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Article

Characteristics of Steel Fibre Reinforced High Strength Concrete Beams: Efficiency in Size Reduction for Flexure

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Abstract. Mechanical properties of concretes substituted with steel fibres and its relative merits on the size reduction of concrete specimens had been investigated in this study. Reinforcing efficiency of steel fibres on the flexural bending characteristics of thick and slender concrete sections had been experimentally verified. High strength concretes were produced using two different types of steel fibre anchorage profile consisting of single hooked and double hooked ends. The effects of steel fibres distribution in random and aligned direction were tested in various fibre concrete mixes substituted with 0.5% and 1.0% V_f of steel fibres. Fracture characteristics of various concrete specimens were tested using notched beam tests subjected to third point loading arrangement. Test results indicated a positive synergy of fibre profile and alignment which provided an effective bonding and increased fracture strength of fibre concretes. Fibre concretes incorporating double hooked end steel fibres showed higher fracture toughness (12.42 N-m) and fracture energy (955 (N/m) than single hooked steel fibre concretes. Better fibre-matrix bonding and alignment of steel fibres along beam axis have contributed for enhanced fracture resistance of fibre concretes as well as size reduction efficiency of fibre concrete sections.

Keywords: Steel fibres, high strength concrete, size reduction, fracture energy, fibre matrix bond.

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1. Introduction

Fibre reinforcements in concrete provide crack growth résistance upon loading and thereby enhance the composite mechanical properties of concrete. The random distribution of discrete fibres in concrete provides good homogeneity and isotropic properties in compression and tension. Steel fibres were commonly used as secondary reinforcement in brittle concrete owing to its high elastic modulus [1, 2]. Several experimental studies were conducted in the past to prove the real merits of different types of steel fibre addition in concrete. However, the significant improvement on the concrete properties with steel fibre addition lies in obtaining the size reduction of concrete. In addition, the effective steel fibre alignment had direct influence on the load carrying capacity of fibre reinforced concrete members [3, 4]. The effects of steel fibre addition had been widely studied in terms of size effect properties of varying cross sectional size of concrete elements [5]. Test results had been indicative that effective steel fibre distribution in small concrete sections exhibited improved fracture properties compared to large concrete sections. Steel fibres provide adequate flexural stiffening to undergo inelastic deformation due to pure bending rather than shear failure in the beam [6].

Experimental studies indicated that self straining of steel fibres occurs at high stresses resulting in either fibre pullout or fibre rupture [7, 8]. However, deformation of steel fibres occurs in the matrix for high volume fibre substituted concrete mixes [9-11]. Ductility of fibre concretes was dependent primarily on the fibre matrix interfacial bond strength and the effective anchorage length [8]. The strain softening response of steel fibres at post cracking depends mainly on the tensile modulus and anchorage length of the steel fibres [12]. The effective bonding of fibres in the matrix and further pullout of fibres can significantly yield high toughness of brittle concrete [13-16]. Crack bridging ability of discrete fibres depends largely on the propensity of cracks intercepted with fibres and its relative fibre volume fraction [17, 18]. However, the actual merits of steel fibre addition in concrete can be realized when the crack propagation is controlled by steel fibres. Further, the efficiency of steel fibres in crack mitigation depends on the direction of orientation of steel fibres across the crack width [19]. When the stresses in concrete are high, the crack widening primarily depends on the number of steel fibres bridging the crack [20-22]. However, the instability in crack growth occurs possibly when the fibre availability is lesser during crack opening.

Literature review on earlier studies indicated that steel fibres were preferred to be distributed homogenously and spatially oriented throughout the entire volume of concrete to achieve isotropic properties. However, the limitation of earlier studies revealed that the random distribution of steel fibres in concrete does not compromise on the required number of effective fibres contributing towards the load sharing capability. This necessitates for increasing the fibre volume fraction for achieving maximum mechanical performance in concrete. However, it is well documented from many studies that high volume fibre addition may lead to loss in workability leading to concrete defects apart from improving the mechanical performance. The review findings suggest that effective steel fibre volume and its preferential alignment in the concrete matrix needs to be well documented inorder to achieve high performance fibre concrete composites. Hence, in this study the effect of steel fibre anchorage and unidirectional fibre alignment in a high strength concrete had been systematically investigated using fracture studies and compared with random distribution of steel fibres.

2. Experimental Program

2.1. Concrete Materials Used

In the present study, an ordinary Portland cement was used as binder, locally available river sand as fine aggregate and crushed granite stone as coarse aggregate. The properties of various materials used are provided in Table 1.

Table 1. Properties of concrete materials used in this study.

S.No	Property	Value
Cement – ordinary Portland cement		
1.	Normal Consistency	31.5%
2.	Initial Setting Time	45 minutes
3.	Final Setting Time	192 minutes
4.	Specific Gravity	3.15
5.	Fineness of Cement	1.37
Fine aggregate – River sand – less than 4.75mm		
1.	Specific Gravity	2.63
2.	Fineness Modulus	2.72
3.	Uniformity coefficient	3.30
4.	Coefficient of curvature	0.95
5.	Bulk density	2518 Kg/m^3
Coarse aggregate – Crushed granite –12.5mm (angular)		
1.	Specific Gravity	2.61
2.	Fineness Modulus	5.72
3.	Uniformity coefficient	1.20
4.	Coefficient of curvature	1.24
5.	Bulk density	2410 Kg/m^3

2.2. Steel Fibres

Steel fibres of two different types namely single hooked and double hooked steel fibres were used as discrete reinforcement in various fibre concrete mixes. The properties of various steel fibres used are given in Table 2 and the profile of fibres is shown in Fig. 1.

Table 2. Properties of steel fibres used in this study.

Type of fibre	Length (mm)	Diameter (mm)	Aspect ratio (l/d)	Tensile strength (MPa)	Elastic modulus (Gpa)
Single hooked steel (SHS)	50	0.8	63	1100	210
Double Hooked steel (DHS)	50	0.8	63	1100	210

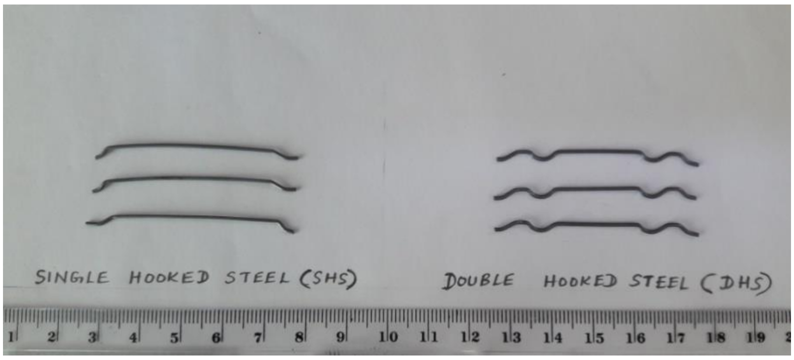

Fig. 1. Steel fibres used in this study.

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2.3. Concrete Production

Concrete mixes were designed using trial mix design procedures with target strength of 40 MPa. Various concrete mixes consisting of plain and fibre concrete mixes were casted as given in Table 3. As the fibre concrete mixes showed lower workability, the addition of superplasticizer was essential to obtain a desired slump range of 90 to 100mm. In the present study, various types of fibre concrete mixes containing single hooked and double hooked steel fibres were added in random dispersion and aligned distribution (using layered filling). Randomly distributed fibre concrete mixes were prepared by filling the fresh fibre concrete mixes to the full volume of the wooden moulds and then compacted using needle vibrator which ensures spatial distribution of steel fibres. On the other hand, aligned steel fibres in concrete were achieved by layered filling technique in which the fresh fibre concrete was filled in the moulds for every 30cm depth and further compacted to align the steel fibres along the beam axis (normal to loading). The required dosage of hyperplasticizer (CONPLAST –SP430) upto 0.5% by weight of cement was added in the concrete mixer to achieve a target slump range of 90 to 100mm. It can be noted that workability of all fibre concrete mixes were desired in the range of 90mm to 100mm, which was found to be a good workable range for easy placing of concrete without any congestion. However, the maximum dosage of hyperplasticizer was restricted to 0.5%.

Table 3. Plain and fibre concrete mix proportions used in this study.

Type of concrete mix	Mix ID	Cement (kg/m³)	Sand (kg/m³)	Crushed stone 12.5mm (kg/m³)	Water (kg/m³)	SP (% by weight of cement)	Volume fraction# of steel fibres (%)	Fibre Dosage (kg/m³)
Plain Thick concrete	PTC-1	480	672	1100	168	0.5	-	-
Plain slender concrete	PSC-2	480	672	1100	168	0.5	-	-
Single hooked steel fibre concrete	SHR-3	480	672	1100	168	0.5	0.5	12
	SHR-4	480	672	1100	168	0.5	1.0	24
	SHA-5	480	672	1100	168	0.5	0.5	12
	SHA-6	480	672	1100	168	0.5	1.0	24
Double hooked steel fibre concrete	DHR-7	480	672	1100	168	0.5	0.5	12
	DHR-8	480	672	1100	168	0.5	1.0	12
	DHA-9	480	672	1100	168	0.5	0.5	12
	DHA-10	480	672	1100	168	0.5	1.0	12

Note: # - denotes the volume fraction of steel fibres in terms of volume of concrete used in the mix;
PTC 1 – Plain thick (150mm) concrete; PSC 2 – Plain slender (100mm) concrete;
SHR – Single hooked random steel fibre concrete; SHA – Single hooked aligned steel fibre concrete;
DHR – Double hooked random steel fibre concrete; DHA – Double hooked aligned steel fibre concrete.

Steel fibres were added into the concrete mixer and a uniform dispersion of steel fibres were maintained for all fresh concretes in order to eliminate fibre balling. Fresh concrete mixes were then transferred into the wooden moulds (shown in Fig. 2) and demolded after 24 hours. The preferred unidirectional fibre alignment along the beam axis was achieved using layered compaction of concrete in the wooden moulds as seen in Fig. 3. Alignment of steel fibres in unidirectional axis was achieved by means of layered casting and compacting (the depth of each pouring of fresh concrete in the mould was limited to less than the steel fibre length used). This ensures the fibres being oriented along beam axis and further application of needle vibration provides wall effect which ensures preferential steel fibre alignment**.** The concrete specimens were then moist cured sufficiently before testing at respective ages and the concealed concrete specimens are shown in Fig. 4 and the details on the various concrete specimens tested are provided in Table 4.

Fig. 2. Fabricated wooden moulds for casting concrete.

Fig. 3. Layered casting of concrete beam specimens for steel fibre alignment.

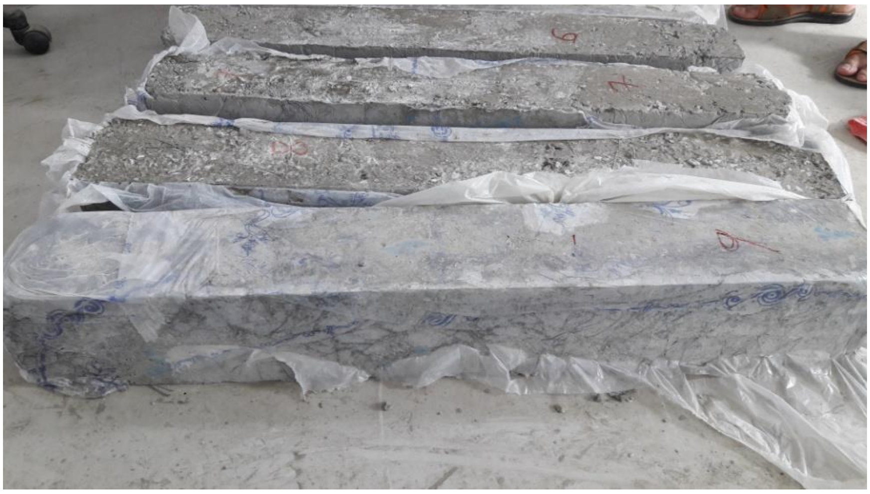

Fig.4. Concealed curing of concrete specimens.

Table 4. Details of various concrete specimens tested for each mix.

Type of concrete specimen	Type of fibre distribution	Mix type	Size of moulds (mm)	No. of. Specimens tested	Age at testing	Concrete Parameters measured
Cube	--	Plain concrete (PTC-1 & PSC-2) and fibre concretes	150X150X150	5	28	Compressive strength, residual strength, fibre efficiency
Notched Beam	Random Aligned	Plain and all fibre concretes	100X150X1000; 150X150X1000 Notch depth– 20mm; width – 5mm	3	28	Load – CMOD curve, Fracture toughness

2.4. Experimental Method

2.4.1. Compressive fracture test

Fracture properties in compression of various hardened concretes were tested in a digital compression testing machine of 2000KN capacity (shown in Fig. 5). The applied rate of loading was maintained at 2.5KN/sec and an average of 5 concrete specimens was tested for each concrete mix type. Fracture load of concrete specimens in compression was noted from the time of occurrence of first visible cracking on the concrete surface. This cracking load was accurately denoted in the digital load indicator with a significant instability in load increment value around 90 to 95% of ultimate load. From the fracture load, the test results of concrete specimens were reported in terms of average compressive fracture strength for various concrete mixes. The following parameters were computed from the compressive strength results:

i) Compressive fracture strength – cracking load at 90 to 95% ultimate load
ii) Residual strength – load corresponding to one complete cycle of loading and unloading of concrete until 95% of ultimate load and then reloaded until failure.
iii) Residual compressive strength ratio – the ratio of residual compressive strength to that of compressive fracture strength of concrete specimens.
iv) Fibre reinforcing efficiency – the ratio of compressive strength of fibre concrete to that of plain concrete specimens.

Fig. 5. Electronic digital controlled compression testing machine.

2.4.2. Bending fracture test

Fracture tests were carried out as per RILEM Technical committee TC- 1985 (1985) [23] recommendations using three point bend tests in notched concrete beams. The experimental setup of fracture test is shown in Fig. 6 and the details of the notched concrete specimens used in this study are shown in Fig. 7.

Fig. 6. Bending fracture test setup conducted in this study.

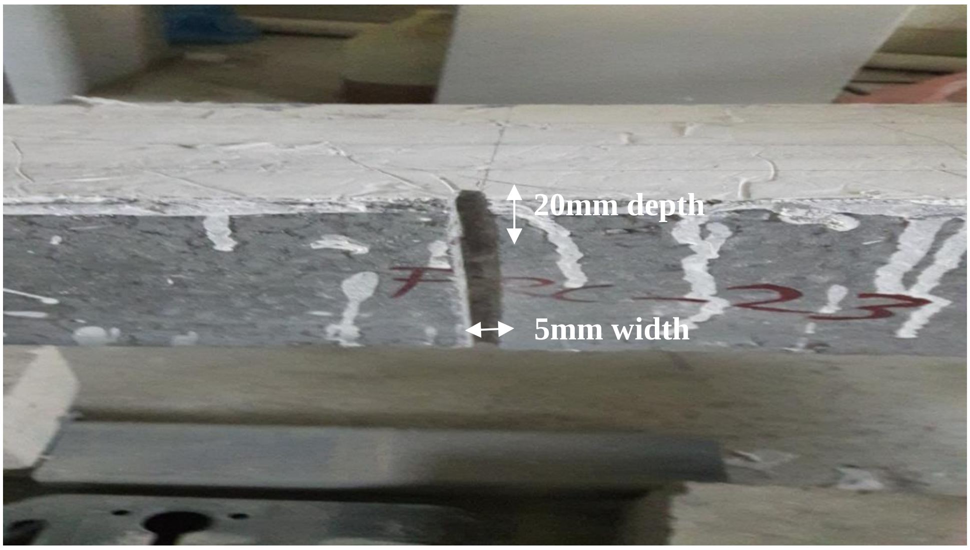

Fig. 7. Notched concrete beam specimen used in the fracture test (5mm width and 20mm depth).

The entire flexural test was carried out in a digital controlled machine of 100KN capacity and the rate of loading was maintained at 0.2mm/min. A clip arrangement was fixed at the crack mouth and a mechanical dial gauge of 0.01mm accuracy was used to measure the crack mouth opening displacement (CMOD). Then the fracture load versus CMOD was used to measure the fracture toughness and fracture energy as given in Eq. (1).

i) Hillerborg's fracture model (1985) [24] is given by the equation:

$$G_f(\alpha, W) = \frac{1}{(W-a)B} \int P.d\delta \quad (1)$$

where $G_f(\alpha, W)$ - fracture energy (N/m)
P – applied load (KN)
$d\delta$- Crack mouth opening displacement (mm)
B – Thickness of concrete beam (mm)
W – depth of concrete beam (mm)
a – notch depth (mm)

From the above expression, the total fracture energy required to open the crack till complete failure was calculated. From the experimental observation of fracture load versus the crack mouth opening displacement, the graphical results are plotted for further computation of fracture energy of various concrete mixes.

ii) Residual fracture strength – the residual strength corresponding to the concrete specimen by loading, unloading and reloading the concrete specimen until 95% of ultimate load.

iii) Fracture toughness is calculated from the entire area under the fracture load versus CMOD curve and the fracture energy is obtained by dividing the fracture toughness with the actual area of fracture across the notch.

iv) Fibre reinforcing efficiency – the ratio of fracture strength of fibre concrete specimen to that of plain concrete specimen.

3. Test Results and Discussions

3.1. Effect of steel fibres in compressive fracture

Compressive fracture results of fibre concrete specimens provided in Table 5 showed enough evidence that steel fibres were ineffective to improve the compressive strength. The strength enhancement in fibre concretes was not apparent irrespective of either fibre type or volume fraction of steel fibres. A maximum compressive strength of 46.87 N/mm^2 and 46.24 N/mm^2 was reported in case plain concrete (PTC-1/PSC-2) and fibre concrete mixes (DHA-9). However, the other fibre concrete mixes had reportedly shown a marginal decrease in strength (upto 5.78%) compared to plain concrete. This evidently shows that steel fibres were not being effectively stressed in compressive fracture mode as the crack opening mode was due to shearing stress rather than crushing failure. Also, the vertical shear deformation during compressive loading did not exhibit in straining of steel fibres. This probably resulted in marginal strength loss around 6% for all the fibre concrete mixes which can be noted from the fibre reinforcing efficiency of various fibre concretes provided in Fig. 8. Further, the aggregate failure occurs in a high strength concrete matrix in which case the reinforcing efficiency of steel fibres in the matrix were not observed. The typical failure crack passing through the aggregates were observed in the fractured concrete specimens after testing. Hence, steel fibres were not being used in bridging the cracks occurring in this type of failure. The failure cracks occurring in compression were due to crushing failure rather than tensile failure in which case the bridging action of steel fibres were not experienced.

However, the fibres surrounding the matrix-aggregate interface provides adequate confinement and hence results in higher residual strength. This can be evidently seen in Fig. 8 that the residual strength of fibre concretes was appreciably higher than plain concretes. The load resistance of fibre concretes even after cracking upto ultimate load possibly provided controlled failure. Compressive test results clearly denoted that fibre concretes showed controlled ductile failure as well as exhibited higher residual strength even though the increase in compressive strength was not anticipated.

Table 5. Compressive fracture test results for various concrete mixes.

Mix ID	Compressive fracture load (KN)	Ultimate compressive load (KN)	Compressive fracture strength (N/mm²)	Ultimate compressive strength (N/mm²)	Residual strength (N/mm²)	Residual compressive strength ratio (N/mm²)	Fibre reinforcing efficiency (%)
PTC-1/PSC-2	1003	1032	44.58	46.87	32.54	0.73	-
SHR-3	985	1014	43.78	45.07	33.71	0.77	-1.79
SHR-4	986	1026	43.82	45.6	32.87	0.75	-1.69
SHA-5	993	1037	44.13	46.09	35.31	0.8	-1.00
SHA-6	990	1020	44.02	45.34	34.32	0.78	-1.30
DHR-7	945	983	42.05	43.67	34.44	0.82	-5.78
DHR-8	967	1002	42.98	44.51	34.38	0.8	-3.59
DHA-9	1005	1040	44.67	46.24	33.95	0.76	0.20
DHA-10	984	1016	43.73	45.15	34.55	0.79	-1.89

Note: Test results reported are an average of 5 specimens with coefficient of variation 0.042 and standard deviation of $\pm$ 4.15 N/mm²

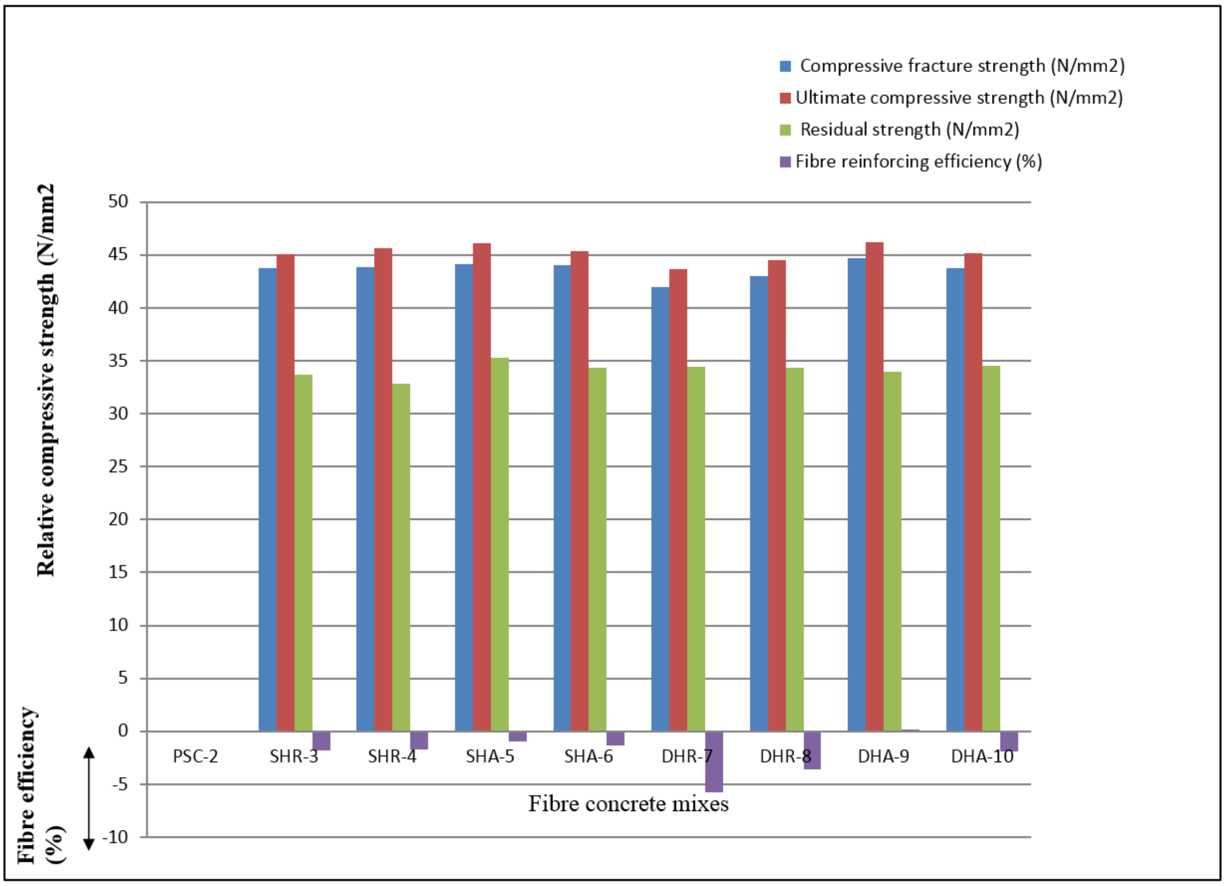

Fig. 8. Relative compressive strength properties and fibre efficiency of various concrete mixes.

3.2. Bending Fracture Strength Results

The bending fracture test results as provided in Table 6 had been reasonable enough to support the real merits of steel fibre reinforcement. The experimental trends on the relative increase in fracture strength as compared to plain concrete specimens (PTC-1 and PSC-2) are represented in Fig. 9. Graphical trends showed negative fracture strength for concretes containing randomly distributed steel fibres. However, a positive increase in fracture strength was noted for double hooked steel fibre substituted concretes at various fibre dosages. Maximum fracture strength of 8.78 N/mm² and 7.56N/mm² was obtained for double hooked steel fibre concretes (DHA-10) and aligned single hooked steel fibre concrete specimens respectively.

Table 6. Bending fracture test results of various concrete mixes.

Mix ID	Fracture load (KN)	Fracture strength (N/mm²)	Residual fracture Strength (N/mm²)	Fracture toughness, P-dδ (N-m)	Fracture energy (N/m)	Fibre reinforcing efficiency (%)
PTC-1	7.16	3.81	0.00	3.26	167.18	-
PSC-2	5.73	4.58	0.00	2.01	154.62	-
SHR-3	6.35	5.07	3.05	2.63	202.30	21
SHR-4	6.75	5.39	3.58	3.87	297.69	78
SHA-5	6.71	5.36	3.89	5.74	441.54	164
SHA-6	7.56	6.04	4.61	6.58	506.15	203
DHR-7	6.68	5.34	3.54	5.94	456.92	173
DHR-8	7.11	5.68	4.12	7.31	562.31	236
DHA-9	7.45	5.95	4.62	7.09	545.38	226
DHA-10	8.78	7.01	5.71	12.42	955.38	471

Note: Test results reported are an average of 3 specimens with coefficient of variation 0.032 and standard deviation of $\pm$ 0.27 N/mm²

This increase was most notably higher when the fibres are aligned in concrete rather than random distribution. Whereas, an appreciable increase in fracture strength was noticed in the case of aligned double hooked steel fibres concretes compared to plain concrete specimens. This denoted that fibre alignment and end anchorages were found to influence the fracture performance of all fibre substituted concrete specimens. Compared to plain thick concrete sections (PTC-1), the fracture strength of slender plain concrete (PSC-2) was suitably improved with an increased steel fibre addition. Most significantly, the increase in fracture strength of fibre concrete was anticipated with an increase in fibre volume fraction (1%) as well as preferential steel fibre alignment normal to loading plane. Strength properties were significantly improved in concretes containing double hooked steel fibres rather than single hooked steel fibres. This was essentially due to the effective end anchorages provided by double hooked end steel fibres and were comparatively higher than single hooked steel fibres. The significant improvement on the strain hardening properties were essentially due to effective pullout resistance offered by the double hooked end steel fibres in the cement matrix. The effects of steel fibre volume fraction (1%) had reasonable influence on the improvement in fracture strength of fibre substituted concretes. Test results also indicated that fracture strength of slender concrete sections can be comparatively increased with the steel fibre addition. Most notably, the fracture properties of aligned steel fibre concretes were found to be higher than randomly distributed fibre concretes. Test results indicate that the alignment of steel fibres showed positive influence on the flexural strengthening of concrete beams. The effect of steel fibre reinforcement was noticed in slender concrete sections at high steel fibre volume fraction. This essentially caused an increase in fracture strength in the case of all slender fibre concretes compared to thick concrete (PTC-1). The presence of steel fibres in uniaxial direction along the beam axis had provided enough fracture resistance to concrete. This occurred due to high stress carrying capacity of steel fibres resulting in fibre straining when it is oriented in beam axis as evidently seen from the fractured surface shown in Fig. 10. Whereas in the case of single hooked steel fibres, fibre pullout occurred due to poor anchorage resistance compared to double hooked steel fibres.

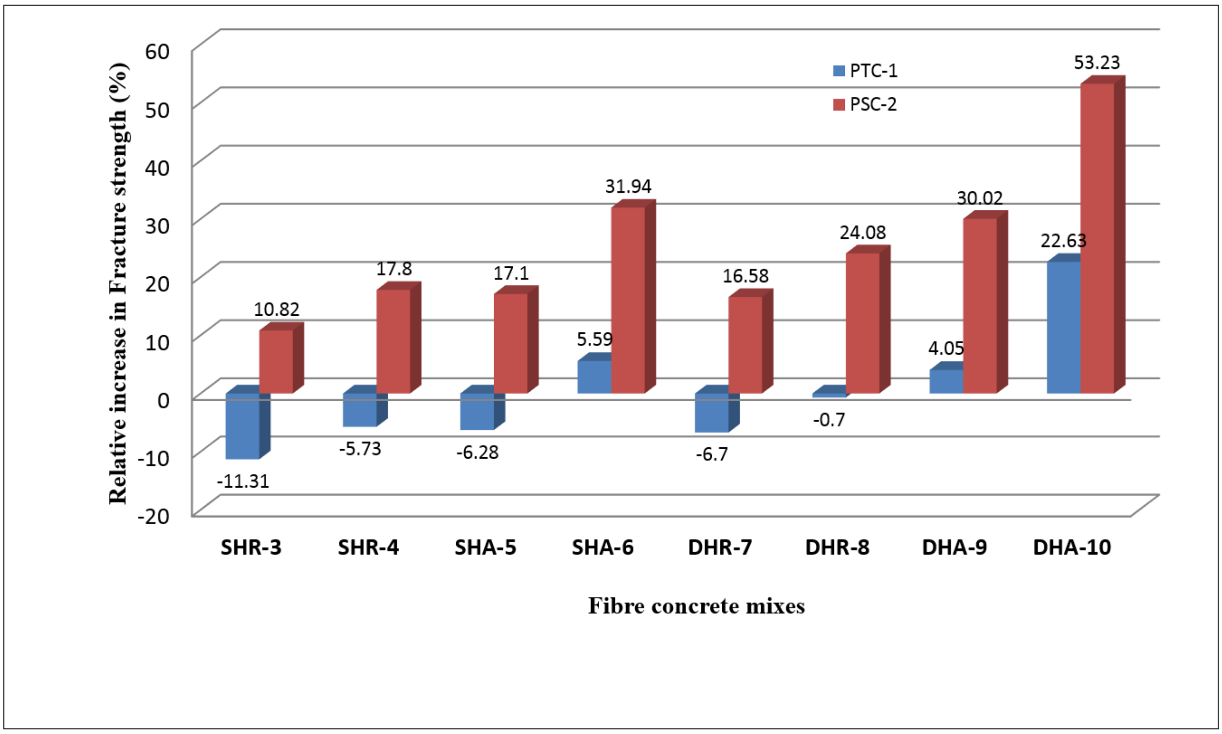

Fig. 9. Relative increase (%) in fracture strength of fibre concretes as compared to plain concrete PTC-1 and PSC-2.

Fig. 10. Fibre straining in case of double hooked steel fibre concretes.

Aligned steel fibres containing single hooked and double hooked ends had exhibited enough improvements on the fracture resistance compared to plain thick and slender concrete specimens. However, this increase was significantly higher in fibre concrete specimens (SHA-6, DHA-9 and DHA-10) with higher volume fraction compared to low volume fraction. The high volume fraction and preferential alignment of steel fibres had witnessed on the size reduction properties of concrete beam. Fracture properties of steel fibre incorporated concrete were found to influence the fracture mode during pure bending resulting in improved composite strength compared to thick concrete sections. The fracture resistance of fibre concretes was notably improved with increasing fibre dosage and preferential fibre alignment normal to loading plane. In addition, the better anchorage and bonding of steel fibres in the matrix can provide increased fracture strength.

3.3. Bending Fracture Toughness and Fracture Energy

Fracture toughness of concrete is the theoretical energy required to produce a new fractured surfaces of a notched concrete specimen. The quantitative estimation of fracture energy and fracture toughness obtained from the bending test is provided in Table 6. Test results of various fibre concrete specimens are compared with that of thick plain concrete (PTC-1) and slender plain concrete (PSC-2) sections. A comparative assessment of various fibre concretes had been made to quantify the improvements on the fracture properties with different types of steel fibre substitution. The fracture load versus crack mouth opening displacement (CMOD) of various concrete specimens tested is provided in Fig. 11. The corresponding fracture energy of the concrete specimens was calculated from the area of these curves divided by the actual fracture area as shown in Fig. 12. The characteristic trends obtained from the fracture properties of various fibre concrete specimens are represented graphically in Fig. 13. Maximum fracture toughness of 12.42N-m and maximum fracture energy of 955.38 N/m was reported in the case of aligned double hooked steel fibre concrete mixes (DHA-10). Whereas, the randomly oriented fibre concrete mixes (SHR-3) showed relatively lower fracture toughness values (2.63N-m) compared to aligned fibre concrete mixes (SHA-5). Test results also indicated that the fracture toughness increased with increasing fibre volume fraction and nevertheless the preferred steel fibre alignment had contributed for the composite performance. The fracture toughness of aligned double hooked steel fibre concretes was 2.25 times higher than single hooked steel fibre concretes. This shows that the steel fibre alignment in concrete matrix had been favorable for an effective load transfer mechanism in the fibre matrix interface. High fibre volume upto 1% and preferential steel fibre alignment had improved the post peak characteristics of the fibre concretes (SHA-6 and DHA-10). The comparative analysis also revealed that the fracture energy of the fibre composites was maximum for high volume fibre substituted concrete mixes and for aligned steel fibre concrete mixes. The load–CMOD plots of various concrete specimens tested showed a clear indication that the post peak region of the curve was controlled with the type steel fibre addition. This essentially caused a smooth transition in the descending curve after post peak fracture. Depending upon fibre volume and its corresponding crack bridging efficiency, the sudden drop in post peak load was controlled in fibre concretes. The effective end anchorages provided by double hooked steel fibres had shown better resistance towards fibre pullout and contributed for the overall increase in the fracture energy of the composite (DHR-7, DHR-8, DHA-9 and DHA-10). Test results convincingly showcased that steel fibre incorporation in slender concrete sections and preferential orientation had improved the fracture energy. This evidently proved the fracture properties can be adequately compensated with steel fibre addition even with reduced concrete thickness. High volume fibre incorporated mixes were subsequently showing higher fracture energy owing to steady state crack propagation with controlled crack widening due to crack bridging effect of steel fibres. It was also imperative that the double hooked end steel fibres offered a better fibre matrix bonding enabling higher pullout resistance leading to increased post peak strain softening region. The real effects of steel fibres had witnessed on the size reduction of concrete at higher fibre volume (1%) owing to efficient formation of crack closing forces. Also, steel fibres getting aligned along beam axis and normal to loading plane can provide high fracture energy owing to effective crack bridging efficiency. Steel fibres bridging the crack opening may have significant effect on the overall fracture resistance due to effective stress transfer mechanism across the growing cracks. Also, the effective steel fibre volume and closer spacing of intermediate fibres had shown subsequent increase on the fracture energy. The presence of steel fibres along the beam axis had been instrumental in load sharing and the corresponding interfacial fibre-matrix strengthening. Apparently, the fracture energy was found to improve with an increase in fibre volume fraction as well as due to preferential fibre alignment. The fracture energy was reportedly higher in the case of double hooked steel fibres compared to single hooked steel fibres owing to better anchorage resistance provided by complex steel fibre profile. In addition crack widths were better controlled in fibre incorporated concretes as evidently seen in Figs. 14 & 15. Hence, steel fibres with good bonding in the matrix are known to provide enough frictional bonding during fibre pullout. The delay in the time required to pullout the steel fibres had essentially caused the increase in the fracture strength of the composite. The alignment of steel fibres normal to loading plane and fibre straining at high fibre volume are known mechanisms for the matrix strengthening. The fracture characteristics of steel fibre concretes were appreciably improved at high volume fibre substitutions and effective unidirectional fibre dispersion favorable in load sharing mechanism.

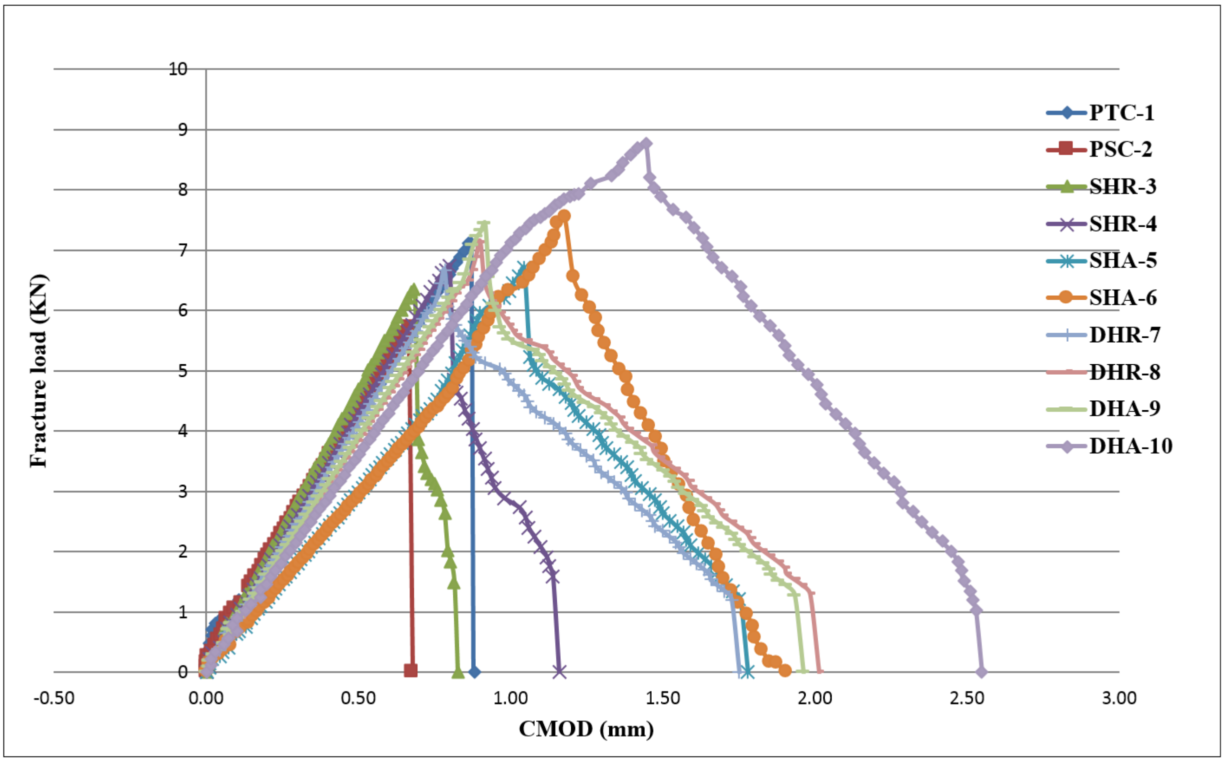

Fig. 11. Fracture load versus Crack mouth opening displacement of various concrete specimens.

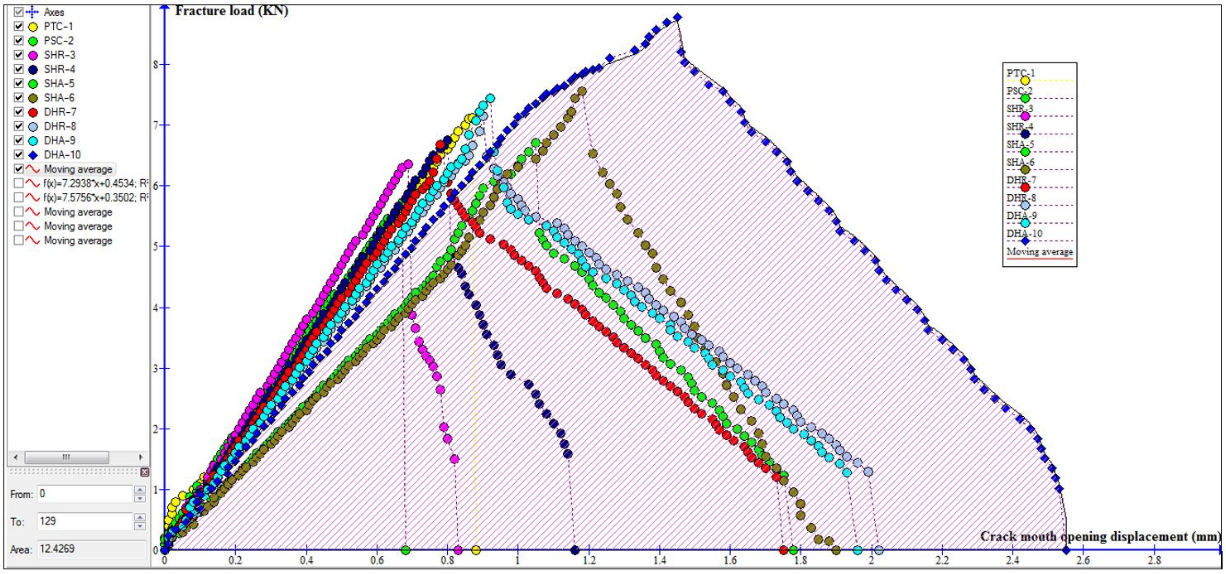

Fig. 12. Fracture toughness calculation for fibre concrete mixes.

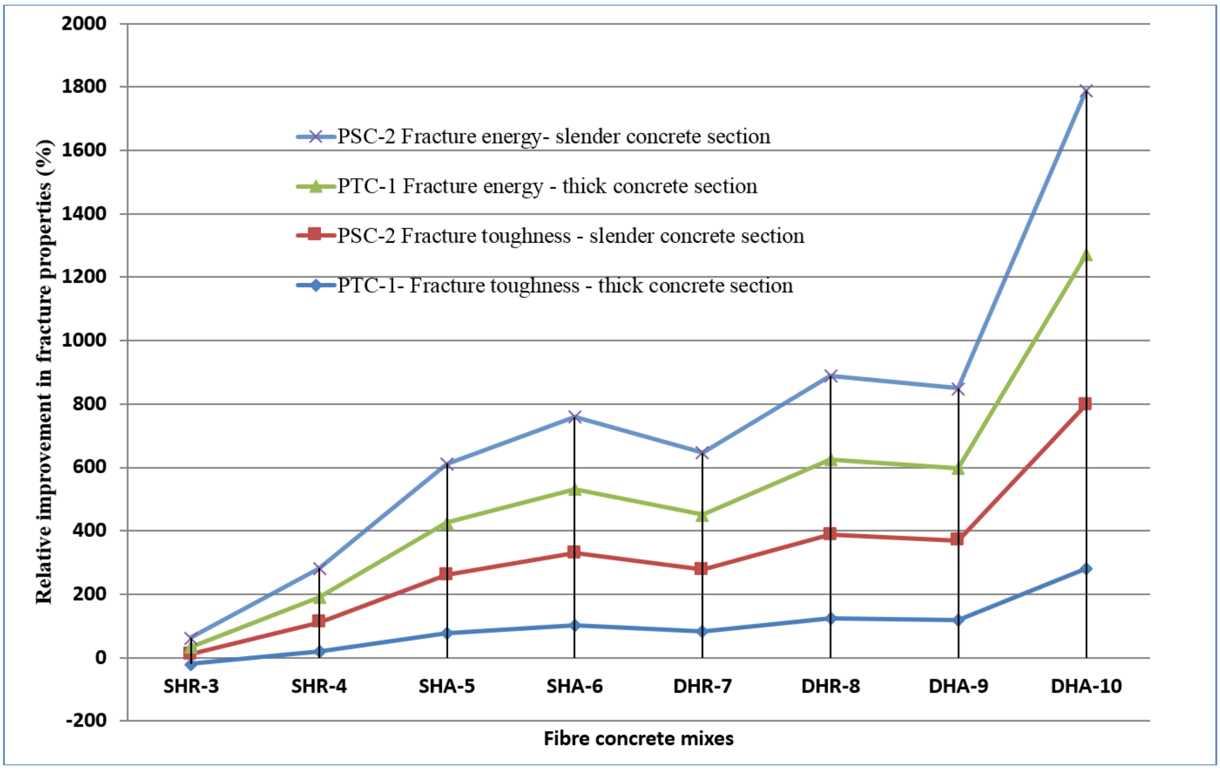

Fig. 13. Relative fracture properties of fibre concrete specimens compared to plain concrete specimens PTC-1 and PSC-2.

Fig. 14. Thin crack width in double hooked steel fibre concrete (DHA-10).

Fig. 15. Thick crack widths in single hooked steel fibre concrete (SHA-6).

3.4. Size Reduction Efficiency of Concrete Sections

The relative performance characteristics of steel fibre substituted slender concretes as compared to thick plain concrete sections are provided in Table 7 and represented in Fig. 16. Comparative analysis indicates that the relative strength properties of a thick plain concrete section can be obtained in slender concrete sections with sufficient steel fibre substitution. However, the reinforcing efficiency of steel fibres can be better synthesized when the fibres are aligned and having effective end anchorages. Among the various concrete specimens, the overall fibre reinforcing efficiency was maximum (363%) in the case of double hooked steel fibre concretes (DHA-10).

Table 7. Comparative assessment of fibre performance in various concrete mixes.

Mix ID	Relative increase (%) in fracture properties of various fibre concretes compared to plain concrete sections (PTC-1, PSC-2): Fracture strength (N/mm^2)		Fracture toughness, P-dδ (N-m)		Fracture energy (N/m)		Overall fibre reinforcing Efficiency (%)	
	PTC-1	PSC-2	PTC-1	PSC-2	PTC-1	PSC-2	PTC-1	PSC-2
SHR-3	-11.31	10.82	-19.33	30.85	21.00	30.84	-3.21	24.17
SHR-4	-5.73	17.80	18.71	92.54	78.07	92.53	30.35	67.62
SHA-5	-6.28	17.10	76.07	185.57	164.11	185.56	77.97	129.41
SHA-6	5.59	31.94	101.84	227.36	202.76	227.35	103.40	162.22
DHR-7	-6.70	16.58	82.21	195.52	173.31	195.51	82.94	135.87
DHR-8	-0.70	24.08	124.23	263.68	236.35	263.67	119.96	183.81
DHA-9	4.05	30.02	117.48	252.74	226.22	252.72	115.92	178.49
DHA-10	22.63	53.23	280.98	517.91	471.47	517.88	258.36	363.01

Relatively, the double hooked randomly distributed steel fibre concretes (DHR-8) at low volume fraction exhibited higher reinforcing efficiency (183.81%) as compared to aligned steel fibre concrete (SHA-6). This possibly revealed that the reinforcing efficiency of steel fibres improved with the addition of double hooked steel fibres in slender plain concrete (PSC-2) specimens due to better end anchorages. Steel fibre addition had been realized in reduced concrete section (PSC-2) and had shown improved fracture properties as compared to thick concrete sections (PTC-1). Compared to thick concrete sections (PTC-1) the increase in fracture toughness was better realized in slender concrete sections at high steel fibre substitution as well as aligned steel fibre substitution. Also, the performance levels of randomly oriented steel fibres were comparatively lower than aligned steel fibre incorporated concretes. The improvement on fracture properties was also significant in the case of complex anchorage profile of double hooked steel fibres which provide adequate resistance for fibre pullout. The inclusion of aligned steel fibres at maximum fibre volume fraction (1%) had shown promising improvements on the fracture properties of concrete even with reduced thickness. Overall test results positively indicate that size reduction in concrete can be achieved if the required flexural resistance is compensated with the supplementary steel fibres added in concrete system. The preferred orientation of steel fibres along beam axis increased the tensile capacity of concrete specimens and hence leading to higher fracture resistance. Test results are also evident that addition of steel fibres in plain concrete can significantly used to reduce the concrete volume without compromising on the fracture properties as that obtained in the case of thick concrete sections. Also, test results indicate that aligned steel fibres at sufficient fibre volume can be useful to reduce the cross sectional size of concrete elements. It is also well documented from the test results that improved fibre matrix bonding and preferential fibre alignment were found to be an important factor for size reduction of concrete. Test results indicated that the preferential alignment of steel fibres along the beam axis and uniform distribution along the depth can influence the bending resistance. Hence, the effective steel fibres in the given concrete matrix (reinforcement index) are more in slender concrete compared to thick concrete beams. Hence, for the given volume fraction the number of steel fibres provides more reinforcement index in slender concrete compared to thick concrete due to difference in volume of concrete. This possibly provides reduced steel fibre spacing in slender concrete compared to thick concrete sections and also maximum steel fibre alignment along the beam axis due to wall effect.

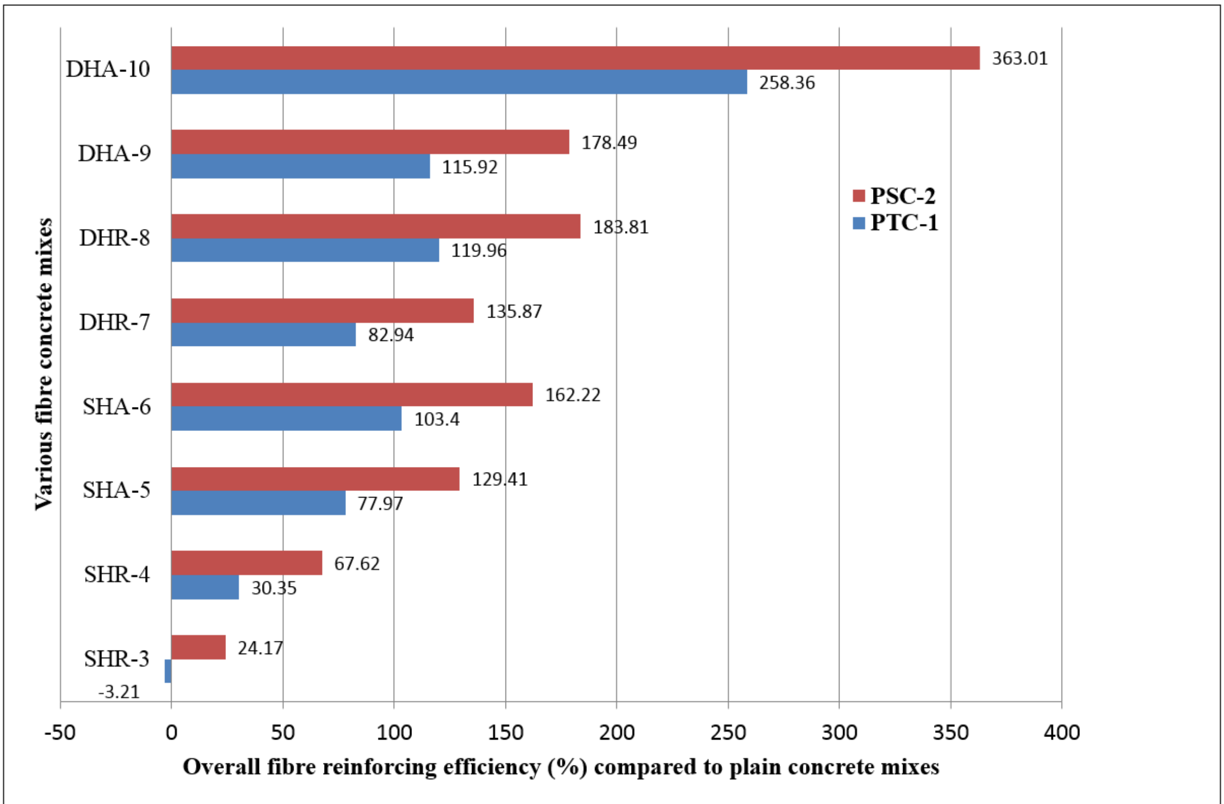

Fig. 16. Comparative assessment of fibre efficiency in various concretes.

4. Conclusions

Based on the test results obtained from this study, the following salient conclusions are drawn:

- The influence of aligned and randomly distributed steel fibres in high strength concrete matrix had been investigated in slender plain fibre concrete sections (PSC-2) and the reinforcing efficiency was compared with thick plain concrete sections (PTC-1).
- Fibre performance in concrete is dependent on the workability of concrete mix and hence in the present study steel fibre addition is restricted to a maximum dosage of 1% V_f to achieve a workable range of 90 to 100mm slump.
- Steel fibres added in high strength concrete had shown marginal decrease on the concrete compressive strength; as it could be justified that steel fibres were not strained effectively to carry stress in compressive

direction. However, the residual compressive strength index was found to be satisfactorily higher in fibre substituted concrete mixes.

- Bending fracture properties of fibre concretes were relatively higher than plain concretes. The effect of steel fibres in aligned direction had shown consistently improved fracture strength than randomly distributed fibre concretes and a maximum fracture strength of 7.01 N/mm^2 was reported for double hooked fibre concrete (DHA-10).
- Bending fracture properties were greatly improved in double hooked steel fibre substituted concretes compared to single hooked steel fibre concretes; Since, the anchorage reinforcing efficiency of double hooked steel fibres were consistently higher.
- Fracture toughness of fibre concretes was also consistently higher at increased fibre volume fraction upto 1.0% and a maximum toughness value of 955 N/m was obtained for double hooked fibre concrete mixes (DHA-10). However, the effects of high fibre volume were significant in aligned fibre concrete mixes compared to randomly distributed fibre concrete mixes.
- Fracture energy of fibre concretes with aligned steel fibres (SHA-6, DHA-10) was reportedly higher at increased fibre volume substitution. Since the fibre reinforcing efficiency of aligned fibres was appreciably higher than unaligned fibres owing to fibre effectiveness in load transfer capacity.
- The real benefits of steel fibre addition were achieved in terms of size reduction properties of concrete in slender concrete beams. Steel fibres at high fibre volume (1.0% V_f) had shown adequate evidence of similar fracture strength as compared to that of thick concrete sections,
- The significant findings from this study showed that steel fibres can be suitably used to reduce the thickness of concrete elements. Also, the comparative assessment of slender concrete sections had witnessed fracture resistance on par that of thick concrete sections. Reinforcing efficiency of steel fibres are better realized when it is aligned in the concrete matrix normal to the loading plane. Hence, the effective dispersion of aligned fibres in slender concrete sections can enhance the matrix strengthening and provide better fracture properties.

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