Impact of the Fiber Distribution Characteristics on the Uniaxial Behaviour of Fiber-Reinforced Composites- An Experimental Study

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Abstract

The demand for development of fiber-reinforced composites has enhanced as the practise of integrating fibres into concrete has become prevalent over the past few decades.. The intersection zone where the fiber crossing the fracture surface and fiber distribution characteristics in the composite plays an important role in predicting the overall performance of the Fiber Reinforced Composite (FRC). To ascertain the orientation and distribution of the fibres in various FRC's, a variety of experimental methods have been proposed in the literature. This study aimed to assess the impact of fibre orientation and fibre distribution characteristics on the fresh and hardened properties of Hybrid FRC's and Hybrid Graded FRC's containing glass and steel fibres. It can be concluded that the methods adopted in this study for calculating the fiber distribution and orientation characteristics were reliable and the proposed equations were successful in predicting the uniaxial behaviour of FRC. Positive synergy was observed in the Hybrid Graded FRC specimens, which was attributed to the superior fibre distribution characteristics displayed by hybrid grading of fibres, which was rationalised by the fact that modifying the fibre distribution characteristics would affect the FRC’s behaviour.

Keywords: Fiber-reinforced composite; Fiber distribution characteristics; Graded fibers; Hybrid graded fibers; Uniaxial behaviour

1 Introduction

Fibers have long been employed in cement-based products to enhance material performance. The best-known attribute of fiber-reinforced composites is a significant increase in tensile strength and toughness (Prashanth et al.,1994; Zollo,1997). Other advantages of employing fibres include higher shear strength, resilience to dynamic stresses, and reduced shrinkage cracking (Ngo et al., 1994). Many types of fibres have been used to reinforce building materials, including concrete. Fiber Reinforced Concrete (FRC) typically uses either steel or glass fibres as reinforcement. High Strength Concrete (HSC) has been shown to be successful at higher stress levels (Singh et al., 2018) because of its increased strength and dense microstructure. HSC has very poor tensile strength and a brittle failure mode. Because of this, using fibres in HSC reinforcement projects increases mechanical characteristics and post-peak performance behaviour.

Most modern fiber-reinforced High Strength Concretes (FR-HSC) are made with a single fibre type that has a finite effectiveness called Mono Fiber-reinforced High Strength concretes (MFR-HSC). It was determined that the inclusion of mono fibres did not significantly enhance the composite as a whole (Kasagani et al., 2021). The Reinforcement of Hybrid Fibers to high strength concrete (HyFR-HSC), is extremely flexible and can be used in a variety of applications because of its ability to increase mechanical qualities and prevent multi-level cracking (Koniki et al., 2021). Positive synergy may be due to mixing fibres of varying lengths, diameters, and Young's moduli (Prathipati et al., 2020; Prathipati et al., 2021).

Different lengths of fibers incorporated into the composite will be beneficial in bridging of micro-cracks by short length fibers and long length fibers will address macro cracking and the composite formed by using both the fibers is called Graded Fiber Reinforced Concrete (GrFR-HSC) (Teja et al., 2021). Concrete's workability and mechanical qualities will be enhanced by using fibres of varying lengths instead of a single strand length (Doyon-Barbant et al., 2018). Therefore, Hybrid Graded Fiber-Reinforced High Strength Concrete (HyGrFR-HSC) refers to the practise of incorporating multiple types of graded fibres into a single batch of concrete in order to increase the mechanical properties of the concrete by making use of the modulus and geometry of the fibres in the blend (Koniki et al., 2021).

The FR-HSC's behaviours are significantly affected by fibre distribution features such the fibre orientation factor and fibre dispersion factor. The distribution of the fibres within the material affects their ability to serve as reinforcement (Doyon-Barbant et al., 2018). Poorly-distributed fibres in some areas offer little to no reinforcement, which causes flaws in the composite material. Uniformly scattered fibres reduce the maximum size of such faults, maximising reinforcing efficiency. Fiber dispersion characteristics influence FRC fresh state qualities and vice versa. Given that mechanical performance is significantly correlated with fresh state attributes & fibre dispersion characteristics, all of which must be controlled for optimal mechanical performance, increasing the number of fibres may improve mechanical qualities, however because fibres are not always aligned in the direction of stress, the effectiveness is questionable. Better would be the homogeneous distribution of fibers, which could enhance FRC performance in a structure at reduced cost. In addition to strength, ductility will also be addressed. The mechanical properties of the composite are improved by the fibres' uniform orientation and distribution (Prathipati et al., 2021a; Prathipati et al., 2021b). Therefore, in order to acquire the high-performance FRC, it is crucial to study the effects of fibre distribution characteristics on the mechanical properties of various FR- HSC's. This suggests that a proper analysis of the FR-HSC's mechanical performance necessitates an examination of fibre dispersion characteristics. Therefore, a reliable testing strategy was required to identify the characteristics of fibre distribution in the FRC mixtures, enabling a more appropriate relationship to be established between fibre distribution features and material behaviour.

X-ray transmission photography, electrical resistivity measurement, and image analysis approach are just a few of the experimental methods that can be used to evaluate the fibre dispersion properties in composites (Yang et al., 2018). The fibre distribution features of all the FRC specimens in this study were assessed using digital image analysis methodology, as suggested by Lee et al., (2003). The necessary specimen cross-section was removed and a picture of it was captured for use in the image analysis. By feeding the collected image into the software, the features of the fibre dispersion may be assessed. Although numerous researchers made use of image analysis, there were discrepancies in their interpretation of fibre dispersion features. In addition, there was a lack of information in the literature between the correlation of mechanical performance and fibre distribution characteristics for different types of FR-HSC's. Hence in this manuscript an investigation was attempted to figure out how different fibre distributions affect the functionality of MFR-HSC, HyFR-HSC and HyGrFR-HSC mixes. Fiber density, dispersion and orientation in the composite are computed by conducting image analysis.

2 Investigational Study

2.1 Materials

The materials used were of the following specific gravities: 3.13 for OPC 53 grade, 2.68 for fine aggregate (Zone-II River sand), and 2.78 for coarse aggregate (crushed granite, 10 mm nominal size). The combination of Silica Fume and Class F Fly Ash as two different SCMs were incorporated. The study employs potable water, Conplast SP430 as a superplasticizer, crimped steel fibres, and AR glass fibres. Fiber characteristics are summarised in Table 1.

Table 1: Fibers properties

Mixes	Steel (mm)		Diameter (mm)	Aspect Ratio		Elastic Modulus (GPa)	Tensile Stength (MPa)
Crimped Steel Fiber	25	50	0.5	50	100	200	1400
Alkali-Resistant Glass Fiber	6	12	0.0135	444	888	73	1168

2.2 Mix Proportions and Designations

The control mix of M70 grade concrete was made in accordance with Indian Standards (IS 10262, 2019). Water-binder ratio of 0.31 and mix proportion of 1:1.05:1.52 were determined from the trail mixes and used in this investigation. Steel fiber: lengths (25 mm & 50 mm), dosage (0.5%, 0.75%,1% & 1.25%) and Glass fiber: lengths (6 mm & 12 mm); dosage (0.1%, 0.2%,0.3% & 0.4%) are also included as independent variables. 1 Control Mix CM, 16 MFR-HSC Mixes were formed, 4 HyFR-HSC Mixes and 1 HyGrFR-HSC Mixes were formed in the study, and their respective mix denotations are given in Table 2 and Table 3.

Table 2: MFR-HSC Mix designations

Mix	Designation	Volume Fraction (%)	Steel Fiber		Glass Fiber	
			25 mm	50 mm	6 mm	12 mm
MFR-HSC	CM	0	-	-	-	-
	M1	0.5	100%			
	M2	0.75	100%			
	M3	1	100%			
	M4	1.25	100%			
	M5	0.5		100%		
	M6	0.75		100%		
	M7	1		100%		
	M8	1.25		100%		
	M9	0.1			100%	
	M10	0.2			100%	
	M11	0.3			100%	
	M12	0.4			100%	
	M13	0.1				100%
	M14	0.2				100%
	M15	0.3				100%
	M16	0.4				100%

Table 3: HyFR-HSC & HyGrFR-HSC Mix designations

Mix	Designation	Volume Fraction (%)	Steel Fiber		Glass Fiber	
			25 mm	50 mm	6 mm	12 mm
HyFR-HSC	Hy1	1.65	100%	-	100%	-
	Hy2	1.65	-	100%	100%	-
	Hy3	1.65	100%	-	-	100%
	Hy4	1.65	-	100%	-	100%
HyGrFR-HSC	HyGr	1.65	50%	50%	50%	50%

2.3 Mixing and Testing Methodology

A pan mixer with a 100 kg capacity was used to mix the concrete. Both aggregates were introduced to the mixer separately at the first stage of mixing, where they were combined for one minute. In the second step, the mixer received different additions of fly ash, cement, glass fibres, and steel fibres for an additional minute. The final step involved thoroughly mixing water and superplasticizer for an additional two minutes to create a uniform mixture. Concrete is poured into moulds, which are then compacted on the vibrating table. The specimens were demolded and allowed to cure for 28 days after casting for 24 hours.For evaluating the compressive strength of all the mixes, steel cube moulds of 100 mm were chosen. According to IS: 516-1959 , compressive strength of all mixes was evaluated in the current investigation using a 1000 kN servo-controlled test system. For the uniaxial tensile test, we employed a dog bone specimen measuring 150 mm in length and 80 mm by 40 mm in cross section. Displacement (at a rate of 0.2 mm/s) was controlled using a servo-hydraulic testing frame. After tensile testing, the damaged samples were chopped with a concrete cutter until the crack was nearly invisible by maintaining the cross-sectional size after cutting at 80 mm by 40 mm. Each failure plane specimen was polished and smoothed using a grinding machine before being photographed using an optical microscope. Micrographs are processed in Image J, with the RGB image converted to greyscale and the scale calibrated. A thresholding method is used to transform a grayscale image into a binary one, and the fibres were discovered in the binary image. There will be an analysis of the fibre distribution parameters, including fibre count, major axis length, and minor axis length. It was not until much later that the fibre dispersion properties were established.

3 Experimental Outcomes

3.1 Compressive Strength

Below, Figure 1 represents the compressive strength of all the different mixtures. There is a shift in the compressive strength of concrete produced using MFR-HSC mixes whenever there is an increase in either the fibre length or the fibre volume. There was an improvement in compressive strength values for MFR-HSC mixes when the volume of glass fibre was increased from 0.1 percent to 0.3 percent and when the volume of steel fibre was increased from 0.2 percent to 1 percent. With an increase in glass fibre length from 6 mm to 20 mm and steel fibre length from 25 mm to 50 mm, compressive strength values decreased regardless of fibre content. When compared the compressive strength values of HyFR-HSC and HyGrFR-HSC mixes from the figure 2, it can be observed that hybridizing fibers at higher volume fraction has resulted in the decrimental effect and which can be compensated by hybridizing graded fibers.

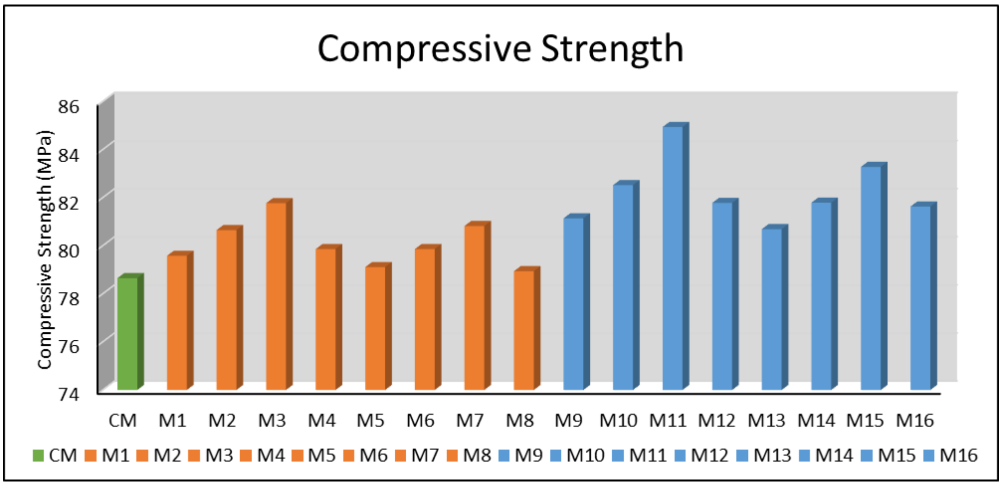

Fig. 1: Compressive Strength of MFR-HSC mixes

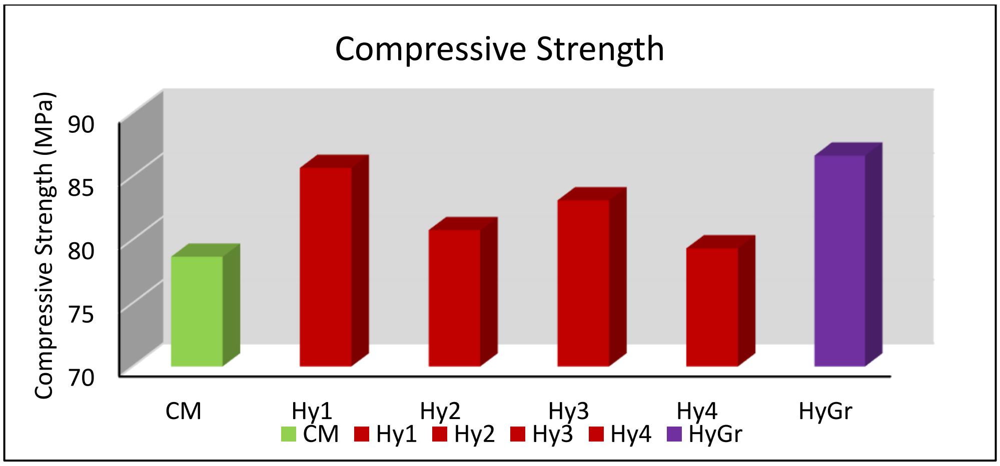

Fig. 2: Compressive Strength of HyFR-HSC and HyGrFR-HSC mixes

3.2 Tensile Strength

In the Figure 3 below, we can see that the hybridization of graded fibres has increased the direct tensile strength of the HyGrFR-HSC mixes in comparison with HyFR-HSC mixes and this can be validated by evaluating the fiber dispersion characteristics of the HyFR-HSC and HyGrFR-HSC mixes and presented in the next section.

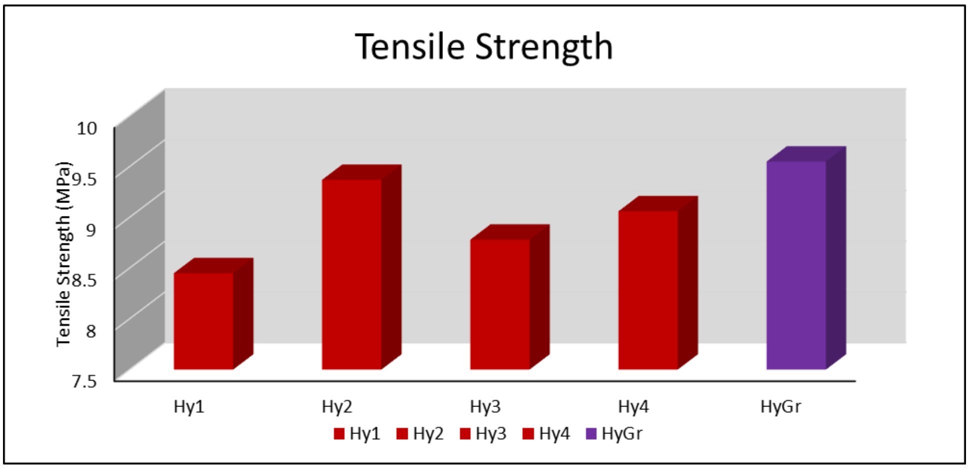

Fig. 3: Tensile Strength of HyFR-HSC and HyGrFR-HSC mixes

3.3 Fiber Dispersion Characteristics

By determining the distribution coefficient (η_d), also known as the fibre dispersion coefficient, as determined by Lee et al., (2009) and given in Eq (1), the orientation coefficient (η_θ) was calculated by superimposing an image of a fibre on a broken plane and dividing the minor axis length by the main axis length of the fibre. The Eq (2) was used to calculate the η_θ. Fiber length affects the Fiber Length Coefficient (η_l). Equations (3) and (4) yield η_l under the assumption of a uniform interfacial shear stress transfer. (Chiang, 1994).

$$\eta_d = exp\left[\sqrt{\frac{\Sigma(x_i - 1)^2}{n}}\right] \qquad (1)$$

$$\eta_\theta = \frac{1}{n}\sum_{i=1}^{n}\frac{bi}{ai} \qquad (2)$$

$$\text{For } L_f < Lc \;\; \eta_l = L_f / 2L_c \qquad (3)$$

$$\text{For } L_f \geq L_c \;\; \eta_l = 1-(L_c / 2L_f) \qquad (4)$$

n : total number of fibers at the image's grid location.

x_i : *i*th square's fibre count.

ai & bi : major & minor axis of the fiber's elliptical imprint on the cutting plane.

L_f & L_c : fiber length and fiber critical transfer length.

The values of η_d, η_Θ and η_l for HyFR-HSC and HyGrFR-HSC mixes were computed and are presented in Table 4 below.

Table 4: Fiber distribution, fiber orientation and fiber length coefficients of HyFr-HSC&HyGrFR-HSC mixes

Mix (1)	**Mix Designation (2)**	**η_d (3)**	**η_θ (4)**	**η_l (5)**
HyFR-HSC	Hy1	0.421	0.470	0.449
	Hy2	0.466	0.544	0.466
	Hy3	0.401	0.536	0.509
	Hy4	0.372	0.548	0.526
HyGrFR-HSC	HyGr	0.479	0.529	0.488

4 Analytical Modeling

The law of mixtures can be used to measure the tensile strength of a composite (σ_{ct}). Fiber contribution to composite strength is determined by fibre orientation and distribution. As a result, the tensile capabilities of composites are primarily influenced by the dispersion, orientation, and quantity of fibres in the cracking area, as well as fibre dispersion parameters. The frequently used Rule of Mixtures equation was modified by Kasagani, et al., (2019), which introduced the fibre dispersion coefficient (d) to account for fibre dispersion in the fracture plane, is used to forecast tensile strength and is given in below equation

$$\sigma_{ct} = \eta_d\, \eta_\theta\, \eta_l\, V_f\, \sigma_{fu} + V_m\, \sigma_{mt} \qquad (5)$$

The experimental peak tensile stress values for all the mixes are given in column 4 of Table 5. The tensile strength of fibre reinforced composite for HyFR-HSC, and HyGrFR-HSC mixes for M70 grade is calculated using equation (5), and the results are shown in column 3 of Table 5. Table 5, column 5, shows the comparison between calculated and experimental composite strengths. From Figure 4 which represents the plot of Analytical vs Experimental Composite Tensile Strength of HyFR-HSC & HyGrFR-HSC mixes, it is clear that the values for composite strength obtained from Equation 5 are remarkably similar to the experimental values. Further analysis of Table 5 reveals that HyGrFR-HSC specimens outperformed HyFR-HSC specimens in terms of positive synergy. This is due to the superior fibre distribution characteristics displayed by hybrid fibre grading, which is supported by the idea that changing the fibre distribution characteristics will affect FRC behaviour.

Table 5: Experimental and Theoretical Tensile strength of HyFr-HSC&HyGrFR-HSC mixes

Mix (1)	**Mix Designation (2)**	**$\sigma_{ct} = \eta_d \eta_\theta \eta_l V_f \sigma_{fu} + V_m \sigma_{mt}$ (3)**	**Experimental Peak Stress (4)**	**Ratio of Theoretical stress to Experimental stress (5)**
HyFRC	Hy1	8.14	8.45	0.96
	Hy2	8.94	9.37	0.95
	Hy3	8.71	8.78	0.99
	Hy4	8.65	9.06	0.95
HyGrFRC	HyGr	9.39	9.55	0.98

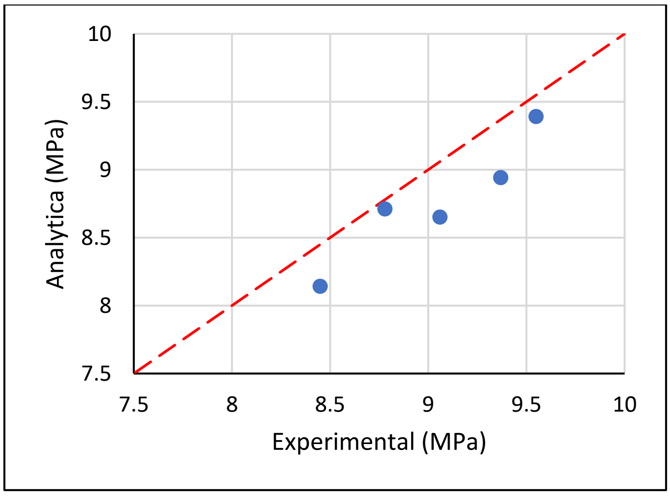

Fig. 4: Analytical vs Experimental Composite Tensile Strength of HyFR-HSC & HyGrFR-HSC

5 Conclusion

The following are some of the important conclusions drawn from this study:

- Irrespective of fiber length in MFR-HSC mixes glass fiber with 0.3% fiber volume and steel fiber with 1% fiber volume have exhibited higher compressive strength.
- When compared to HyFR-HSC mixes, the peak stresses under both compression and tension improved for HyGrFR-HSC mixes.
- HyGrFR-HSC mixes have shown higher values of fiber dispersion coefficient (η_d), fiber orientation coefficient (η_θ) and fiber length coefficient (η_l) when compared to HyFR-HSC mixes at the same fiber volume fraction and thereby indicating better fiber distribution and fiber pullout strength in HyGrFR-HSC mixes.
- It has been found that the composite's strength in uniaxial tension is affected by the fibre dispersion, fibre orientation, and fibre embedded length. In this investigation, the tensile strength of the composite was estimated using an equation that takes into account the aforementioned properties, and the predicted values are more in line with the experimental values.

The mechanical properties and fibre dispersion characteristics of Hybrid Graded FRC incorporating steel and glass fibres were only studied in this study; therefore, in the future, the impact of using fibers of varying geometries on the properties of HyGrFRC will be studied.

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