Inferences on Strength and Ductility of High Performance Concrete Mixed with Steel and Macro-synthetic Fibres

S. Syed Ibrahim and S. Kandasamy

1 Introduction

Fibre-reinforced concrete (FRC) is often known as a type of high-performance concrete, in which short, discrete fibres effectively arrest/control the formation and propagation of structural cracks (right from pre-cracking to post-cracking stages) [1–3]. According to the current scenario, a single type of short-fibres has been predominantly used in the FRC for field applications. Studies reveal that a given single fibre type could be provided with a bridging effect only at any above one stage and have some degree of strain hardening/crack opening of FRC. To achieve an optimum (synergic) performance, multiple (i.e. more than one) types of fibres can combine suitably either based on fibre constitutive response or fibre dimensions or fibre function, which eventually produces a hybrid fibre-reinforced concrete (HFRC) matrix [4, 5].

The following salient observations draw an overview of distinctive studies on the HFRC. Nevertheless, studies wherein different shapes and sizes of steel fibres have been used, and referred to as ‘hybrid fibres’ by the various authors, have not been considered under. From 2000 onwards, there has been renewed interest in the study of HFRC. Most of the authors considered normal strength of concrete and few studies were conducted with high-strength concrete. Of all the combinations of hybrid system, combination of rigid with flexible fibres has been extensively used. In a hybrid fibre combination, steel fibres have been consistently mixed, which can be rigid by nature. Of the flexible type of fibres, polypropylene (PP) fibres have been

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extensively used in the study of HFRC, more so, in combination with steel fibres, until now. Almost all the studies were carried out with a fibre volume fraction ranges from 0.2 to 1.5%. Ratio between Young's modulus of (rigid/flexible) fibres was of ranges from 4.5 to 57.1. Various parameters like toughness, compressive strength, split-tensile strength, modulus of rupture, crack-width, deflection ductility, energy ductility, shear strength, fracture energy, and bond strength have been investigated to evaluate of performance of HFRC. And found significant enhancement in HFRC than using single fibre types. Apart from PP fibre, other types of flexible/non-metallic fibres used in the reported studies are polyvinyl alcohol fibre (PVA), recron, glass, polyolefin (PO), and nylon. However, such studies are a few. Among the above, PO fibre has been used rarely, especially with steel fibres in HFRC.

Consequently, the 'hybrid effect' in respect of fibre constitutive response by 3D hooked-end steel and polyolefin hybrid fibres with different total fibre volume contents-cum-proportions was experimentally evaluated in the present study. The primary purpose of the multiple types of fibre used in the HFRC matrix is that the steel fibres have strong and also stiff, which improves first-crack stress and ultimate strength, while the other one, polyolefin fibre, which is more flexible and ductile, leads to improve strain-capacity and toughness in the post-cracking zone. The study parameters include strengths (compressive and split-tensile), modulus of elasticity, modulus of rupture, and ductility indices.

2 Experiments

2.1 Materials and Properties

The required quantity of Portland Pozzolana Cement (PPC), conforming to IS 1489 Part I [6], was procured in a single batch stored in air-tight bags and used for the entire study. River sand and crushed granite (20 mm) as fine and coarse aggregates, respectively, were used. The salient properties of the aggregates are determined as per IS 2386 Part III [7] and IS 383 [8], as given in Table 1. Selecting the suitable type of fibre for preparing concrete is vital, especially in the context of assurance of strength, safety, and longevity of structures. Before adding a specific fibre type to concrete, it is necessary to understand the available fibres today and their potential for different applications. Polymeric fibres are divided into two classes: micro-fibre and macro-fibre. The size of micro-fibres is generally less than 0.3 mm dia. Features of the above fibre in concrete were to control the plastic shrinkage and to increase the impact resistance and inert protection from fire. However, concrete containing only these fibres has less structural benefit in a hardened state. Thereby, it can use for non-structural elements. Generally, the diameter of a macro-fibre is higher than 0.3 mm, which is more suitable for structural concrete. These macro-synthetic fibres increase the toughness at the post-crack stage, similar to steel fibres and improve the durability of the concrete [9].

Table 1 Properties of aggregates

Properties	Fine aggregate	Coarse aggregate	Unit
Specific gravity	2.63	2.70	–
Fineness modulus	2.70	7.98	–
Water absorption	0.60	0.50	%
Bulk density	1553	1530	kg/m^3
Zone	II	–	–

On the above aspects, two different types of short-fibres that is 3D hooked-ends steel (rigid) fibre and macro-synthetic polyolefin (flexible) fibre, were selected, both available commercially and were used in this study. As far as steel fibre is concerned, the hooked-ends act as an anchorage that resists cracking, which leads towards more durable concrete. In addition to steel fibre, commercially available straight polyolefin fibres bear a low aspect ratio mixed with concrete. There are several advantages of the above fibre, such as non-corrosive, non-magnetic, chemical inertness, and non-hazardous or nuisance conditions when fibres become loose or protrude from the concrete surface. This fibre can add a maximum of 20% (by volume) without causing any balling effect, segregation, or increase in air entertainment in concrete. However, the performance of these fibres in fresh and hardened concrete depends on the aspect ratio of the fibres. Figures 1 and 2 show hooked-end steel fibres and polyolefin fibre and their properties, given in Table 2. For casting potable water with the water-reducing admixture, 'Classic Superflo SP', which conforms to IS 9103 [10], was used.

Fig. 1 Hooked-end steel fibre

Fig. 2 Polyolefin fibre

Table 2 Properties of steel and polyolefin fibres

Properties	Steel fibre	Polyolefin fibre	Unit
Shape	Hooked ends	Straight	–
Length	30	48	mm
Diameter/size	0.5	1.22 × 0.732	mm
Aspect ratio	60	39.34	–
Tensile strength	532	550	MPa
Young's modulus	210	6	GPa
Specific gravity	–	0.90–0.92	–
Density	7850	920	kg/m^3

2.2 Preparation of Specimens

The concrete grade of M20, having a mix proportion of 1: 2.01: 3.36, was designed according to IS 10262 [11] with a water-cement ratio of 0.50. The design mix considered for casting control specimens that are in Table 3. Experimental investigations conducted in three different concrete matrices include (plain) concrete without fibre, concrete with steel fibre only (i.e. SFRC), and with steel-polyolefin hybrid fibre (i.e. HFRC) to study its various mechanical behavioural exclusively, compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, and ductility index as per Indian standards. Cylindrical moulds having a diameter and height equal to 150 mm and 300 mm, respectively, were used to determine the compressive strength of the various types of concrete. Another size of a cylindrical mould having a diameter and height of 100 and 200 mm, respectively, was used to determine the splitting tensile strength of the concrete. Prisms having a cross section of 100 × 100 mm and a length equal to 500 mm were used to determine the flexural strength of the concrete. One plain concrete (HC0-S0P0) was left without fibres to act as a control specimen. Five HFRC containing various proportions of steel and polyolefin fibres (i.e. steel [S]: polyolefin [P] = 100:0, 80:20, 70:30, 60:40, 50:50) with a consistent V_f. The HFRC specimen details are as in Table 4.

Table 3 Details of concrete mix

Material	Quantity	Unit
Cement	354	kg/m^3
Fine aggregate	710	kg/m^3
Coarse aggregate	1190	kg/m^3
Water	177	kg/m^3
Superplasticizer	1.77	kg/m^3
Slump	100	mm

Table 4 Details of HFRC specimens

S. No.	Specimen ID	Fibre volume fraction, V_f (%)	Fibre proportion	
			Steel (%)	Polyolefin (%)
1	HC0-S0P0	0	0	0
2	HC0.5-S100P0	0.5	100	0
3	HC0.5-S80P20		80	20
4	HC0.5-S70P30		70	30
5	HC0.5-S60P40		60	40
6	HC0.5-S50P50		50	50
7	HC1.0-S100P0	1.0	100	0
8	HC1.0-S80P20		80	20
9	HC1.0-S70P30		70	30
10	HC1.0-S60P40		60	40
11	HC1.0-S50P50		50	50
12	HC1.5-S100P0	1.5	100	0
13	HC1.5-S80P20		80	20
14	HC1.5-S70P30		70	30
15	HC1.5-S60P40		60	40
16	HC1.5-S50P50		50	50

2.3 *Testing of Specimens*

According to IS 516 [12], compression test on the cylindrical specimens was carried out with an extensometer to measure the deformation in concrete at equal intervals of loadings. The splitting tensile test was carried out on the cylinder specimens as per IS 5816 [13]. In accordance with IS 516, the prisms were supported with a span of 400 mm and tested. The readings were born at different load levels till the failure of the specimens. Figure 3a–c shows all three experimental test setups.

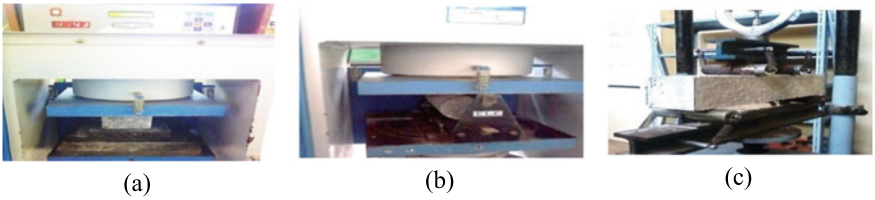

(a) (b) (c)

Fig. 3 Experimental setup: **a** compression test; **b** split-tensile test; **c** flexural test

3 Results and Inferences

The experimental investigations were carried out on HFRC specimens, incorporated with 'steel' (rigid) and 'polyolefin' (flexible) hybrid fibres. A total of 144 samples using sixteen concrete mixtures with and without fibre, the specimens were cast and tested for obtaining the (average) compressive strength, splitting tensile strength, modulus of rupture, and ductility indices. The inferences have been highlighted below, based on the results of the tests.

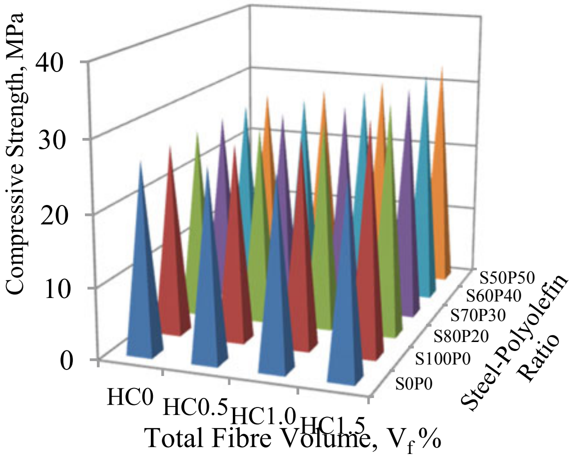
3.1 Strength Characteristics

Table 5 gives various HFRC specimens' salient results in respect of the compressive strength (f_{ck}), split-tensile strength (T_{sp}), and modulus of rupture (MOR). The difference of compressive strength in respect of volume fractions (V_f) and the ratio of hybrid fibres [steel (S): polyolefin (P)] is shown schematically in Fig. 4. The discussion and also salient inferences are given below based on the above (V_f and S:P).

Table 5 Strength properties and ductility indices of HFRC

S. No.	Specimen ID	Compressive strength (MPa)	Split-tensile strength (MPa)	Modulus of rupture (MPa)	Deflection ductility ratio	Energy ductility ratio
1	HC0-S0P0	26.70	3.80	5.45	1.00	1.00
2	HC0.5-S100P0	27.50	4.10	6.25	1.17	1.24
3	HC0.5-S80P20	27.65	4.20	6.55	1.20	1.28
4	HC0.5-S70P30	27.90	4.35	6.80	1.22	1.33
5	HC0.5-S60P40	28.25	4.60	7.10	1.25	1.39
6	HC0.5-S50P50	28.10	4.40	7.00	1.23	1.35
7	HC1.0-S100P0	29.05	5.55	8.05	1.30	1.41
8	HC1.0-S80P20	29.20	5.80	8.25	1.34	1.45
9	HC1.0-S70P30	29.65	6.10	8.70	1.38	1.48
10	HC1.0-S60P40	30.10	6.40	9.05	1.41	1.52
11	HC1.0-S50P50	30.00	6.35	8.90	1.40	1.49
12	HC1.5-S100P0	32.25	7.65	10.35	1.46	1.54
13	HC1.5-S80P20	32.55	7.95	10.65	1.49	1.57
14	HC1.5-S70P30	32.85	8.20	10.90	1.54	1.62
15	HC1.5-S60P40	33.20	8.45	11.25	1.61	1.70
16	HC1.5-S50P50	33.05	8.25	11.10	1.58	1.66

Fig. 4 Compressive strength for specimens with and without fibres

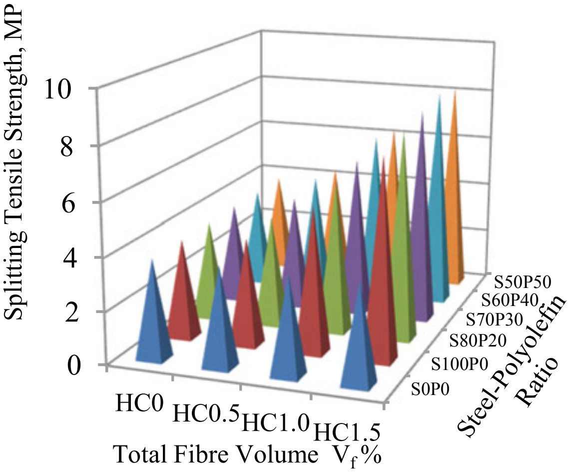


Compressive Strength: It observed that the characteristic compressive strength of HFRC specimens varies with respect to fibre volume content (V_f) and the proportion of hybrid fibres [namely: steel (S): polyolefin (P)]. Thus, not only the V_f but also the amalgamation of hybrid fibre plays a role in influencing the compressive strength. The above phenomenon seems to hold good for the range of V_f (i.e. 0.5–1.5%) and the various ratios of hybrid fibres (i.e. S:P = 100:0, 80:20, 70:30, 60:40, 50:50) considered in this study. As the V_f increases, the compressive strength of SFRC specimens also increases with respect to the control specimen for the range of V_f considered. However, the increase of the compressive strength is not significant up to $V_f = 1.0$, but it becomes considerable and substantially higher (20.8%) at $V_f = 1.5\%$. Thus, steel fibre incorporation contributes to a significant and higher compressive strength of SFRC specimens only if V_f is higher than 1.0% and at 1.5%. The above phenomenon highlights the role of steel fibres (alone) on the compressive strength (of specimens) [14, 15].

However, the increase in the above strength is maximum at the highest V_f (i.e. at 1.5%) and the lowest raise at the lowest V_f (i.e. at 0.5%). The increase in compressive strength of the HFRC specimen ranges from 3 to 5.8%, 8.8 to 12.7%, and 20.8 to 24.3%, over the control specimen, for the respective V_f equals 0.5, 1.0 and 1.5%. However, the rise of the compressive strength is significant for $V_f = 1.5\%$, and the compressive strength is maximum for the hybrid fibre combination 60:40 (S:P) for the range of V_f considered. The maximum increase of the compressive strength of HFRC specimens with respect to SFRC specimen is less than that of control specimen, for corresponding V_f considered. Further, the increase in the strength of the HFRC specimen over the SFRC specimen is found insignificant. It indicates the ‘hybrid fibres’ effect in influencing the compressive strength of HFRC specimens is inconsequential which are similar to the observation/(s) of some of the cited investigations [16, 17].

Splitting Tensile Strength: Variations of split-tensile strength with respect to fibre volume (%) and the ratio of hybrid fibres (S:P) as shown in Fig. 5. Based on the

Fig. 5 Splitting tensile strength for specimens with and without fibres



analysis of results in Table 5 and Fig. 5, the following are the salient inferences. The role of V_f and the combination of fibres in influencing the split-tensile strength are similar to that of the compressive strength. It observed that the split-tensile strength is maximum for the hybrid fibre combination 60:40 (S:P) for the range of V_f considered, which is the same as in the case of the compressive strength. However, the increase in the above strength is not significant up to $V_f = 0.5\%$. Afterwards, there is a sudden increase and much higher jump in the above strength for $V_f = 1.0$ onwards. The maximum increase in split-tensile strength is 3.6, 5.4, and 5.9 times that of compressive strength under identical conditions. In other words, the maximum split-tensile strength ranges from about 3–6 times the compressive strength under similar conditions. It highlights the significant role played by the ‘hybrid fibres’ in enhancing the split-tensile strength, unlike the case of compressive strength, where the role of the ‘hybrid fibres’ is found to be insignificant.

Modulus of Rupture: Comparison of modulus of rupture (MOR) with respect to fibre volume content (V_f) and the ratio of hybrid fibres (S:P) is shown in Fig. 6. Based on the analysis of results in Table 5 and Fig. 6, the following are the salient inferences. The role of V_f and the combination of fibres in influencing the MOR are similar to that of compressive strength. The trend with respect to the increase in MOR over the control specimen and SFRC specimens is similar to that of compressive strength. The maximum increase in the MOR of SFRC specimens with respect to the control specimen is 14.7, 47.7, and 89.9%, for $V_f = 0.5$, 1.0, and 1.5%, respectively. It can be seen that the above increase becomes not only significant but also becomes very high for $V_f > 0.5\%$. The above behaviour is similar to that of the behaviour of split-tensile strength.

The maximum increase in the MOR of HFRC specimens over the control specimen is 30.3, 66.1, and 106.4% for $V_f = 0.5$, 1.0, and 1.5%, respectively. This highlights the significant role of hybrid fibres in enhancing the MOR. It is seen that

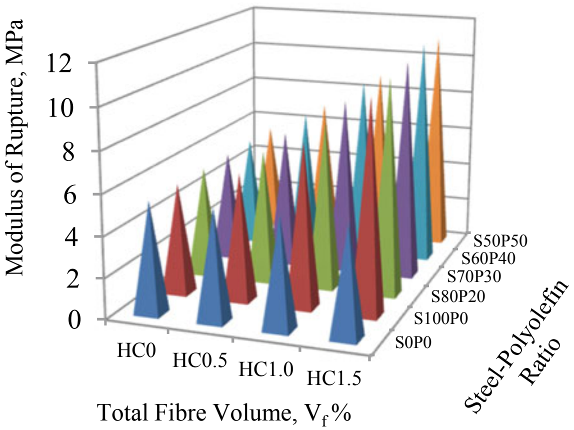


Fig. 6 Modulus of rupture for specimens with and without fibres

the above maximum increase in MOR of HFRC specimen over SFRC specimen with respect to control specimen under identical conditions is considerably increased due to the 'hybrid' effect between the steel and polyolefin fibres used in this study. Such improvements can be made possible by the ability of fibres to modify the failure mechanisms of composite material [18]. Further, the above maximum increase in MOR of HFRC specimens with respect to SFRC specimens can be considered as closer to significant but not significant for all the V_f considered.

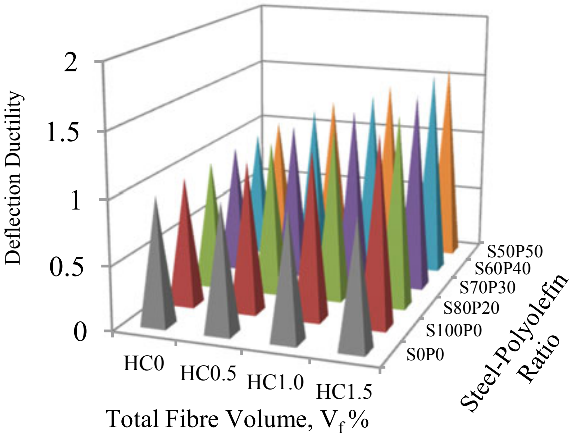
3.2 Ductility Indices

Ductility is measured via deflection and energy by a ratio called the ductility index or factor. Table 5 gives the indices of deflection and energy ductility of HFRC specimens.

Deflection Ductility: Fig. 7 shows variations of the 'deflection ductility index' in respect of fibre volume (%) and the ratio of hybrid fibres (S:P). The deflection ductility of HFRC specimens increases with an increase in V_f and with respect to the proportion of hybrid fibres (S:P) used in this study. The deflection ductility was highest for the hybrid combination 60:40 (S:P) for the V_f range considered. The maximum increase in the deflection ductility index of the SFRC specimen is 1.17, 1.30, and 1.46 with respect to the control specimen, for V_f: 0.5, 1.0, and 1.5%, respectively. Thus, the increase in the deflection ductility index was highest for $V_f = 1.5\%$. The deflection ductility of HFRC specimens seems to be higher than that of SFRC specimens, irrespective of V_f, due to the 'hybrid' effect of the types of fibres used. Further, the above increase in deflection ductility index is significant for the V_f considered attributed to the 'role of hybrid fibres' used.

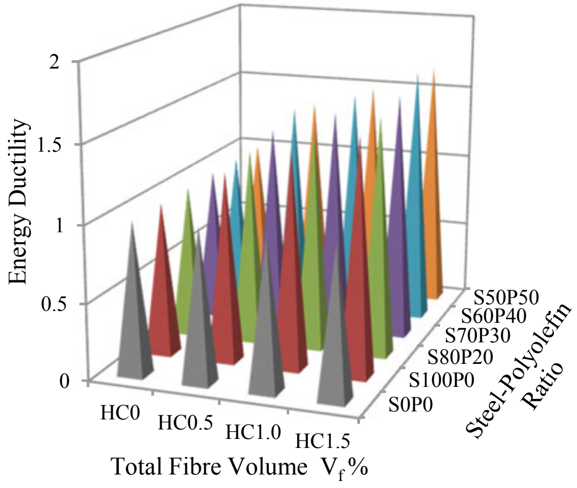
Energy Ductility: Comparison of the energy ductility index with respect to V_f and the ratio of hybrid fibres (S:P) is in Fig. 8. The energy ductility of HFRC specimens

Fig. 7 Deflection ductility for specimens with and without fibres



increases with an increase in V_f and with respect to the proportion of hybrid fibres (S:P) used in this study. The energy ductility index increases to the maximum for the SFRC specimens are 1.24, 1.41, and 1.54 with respect to the control specimen, for V_f: 0.5, 1.0, and 1.5%, respectively. It seems that the energy ductility of HFRC specimens is higher than that of SFRC specimens irrespective of V_f due to the 'hybrid' effect of the types of fibres used. The maximum increase in energy ductility index of HFRC specimens is 1.39, 1.52, and 1.70 times, over the control specimen, for V_f: 0.5, 1.0, and 1.5%, respectively. The above phenomenon is also similar to that of deflection ductility. However, energy ductility is consistently slightly higher than the deflection ductility for all V_f considered. Thus, the 'role of hybrid fibres' used is better in energy ductility than deflection ductility.

Fig. 8 Energy ductility for specimens with and without fibres



4 Conclusions

- The compressive strength, split-tensile strength, and modulus of rupture (MOR) of the HFRC specimens influences by the fibre volume content (V_f) and the combination of hybrid fibres [that is, steel (S): polyolefin (P)]. The above phenomenon holds good for the range of V_f (i.e. 0.5–1.5%) and various ratios of hybrid fibres ($\geq$ 20% to $\leq$ 100%) considered in this study. All the above three strengths are maximum for the hybrid fibre combination 60:40 (S:P) for the range of V_f considered. Further, the highest strength is attained at $V_f = 1.5\%$ and for the above combination. However, the influence of 'hybrid fibres' on the above three strength parameters is dissimilar.
- In the case of compressive strength, the effect of 'hybridization of fibres' is not significant, whereas it is significant and very high in the case of the other two strength parameters for all the V_f considered. The above effect of fibres, in general, on the compressive strength is along expected lines and in line with the reported results in the literature. The maximum increase in the split-tensile strength of 'HFRC specimens', over the 'control specimen', ranges from 21 to 122.3% for the range V_f 0.5 to 1.5%, with the highest increase in strength occurring at the highest V_f (= 1.5%).
- The maximum increase in the 'MOR' of HFRC specimens over the control specimen ranges from 30.3 to 106.4%, for the V_f ranging from 0.5 to 1.5%, with the highest increase in the above strength occurring at the highest V_f content (= 1.5%). It highlights the role of hybrid fibres in enhancing the above strength and is similar to that of the split-tensile. The modulus of elasticity (MOE) of HFRC specimens ranges from 26.19 to 28.79 MPa. It seemed that the MOE of the HFRC specimen is maximum for the hybrid fibre combination 60:40 (S:P) for the range of V_f considered. The above behaviour is similar to the strength behaviour of HFRC specimens. The MOE of HFRC specimens is not significantly different from that of the 'control concrete'.
- The maximum increase in 'deflection ductility ratio' of HFRC specimens ranges from 1.25 to 1.61 times the 'control specimen', for the Vf range 0.5–1.5%, with the highest increase occurring at $V_f = 1.5\%$ and S:P = 60:40. The above phenomenon may also be attributed, to the 'positive and very high influence of the hybrid fibres'. Similarly, the maximum increase in the 'energy ductility ratio' of HFRC specimens ranges from 1.39% to 1.70 times the 'control specimen' for the V_f range from 0.5 to 1.5%, with the highest increase occurring at $V_f = 1.5\%$, and S:P = 60:40. However, the effect of hybrid fibre seems to be slightly higher in the 'energy ductility ratio' than in the other ratio for the range of V_f considered. Thus, the role of hybrid fibres is 'consistently better' in 'energy ductility' than in 'deflection ductility'.

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