in steel fibre reinforced concrete followed by hybrid and macro-synthetic fibers, where fracture process zone is less distributed in case of concrete with macro-synthetic fibers as compared to the concrete with steel or hybrid fibre. Bhosale and Prakash in another study analyzed the crack propagation in synthetic, steel and hybrid fiber reinforced concrete using digital image correlation techniques. The study concluded that hybrid fiber reinforced concrete had longer cracks than steel fiber reinforced concrete at particular load [25].

The present study attempts to evaluate the effect of adding 1% hybrid fiber [i.e. 0.25% Poly Propylene Fibre (PPF) + 0.75% Steel Fibre (SF)] by volume in the concrete mixes of three different strength ranges. The obtained results have been compared with the findings of Ojha et al. [12]. Ojha et al. [12] studied fracture behaviour of plain and fiber reinforced concrete with a strength range between 30 MPa and 90 MPa. The study presented an elaborate comparison between fracture behavior of concrete with and without fiber. However, the effect of using hybrid fiber in place of steel fiber was not discussed. The concrete mixes reported by Ojha et al. [12], were used for preparation of concrete specimens with hybrid fiber for evaluating the fracture energy. Study was conducted on twelve notched beams to determine fracture parameters such as fracture energy, stress intensity factor, energy release rate, and characteristic length. The three concrete mixes adopted in the study has a compressive strength of 40 MPa, 60 MPa and 90 MPa. The results from the current study has been clubbed with the data presented by Ojha et al. [12], and a comparative analysis has been performed to evaluate the effect of hybrid fiber on the fracture parameters.

1.1 Research Significance

There has been extensive study on the fracture behaviour of hybrid fiber reinforced concrete [14,22,23,26-28], but the novelty of the present study is the use of high strength steel fiber along with polypropylene fibers and consideration of mix in three strength range. The strength of the fibers governs the fracture mechanism in the concrete. For lower strength fibers, the failure may take place by yielding and rupture of the steel fibers in tension, however for higher strength steel fibers the failure takes place through pull up mechanism. Using hooked-end fibers further improves the pull up resistance. The present study considered a hooked-end high strength steel fiber with polypropylene fiber. The literature on fracture performance of high strength hooked-end steel fiber reinforced concrete with polypropylene fiber is sparingly available. Also most of the available studies has been based on single strength range concrete mix. The shape dependent fracture parameters depend on the notch depth ratio and size of the specimen. Different authors have separately studied different strength concrete mix but comparing the fracture parameters becomes difficult due to variations in specimen size, notch depth ratio, aggregate type and loading rate. The present study gives a better comparison of fracture parameters at different strength range of the mix, and different fiber composition in the mix (without fiber, with steel fiber, and with hybrid fiber) through experimental investigation considering consistent notch depth ratio, specimen size and aggregate type. The comparison of present study with existing literature has been shown in table 1.

2. Concrete Ingredients

In present study, granite type coarse aggregate having 20 mm nominal size has been used. Fine aggregate (crushed sand) mostly quartz conforming to specifications of zone II sand as per IS: 383-2016 have been used. Figure 1(a) and 1(b) shows the coarse and fine aggregates used in study. A series of physical and chemical tests were performed on the aggregates and results have been presented in table 2. Ordinary Portland Cement (OPC)-53 grade along with fly ash and silica fume have been used as cementitious binders for preparation of concrete mixes. The physical and chemical properties of cementitious materials have been given in table 3. Polycarboxylic group-based superplasticizer conforming to requirements of IS 9103, has been used in present study to develop mixes of adequate workability.

Table 1. The novelty of present study

Literature	Fiber reinforcement details	Base Concrete mix
Present Study	Hooked-end Steel fiber having 1467 MPa tensile strength and polypropylene fiber.	Three base concrete mix with different strength range. Alteration in mix as per fiber content.
Bencardino et al.,	Hooked-end, 1050 MPa tensile strength steel fiber with polypropylene fiber.	One base concrete mix. Alteration in mix as per fiber content.
Xiangjun et al.,	Hooked-end, 1200 MPa tensile strength steel fiber with polypropylene fiber.	One base concrete mix. Alteration in mix as per fiber content.
Smarzewski, and Barnat-Hunek	Hooked-end, 1100 Mpa tensile strength steel fiber with polypropylene fiber	One base concrete mix. Alteration in mix as per fiber content.
Kazemi et al.,	Hooked-end, 2100 Mpa tensile strength steel fiber, study does not include hybrid fiber effect	One base concrete mix. Alteration in mix as per fiber content.
Ghasemi et al.,	Hooked-end, 1200 MPa tensile strength steel fiber	Discuss self-compacting concrete, One base concrete mix. Alteration in mix as per fiber content.
Alwesabi et al.,	Non-hooked end steel fiber, 2800 Mpa tensile strength	One base concrete mix. Alteration in mix as per fiber content.

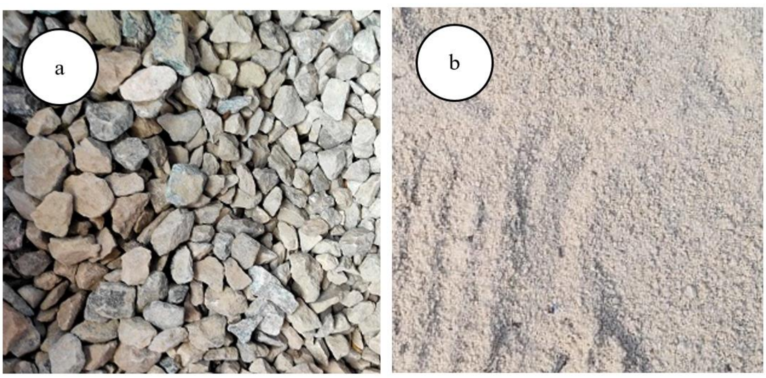


Fig. 1 (a) Coarse aggregate and (b) crushed Fine aggregate

Table 2. Properties of aggregates

Property		Granite 20 mm	Granite 10 mm	Fine Aggregate
Specific gravity		2.83	2.83	2.65
Water absorption (%)		0.3	0.3	0.59
Sieve Analysis Cumulative Percentage Passing (%)	20mm	98	100	100
	10 mm	1	68	100
	4.75	0	2	99
	2.36	0	0	89
	1.18	0	0	64
	600 µ	0	0	43
	300 µ	0	0	26
	150 µ	0	0	14
	Pan	0	0	0
Abrasion, Crushing & Impact Value		19,19,13	-	-
Flakiness % & Elongation %		29, 25	-	-

Table 3. Physical and chemical properties of cementitious materials

Characteristics	OPC -53 Grade	Silica Fume	Fly Ash
Physical Tests:			
Fineness Blaine's (m^2/kg)	320.00	22000	403
Soundness Autoclave (%)	00.05	-	-
Soundness Le Chatelier (mm)	1.00	-	-
Setting Time Initial (min.) & (max.)	170.00 & 220.00	-	-
Specific gravity	3.16	2.24	2.2
Chemical Tests:			
Loss of Ignition (LOI) (%)	1.50	1.16	0.4
Silica (SiO_2) (%)	20.38	95.02	60.95
Iron Oxide (Fe_2O_3) (%)	3.96	0.80	5.70
Aluminum Oxide (Al_2O_3)	4.95	-	26.67
Calcium Oxide (CaO) (%)	60.73	-	2.08
Magnesium Oxide (MgO) (%)	4.78	-	0.69
Sulphate (SO_3) (%)	2.07	-	0.29
Chloride (Cl) (%)	0.04	-	0.009
IR (%)	1.20	-	-
Moisture (%)	-	0.43	-

Ojha et Al. [12] incorporated 1% of steel fibers by volume of concrete. Trough and hooked-shaped steel fiber were used in the study. In the present study, 0.75% of steel fiber (SF) and 0.25% of polypropylene fiber (PPF) have been added. The amount of polypropylene fiber has been added to keep a note on the fiber requirement to impart the fire resistance to the concrete as per literature [20], [29]. Also, studies [14] have reported an increase in fracture performance of the concrete by the inclusion of certain amount of polypropylene fiber in the concrete mix along with steel fiber. The steel fiber used in the study has a diameter of 0.55 mm and a length of 35 mm. According to the manufacturer, the tensile strength of steel fiber is 1468.99 N/mm^2. For PPF, a Polypropylene triangular fiber of 6mm length has been used. The density of SF is 7860 kg/m^3 and the density of PPF is 910 kg/m^3. Detailed properties of the used polypropylene fiber have been given in table 4 and Fig 2 shows the steel and Polypropylene fiber used in the study.

Table 4. Properties of polypropylene fiber

S. no.	Properties	Value
1	Shape	Triangular
2	Cut length (mm)	6
3	Effective Diameter (microns)	20-40
4	Specific Gravity	0.90-0.91
5	Melting Point(degree C)	160-165
6	breaking tenacity (Gpd)	4-6
7	Tensile Strength (estimated in Mpa)	320-490
8	Elongation (%)	60-90
9	Young's Modulus (Mpa)	>4000

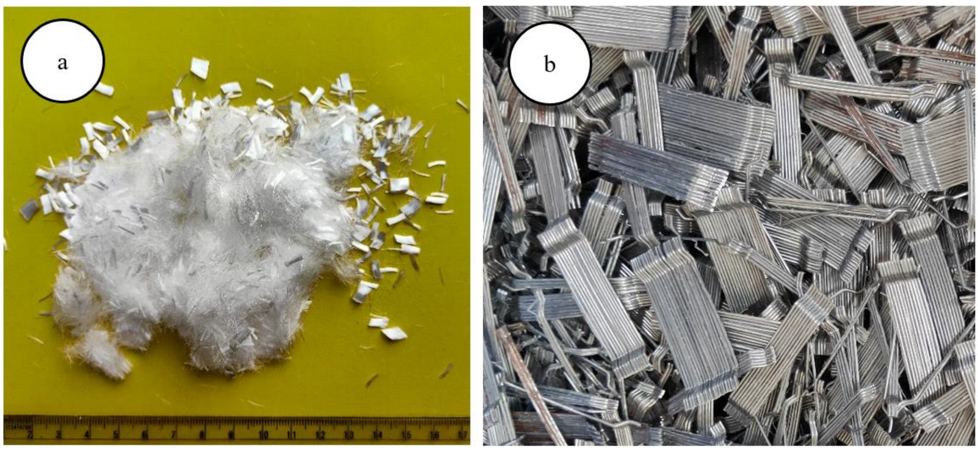


Fig. 2 (a) Polypropylene fiber and (b) steel fiber used in the study

3. Mix Design Details

In present study, concrete mixes (with and without fibers) of different strength ranges were developed and mix design details of concrete mixes have been adopted from previous studies conducted by Ojha et al., [12]. The w/c (water/cementitious content) ratios for the concrete mixes adopted in the study were 0.47, 0.36 and 0.20. For obtaining an optimized mix of 90 MPa, silica fume has been added in the mix. Mix design detail used in the study by the Ojha et al., [12] and the present study has been given in table 5. As given in the table, the concrete mixes studied previously by Ojha et al.,[12] consist of plain concrete and concrete with 1% of steel fiber. In mixes of present study, a combination of 0.75% SF and 0.25% PPF has been used. Such mixes has been referred as Hybrid Fiber-reinforced (1% HF) concrete in the subsequent sections. The mixes were prepared in small batches in a pan type mixer. The terminologies, HF and SF used in for mixes identification represent Steel Fiber and Hybrid Fiber.

The coarse and fine aggregates were first mixed together and combined with half the amount of water in the pan mixture for the preparation of the mix. Thereafter, polypropylene fiber was mixed with the remaining half of the water to be added in the mix in a separate container. The cement, flyash, silica fume, and the water with the polypropylene fiber was then added to the homogenized aggregate mix. After that the superplasticizer was added. Once the constituents were thoroughly mixed, steel fiber was sprinkled uniformly in the pan mixture. The concrete batch was then poured into moulds covered with an anti-adhesive material and then compacted on a vibrating table. To reduce moisture loss after compacting, the samples were covered with foil. All of the samples were kept in a controlled environment at a constant temperature of 27 °C until they were taken out of the moulds after 24 hours and allowed to cure for 28 days in a water tank at 27 °C.

Table 5. Mix Design Details

Mix Id	Fiber (% by volume of concrete)	Total Cementitious kg/m^3	Cement kg/m^3	Fly Ash kg/m^3	Silica Fume kg/m^3	Water kg/m^3	Water/ Total cementitious
A	-	362	290	72	0	170	0.47
A-SF	1% SF	362	290	72	0	170	0.47
A-HF	0.75% SF +0.25PPF	362	290	72	0	170	0.47
B	-	417	334	83	0	150	0.36
B-SF	1% SF	417	334	83	0	150	0.36
B-HF	0.75% SF +0.25PPF	417	334	83	0	150	0.36
C	-	750	548	112	90	150	0.20
C-SF	1% SF	750	548	112	90	150	0.20
C-HF	0.75% SF +0.25PPF	750	548	112	90	150	0.20

4. Experimental Plan

The present section discusses the test procedures adopted for the studies conducted on the concrete specimens of different mixes.

4.1. Compressive strength test

Compressive strength of concrete has been performed on cubical specimen of size 150 mm x 150 mm x 150 mm. The test is performed according to the specification given in IS 516. For the test, 3 sets of cubical specimens were cast using the mix design presented in the table above. The test is performed in a compression testing machine of capacity 3000 KN.

4.2. Split Tensile Strength Test

The split tensile strength of concrete has been estimated using Indian standard IS 516: Part I section I. A specimen with sizes of 300 mm height and 150mm diameter was used for determining split tensile test. The test has been performed on three samples and the average value has been reported.

4.3. Three-point bend test on notched beams

A 3-point bending test based on the method described by RILEM [21], [30] was used to calculate the fracture characteristics. The experiments yielded several fracture parameters, which has been addressed in the following sections. Figures 3(a) and 3(b) illustrate a schematic diagram for the three-point bend test and the laboratory setup for the actual test. A beam with dimensions of 100mm × 100mm × 500mm and a notch of 35 mm at the mid-span was used as test specimen. Displacement control machine of 300 KN capacity was used for flexural testing of beam specimen. Deflection at mid-span of the beam was recorded using Linear Variable Displacement Transducer (LVDT) and Crack Mouth Opening Displacement (CMOD) at the bottom of the beam was recorded using clip gauge placed between steel knife edges. A total of twelve beams were examined in this investigation as per mix design details listed in Table 5.

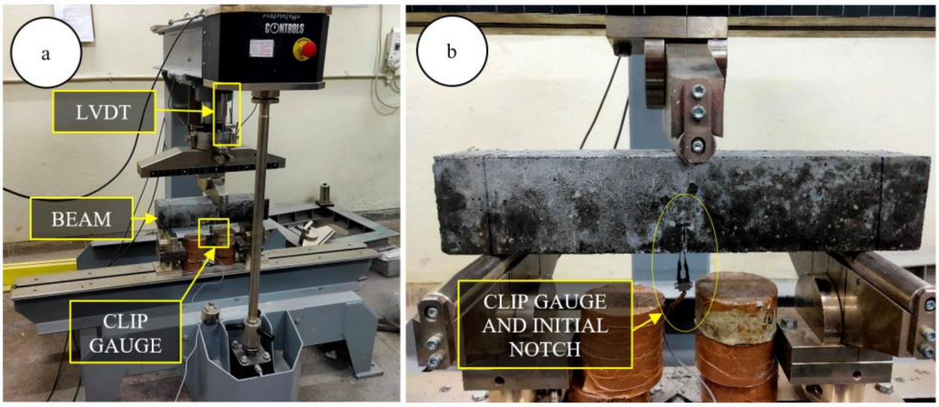


Fig. 3 (a) Experimental setup for three-point bend test (b) Clip gauge and initial notch on the Beam

5. Results and discussions

5.1. Compressive strength and Split tensile strength

Compressive strength and split tensile strength of the hybrid fiber reinforced concrete have been evaluated and compared with the values for the plain and steel fiber reinforced concrete presented by Ojha et al.,[12] for the similar mix. The results have been tabulated in table 6. The change in the compressive strength of normal strength concrete mix with w/c ratio of 0.47 is not significant after the addition of steel or hybrid fiber. This has been established in past study [12] also. But for the concrete mix with w/c ratio of 0.36 and 0.20 about 10% decrease has been observed in the compressive strength after addition of hybrid fibers. However, the compressive strength of the steel fiber reinforced concrete with similar w/c ratio has not changed significantly. The findings suggest that the polypropylene fiber present in the hybrid mix affects the microstructure and interfacial transition zone (ITZ) in optimized and dense mix of higher strength concrete due to its diameter being comparable to the pore size present in the concrete. These fibers has been flexible and can properly fill the voids and improves the compressive strength of the mix when added in extremely small quantity (less than 0.1%) [14]. Also, high-strength concrete consists of silica fume whose functionality in the matrix is most likely to get affected by these hybrid fibers leading to reduction in the compressive strength.

The values of the split tensile strength show a direct correlation with the compressive strength as established in the literature [1]. Similar to compressive strength, addition of steel or hybrid fiber does not affect the split tensile strength of normal strength concrete mix with w/c ration of 0.47. For the concrete mix with w/c ratio of 0.20, addition of steel fiber shows enhancement in the split tensile strength of the mix. For same mix, the addition of the hybrid fiber also shows enhancement in the split tensile strength, but the enhancement is lower than the addition of steel fiber alone. In the concrete mix with w/c ratio of 0.20, the compressive strength reduced significantly after addition of hybrid fiber.

Such significant reduction in the split tensile strength has been not observed in the mix with hybrid fiber and it can be concluded that the fiber action helped in compensating for the matrix strength reduction in higher strength concrete.

Table 6. Compressive strength and split tensile strength

Water/Cementitious (W/C)	Mix Id	Compressive Strength (MPa)	Split Tensile Strength (MPa)
0.47	A	36.90	3.37
	A-SF	37.40	3.95
	A-HF	34.90	3.34
0.36	B	51.60	4.04
	B-SF	53.20	4.73
	B-HF	45.40	3.82
0.20	C	92.20	5.35
	C-SF	91.70	7.19
	C-HF	79.00	6.28

5.2. Load-Deflection and Load-CMOD behavior

The three-point bend test conducted on the notched beams yielded load versus CMOD and load versus midpoint beam deflection curves, which have been presented in figure 4. Each plot in figure 4 consists of three sets of values, the line in green color (Plain) shows the curves for the control beams, i.e. beams without any fiber reinforcement. The curves in the brown (1% SF) represent the curves for beams with 1% of steel fiber reinforcement. These two curves have been incorporated from the study conducted by Ojha et al.,[12]. The lines in purple shows the curves obtained for 1% of hybrid fiber (1% HF) which consists of 0.75% of steel fiber and 0.25 percent of Polypropylene fiber by volume of the concrete. Ojha et al.,[12] gave three sets of curves for each mix design of plain and steel fiber reinforced concrete. In this study, four curves were obtained and reported for the respective four beams tested having 1% of hybrid fiber.

Figure 4(a) and Figure 4(b) shows the load-CMOD and load-deflection curves respectively, for the mix made at w/c ratio of 0.47. It can be observed that curves for 1% of hybrid fiber reinforcement show similar curves as obtained in 1% of steel fiber reinforcement. Peak values of these curves exceed the peak values for steel fiber reinforced beams in some cases. Figure 4(c) and 4(d) show load-CMOD and load-deflection curves for mixes made at w/c ratio of 0.36. Similar to the w/c ratio of 0.47, curves resemble the behaviour of concrete having 1% steel fiber. Also, the peak load in some of the cases exceeded the peaks of the curves for mixes prepared at w/c ratio of 0.36. Figures 4(e) and 4(f) represent the curves corresponding to the mixes prepared at w/c ratio of 0.20. Contrary to the behaviour of mixes prepared at 0.47 and 0.36 w/c ratios, here the curves for hybrid fibers lie in between the curves for the plain concrete and curves for the steel fiber reinforced concrete. These curves have direct implications on fracture parameters as discussed in further sections of this manuscript. Comparing the curves of mixes prepared at different w/c ratios, a gradual increase in the peak load from the mixes made at w/c ratio of 0.47 to 0.36 has been observed. This gradual increase remained approximately unchanged for mixes at w/c of 0.20, which is contrary to the behavior of concrete without fiber and with steel fiber only. Ojha et al., [12] suggested that with an increase in the compressive strength of the concrete, the peak load in the three-point bend test increases for plain and steel fiber reinforced concrete (1% SF). This generalization doesn’t hold good for hybrid fiber reinforced concrete tested in the present study. The steel and hybrid fibers used have different tensile strength, therefore have different failure mechanism. Most of the high strength steel fiber fail by pull out mechanism and not by rupture of the fibers. Higher strength concrete enhances the pull out resistance of the steel fiber thereby improving the peak load taken by the beam in three-point bend test. On contrary the polypropylene fiber may fail by rupture due to its relatively lower tensile strength. Therefore, the strength of concrete and fiber-concrete bond are not only the factors affecting the peak load of a hybrid fiber reinforced concrete beams. The tensile strength of fibers also becomes a crucial factor in case of hybrid fiber reinforced concrete.

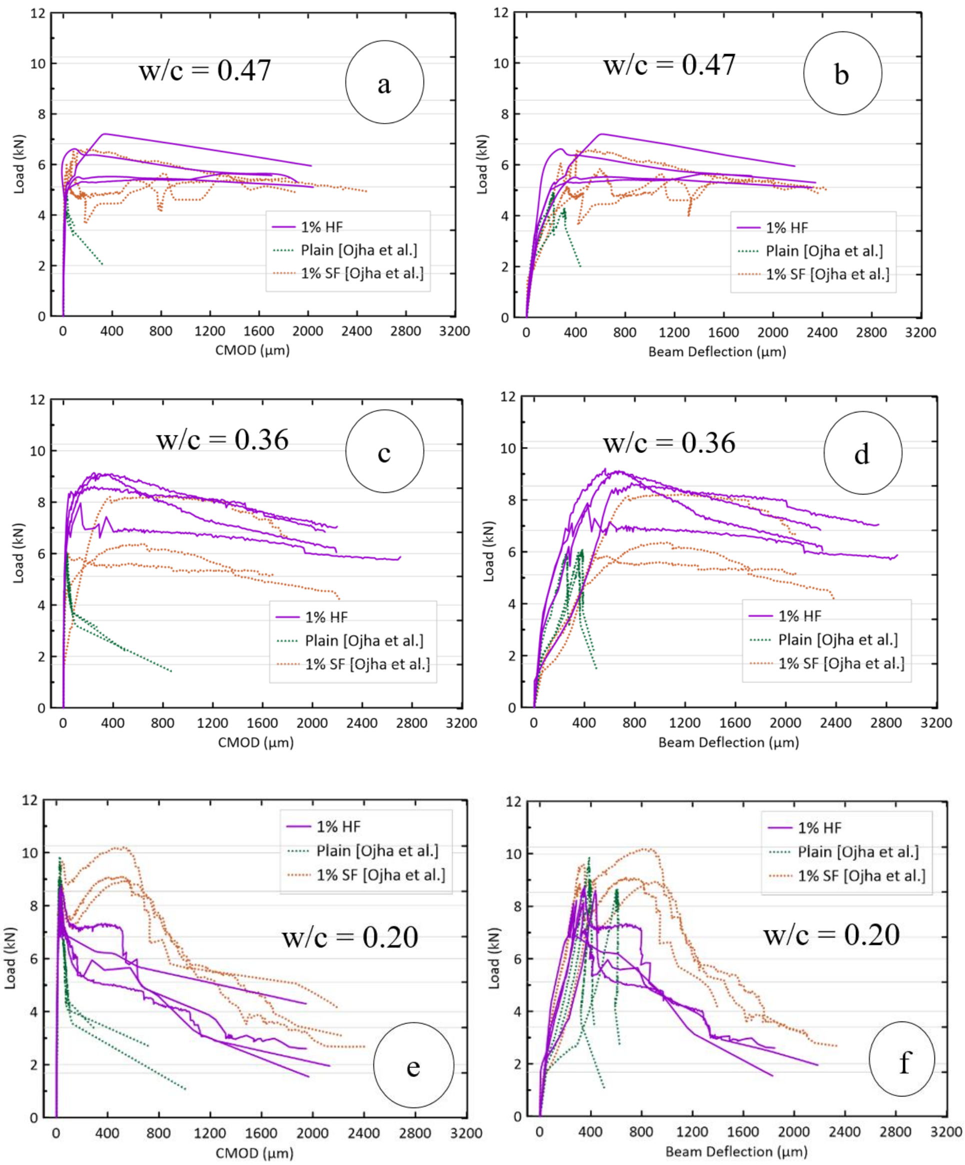


Fig. 4 (a-f) Load-deflection and Load-CMOD behavior of notched beams

5.3. Calculation of initial compliance and modulus of elasticity

The initial part of the load-CMOD curve has a li on where elastic deformation in the beam takes place. Initial compliance is the inverse of the slope of this initial straight part. Based on the value of initial compliance, the modulus of elasticity of the beam can be calculated. RILEM [30] presented equation (1) to derive the value of modulus of elasticity of the material from the value of initial compliance obtained from the load-CMOD curve.

$$E\ (MPa) = 6S\ \frac{\alpha V_1(\alpha)}{C_i d b^2} \tag{1}$$

Here Ci is the initial compliance and $V_1(\alpha)$ can be calculated using the equation by Tada et al. [31] as follow:

$$V_1(\alpha) = 0.76 - 2.28a + 3.87a^2 - 2.04a^3 + \frac{0.66}{(1-a)^2} \tag{2}$$

Table 7. Initial Compliance (C_i) and Modulus of Elasticity (M.O.E.)

Water/ Cementitious (w/c)	Mix Id	Initial Compliance (10-9 m/N)	M.O.E. (GPa) Calculated from load-CMOD	M.O.E. (GPa) [Arora et al.][27]
0.47	A	5.26	31.08	29.52
	A-SF	4.54	35.17	29.64
	A-HF	5.35	29.96	29.03
0.36	B	5.00	32.27	32.64
	B-SF	4.00	40.55	32.94
	B-HF	3.67	43.71	31.41
0.20	C	2.63	60.61	38.85
	C-SF	2.22	72.63	38.79
	C-HF	2.02	79.53	37.09

Table 7 presents the values of the calculated initial compliance and modulus of elasticity of the mix in table 5. Modulus of elasticity has been calculated using two methods. The first method involves calculation from the initial compliance of load-CMOD curve using equation (1). The second method is based on the method given by Arora et al. [32] , which relates compressive strength with modulus of elasticity. Comparing values of modulus of elasticity of different mixes, it can be observed that the value of initial compliance decreases drastically for higher strength concrete which gives an unrealistic value of modulus of elasticity. Similar findings have been reported in past [12], and therefore for the subsequent sections, values of M.O.E. obtained using method of Arora et al. has been used.

5.4. Fracture Energy

Fracture energy is one of the attributes which can quantify and indicate the material's toughness and resistance against cracks. It is defined as the average energy required to create a unit crack in the material. It is directly related to the area under the load-deflection curve obtained in the three-point bend test of notched beams. Higher fracture energy represents that the material is having a higher resistance to the cracks. In the present study, the fracture is determined using equation (3) as given by RILEM [21].

$$G_f(N/m) = (W_o + mg\delta_o)/A_{lig} \tag{3}$$

G_f denotes the fracture energy, W_o denotes the area under the load-deformation curve for the beam, and m denotes the total weight of the beam including the support and the weight of the part of the loading arrangement that is not attached to the machine but follows the beam until failure. The acceleration due to gravity is g, which equals 9.81 m/s^2. Alig. is the area of the ligament, which is the area of the projection of the fracture zone on the plane perpendicular to the beam axis. δ_0 is the deformation of the beam, at the stage where entire beam height is cracked.

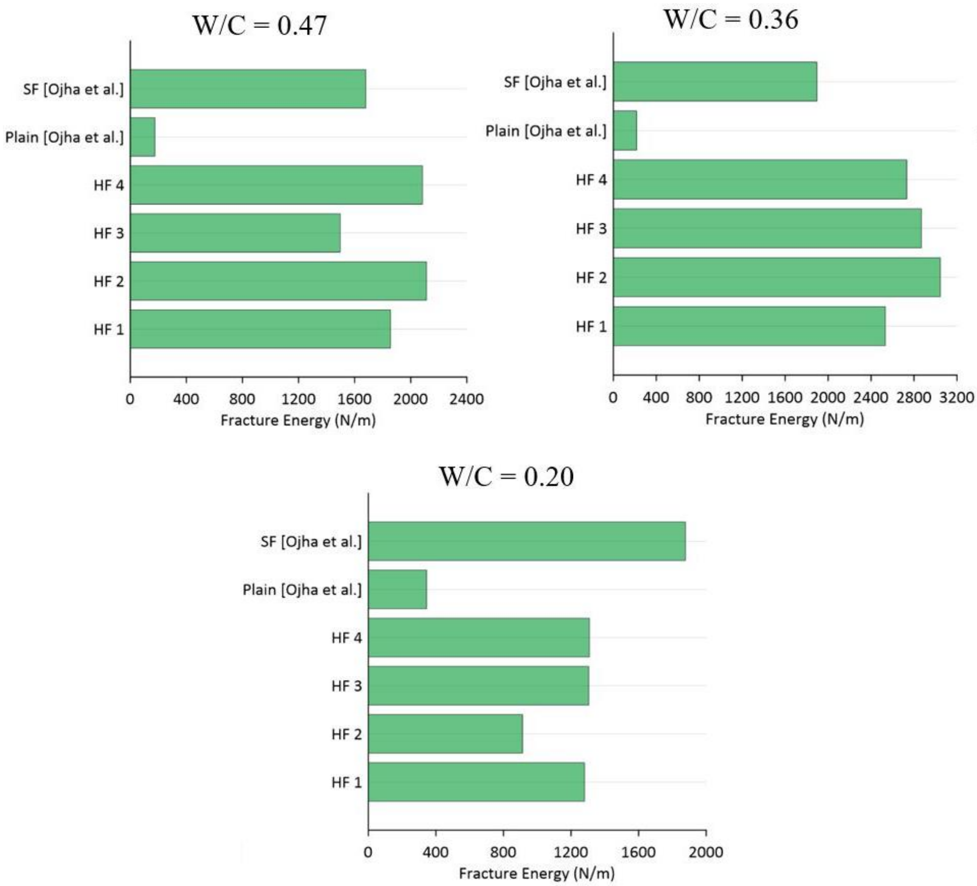


Fig. 5 Calculated fracture energy of beams and comparison with literature

Figure 5 shows the comparison of the calculated fracture energy for the three categories of the concrete mixes studied. In the figure, Plain and SF denotes the average fracture energy obtained by Ojha et al.[12] for the plain and steel fiber reinforced concrete. HF 1 to HF 4 represents the values of the obtained fracture energy for the four beams studied which contains 1% of hybrid fiber (0.25% PPF + 0.75% SF). On comparing the results, it can be seen that there is an increase in the fracture energy of the hybrid fiber reinforced concrete for w/c ratio of 0.47 and w/c ratio of 0.36. These two w/c ratios represent normal to high strength concrete limited up to strength of 50MPa. However, for high strength concrete, hybrid fiber reinforcement gave a lower improvement in fracture performance than the steel fiber reinforcement. The literature [14] also suggested a similar trend for Polypropylene fiber added concrete. The possible explanation to this can be attributed to (a) lower tensile strength of the polypropylene fibers than the steel fibers (b) less available voids and higher packing density in the high strength mix and (c) smaller diameter of the hybrid fibers. With increase in the strength of concrete, the concrete-fiber bond strength increased. This changes the mode of failure of the fibers. In normal strength concrete the failure is mostly from the slippage and pulling out of fibers whereas in higher strength concrete, the low strength fibers may rupture before pulling out. Since the polypropylene fiber have lower tensile strength than the steel fibers, in higher strength concrete the polypropylene fibers gets ruptured giving a lower fracture energy. Most probably the addition of fibers affects the packing density of the mix reducing its strength and ultimately other mechanical properties. Due to smaller diameter of the hybrid fibers, it may also be interfering with the ITZ of the mix reducing its fracture performance. Additionally, the mix with w/c ratio 0.20 consists of silica fume whose action may be affected by these polypropylene fibers leading to a lower fracture energy.

5.5. Crack Propagation and Crack Pattern

The crack patterns were captured while testing the beams. Figure 6 shows major events during the testing of the beams.

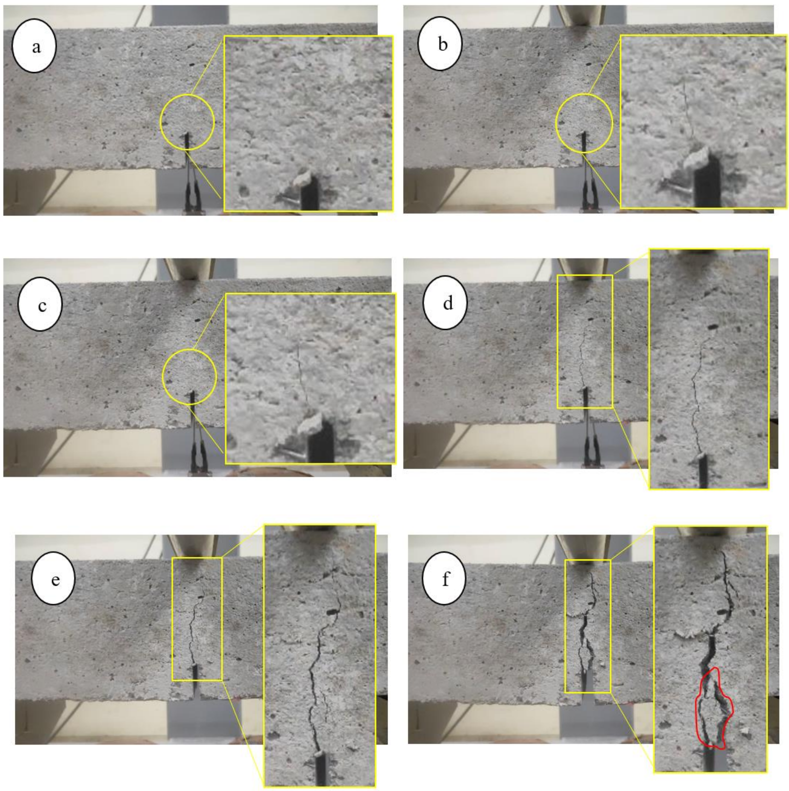


Fig. 6 Crack propagation and crack pattern in hybrid fiber reinforced concrete

In figure 6 (a), no crack on the beam was observed. This picture represents beam before loading. After loading, the visible cracks first initiated near the notch as shown in figure 6 (b) and figure 6(c) after initiation of the first crack it spread rapidly and covers the approximately entire height of the beam. The attached clip gauge has capacity to capture mouth opening up to 2 to 3 mm only and once the CMOD value reaches this value, the clip gauges gets detached. Although it can be seen that in figure 6(e), at the moment of the detachment of the clip gauge, the crack has reached the top portion of the beam, and the beam can be considered to be cracked at the full height. If the loading was continued, a fully damaged beam as shown in figure 6(f) has been obtained. In Figures 6(a) to 6(e), a single hairline crack in the beam which originated from the notch and spread in a single straight line was noticed. But in figure 6 (f), two crack paths originating from the notch and merging at some beam height was seen. It creates a portion of hanging concrete in the beam, which again affirmed the idea, that although fiber reinforced concrete may get cracked but it will give sufficient time for evacuation as well as it prevents sudden falling off of the cracked concrete to some extent.

5.6. Stress Intensity Factor

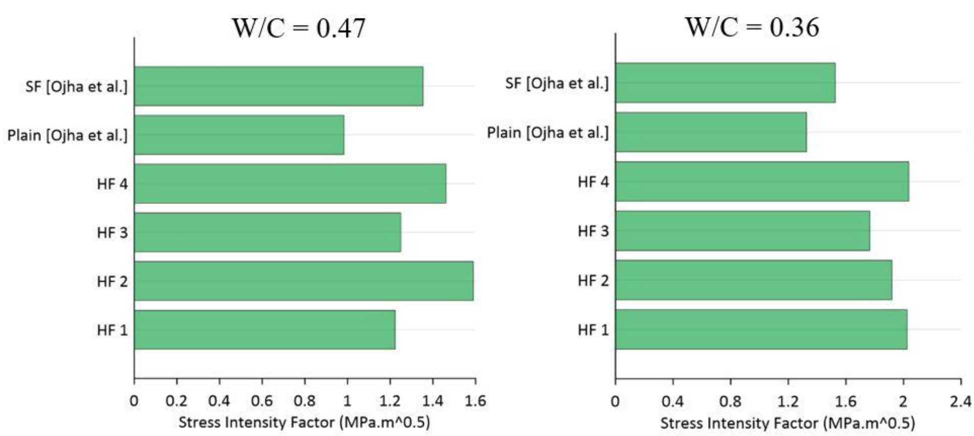
The stress intensity factor (KIC) can be used to compare the capacity of material to sustain the stress caused by the residual stresses near the notch's or crack's tip. It can be defined as a measurement for stresses in the crack's immediate vicinity. A material with higher K_{IC} has been considered to have a better fracture and crack initiation and propagation resistance. The stress intensity factor is determined as follows using RILEM [30] as given in equation (4):

$$K_{IC}\,(MPa\,\sqrt{m}) = 3(P_{Nmax} + 0.5mg)\frac{S\sqrt{\pi a}}{2d^2\,b}f(\alpha) \tag{4}$$

In equation (4) S, a, d and m are Span, height, notch depth, and mass of the beam respectively. P_{Nmax} is the peak load on the beam in the three-point bend test. Alpha is the ratio of a and d i.e., α = a/d = 0.35 for the present study. F(α) is the geometry correction given by equation (5).

$$f(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.9\alpha + 2.7\alpha^2)}{\sqrt{\pi}(1+2\alpha)(1-\alpha)^{3/2}} \tag{5}$$

Figure 7 shows the values of the calculated characteristic strength as well as the values from the literature. The symbols has their usual meanings as explained for the figure 6. Similar to the fracture energy, the hybrid fiber improved the values of stress intensity factor for normal strength concrete. However, the stress intensity factor gets reduced in case of high strength hybrid fibre reinforced concrete in comparison to the high strength mix with steel fiber alone. The reasoning for this behavior were similar as in case of fracture energy. As explained earlier, in case of high strength concrete, when the dosage of PP fibre exceeds a certain amount (compared to the available voids in high strength concrete), instead of improving, it further deteriorates the fracture properties.



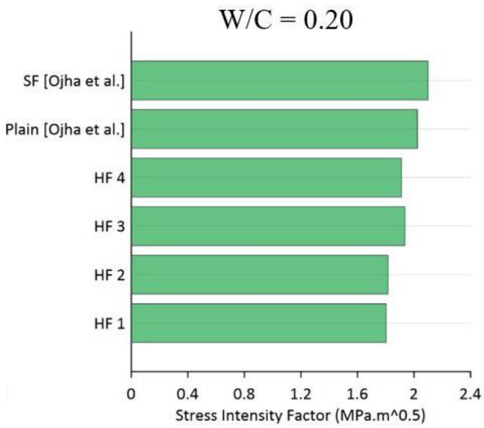


Fig. 7 Calculated Stress Intensity Factor of beams and comparison with literature

5.7. Critical Energy Release Rate

The cracking of the material releases a certain amount of energy and thereby reduces the overall stored potential energy. The decrease in total potential energy with respect to increase in fracture surface area may be calculated quantitatively. The critical energy release rate, or G_{IC}, is the rate at which energy changes, when a material fractures and a new surface is created. The energy release rate is a critical component in evaluating material properties related to fracture and fatigue. G_{IC} is calculated using the equation presented by Taha et al. [33], which is stated in equation (6) as follows:

$$G_{IC}(N/m) = \frac{{K_{IC}}^2}{E} \quad (6)$$

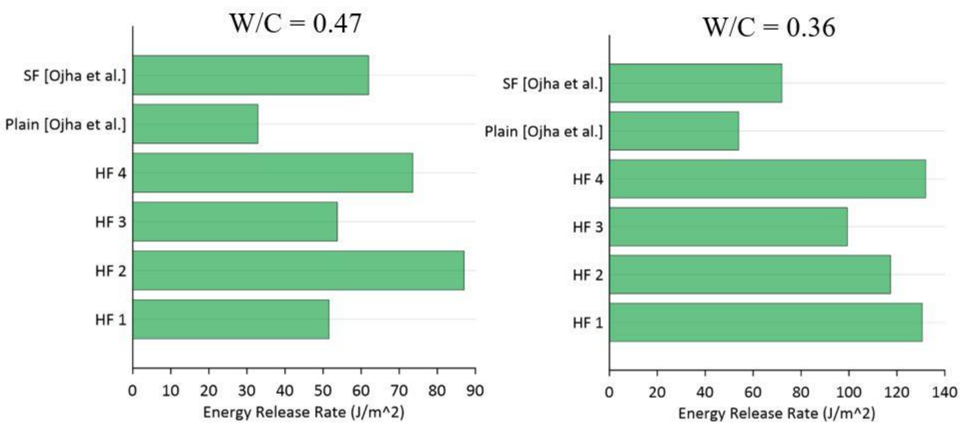


Fig. 8A Calculated energy release rate of beams and comparison with literature

Experimentally obtained values of the energy release rate for the beams and its comparison with plain and steel fiber reinforced concrete is given in figure 8. As the previous trends for the fracture energy, energy release rate also shows a marginal improvement in two beams of w/c ratio 0.47 and all the beams of w/c ratio 0.36.

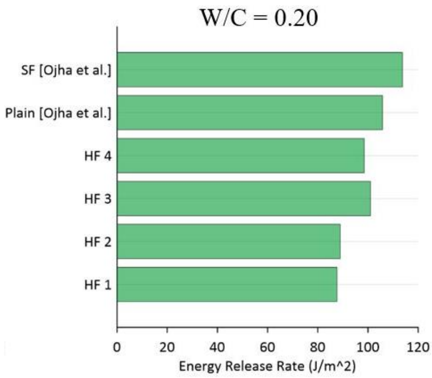


Fig. 8B Calculated energy release rate of beams and comparison with literature

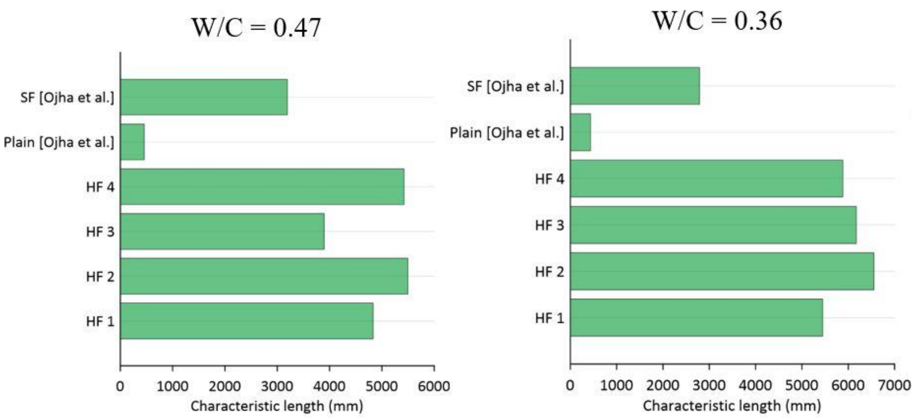
These two w/c ratios represent concrete with available voids for the PPF present in the hybrid fiber. Whereas the dense mix of high strength concrete with w/c ratio of 0.20 got a marginal reduction in the values of energy release rate by addition of hybrid fiber when compared to the steel fiber reinforced concrete. The fiber in the concrete with dense packing disturbed the optimized particle matrix and reduced the amount of potential energy release when new cracked surface gets created.

5.8. Characteristic Length

In non-local continuum formulations, characteristic length is a material parameter that indicates the smallest possible breadth of a zone of strain-softening damage. In discrete fracture models, it may be thought of as the smallest feasible fracture spacing. Finding the characteristic length can help in judging the comparative brittleness of two materials following the beginning of early fractures. Smaller characteristic length materials are more brittle; therefore, fracture propagation is easier in these materials. The equation (7) presented by [34] gives a method to estimate the characteristic length based on Modulus of elasticity (E), Fracture energy (G_f) and split tensile strength (fst).

$$L_{ch}(mm) = \frac{E G_f}{{f_{st}}^2} \tag{7}$$

Calculated values of the characteristic length and the values from the literature has been shown in figure 9.



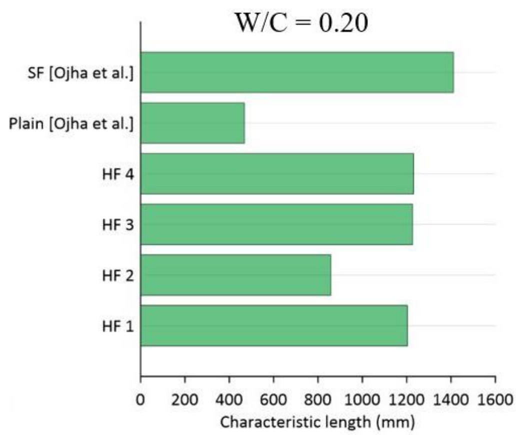


Fig. 9 Calculated characteristic length of beams and comparison with literature

The trend for the characteristic length upon addition of hybrid fiber is similar to other fracture parameters discussed above. The values for the characteristic length after addition of hybrid fiber improved for w/c ratios of 0.47 and 0.36 and it reduced for optimized mix with w/c ratio of 0.20 when compared with steel fiber reinforced concrete. This suggests that crack propagation got easier in the mix with w/c ratio of 0.20 when hybrid fibers were added. The PPF in the hybrid fiber when doesn't find enough voids helps in crack propagation in the concrete. Compared to plain un-reinforced beam, the characteristic length was significantly higher for all the mixes with hybrid reinforcement. This can be credited to the interlocking provided by SF in the hybrid fiber for all the mixes and interlocking provided by PPF in the hybrid fiber for mixes with w/c of 0.47 and 0.36.

Table 8 gives the mean and the standard deviation of the evaluated fracture parameters for the hybrid fiber reinforced concrete beams considered in the study. The standard deviation of concrete with w/c ratio 0.47 has been the highest for the studied fracture parameters suggesting the highest variation in the normal strength concrete. It appears that due to lower strength among all the mixes, the concrete with w/c ratio 0.47 is not able to provide enough and uniform grip to the fibers resulting in more variation among different mix. On contrary the higher strength mix is providing strong and uniform bonding to the fibers giving a lower standard deviation at higher strength.

Table 8. Mean and Standard deviation of the evaluated fracture parameters for hybrid fiber reinforced concrete beams

		Fracture Energy (N/m)	Stress Intensity Factor (MPa.m^0.5)	Energy Release Rate (J/m^2)	Characteristic length (mm)
0.47	Mean	1887.64	1.38	66.47	4912.16
	Standard Deviation	246.44	0.18	16.92	740.53
0.36	Mean	2794.97	1.94	119.81	6016.15
	Standard Deviation	188.00	0.13	15.17	467.28
0.2	Mean	1201.54	1.87	94.03	1130.00
	Standard Deviation	167.16	0.07	6.72	181.53

6. Conclusions

In this paper, the fracture performance of hybrid fiber reinforced concrete with strength in three different ranges – Normal, Normal to High and High strength is studied. The obtained fracture parameters has been compared with the findings for a similar mix of plain and steel fiber reinforced concrete. In total 12 beams were tested, which includes 4 beams from each strength category. Based on the experimental finding and comparative analysis with the literature following can be concluded as given below:

- Addition of hybrid fibers (0.25% Polypropylene + 0.75% steel by volume of concrete) in the concrete does not have a significant impact on the compressive and tensile strength of the normal strength mix with w/c ratio of 0.47. But at higher strength, the hybrid fiber reinforced concrete shows a 10% lower compressive strength than the plain or steel fiber reinforced concrete.
- For normal strength and normal to high strength concrete, the load-deflection and load CMOD curves for the hybrid fiber reinforced concrete shows a better fracture performance as compared to steel fiber reinforced concrete with a significant improvement in the peak load and maximum deflection compared to the plain concrete. Whereas for the high strength concrete, the steel fiber reinforcement shows a better fracture performance than the hybrid fiber reinforcement.
- The fracture parameters – Fracture energy, Stress intensity factor, Energy release rate, and Characteristic length shows similar trends. For high and normal to high strength concrete, addition of hybrid fibers gave slightly better results than steel fiber reinforced concrete but for high strength concrete the steel fiber reinforcement resulted better fracture behaviour than hybrid fiber.
- The issue of brittle failure has been mostly discussed for high strength concrete due to smaller post peak stain capacity in the high strength concrete. Based on the study it was found that, addition of hybrid fibers improved the fracture performance of normal strength concrete and prevented the sudden failure of concrete. But such risk can be mitigated for normal strength concrete by already existing methodologies like by designing under reinforced beam and providing proper detailing of the reinforcement. The normal strength concrete structures are more economically sensitive and therefore it is not necessary to use hybrid fibers in normal strength concrete mixes unless fracture is a critical issue. But in certain special cases where the fracture performance and crack prevention are critical parameters, the proposed hybrid fiber reinforcement can be suitably employed in the normal strength concrete also.

The study concludes that the choice of fiber reinforcement for improving the fracture behaviour of concrete depends upon the strength of the concrete as well as the properties of fibers. For normal and normal to high strength concrete, hybrid fiber reinforcement is more suitable choice than the steel fiber alone. Whereas for higher strength concrete, the high strength steel fiber reinforcement alone performed better than the hybrid fiber reinforcement considered in the study.

Acknowledgements

Authors acknowledge the funding received from Ministry of Commerce & Industry, Govt. of India

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