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Mechanical Behavior of Hybrid Fiber Reinforced High Strength Concrete with Graded Fibers

S. R. R. Teja Prathipati*[a], C. B. K. Rao[a], N. R. Dakshina Murthy[b]

[a] *Department of Civil Engineering, National Institute of Technology Warangal, Telangana, India*
[b] *Civil Engineering Department, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad, Telangana State, India*

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ABSTRACT

Brittleness, which was the inherent weakness in High Strength Concrete (HSC), can be avoided by reinforcing the concrete with discontinuous fibers. Reinforcing HSC with more than one fiber is advantageous in an overall improvement of the mechanical performance of the composite. In this experimental study, Hybrid Fiber Reinforced High Strength Concrete (HyFR-HSC) mixes were formed by blending single length glass fiber and single length steel fiber with a total volume fraction of 1.65% into the concrete and Hybrid Graded Fiber Reinforced High Strength Concrete (HyGrFR-HSC) mixes were obtained by mixing different lengths of glass fiber with different length of steel fibers at a total volume fraction of 1.65% into the concrete. A comparative study was made between HyFR-HSC and HyGrFR-HSC specimens to investigate the effect of fiber grading on strength properties and the uniaxial compressive behaviour of HSC with hybrid fibers. In both HyFRC and HyGrFRC mixes, glass fibers improved the pre-peak behaviour, and steel fibers improved the post-peak behaviour of concrete, thereby exhibiting a positive synergy in combining glass and steel fiber into the concrete. Among the two-hybrid FRC's, HyGrFRC outperformed HyFRC with substantial improvement in both strength and ductility. Among all the HyGrFRC mixes, HyGr9 mix, which contain a higher amount of long-length fibers exhibited better improvement in peak strain, ductility factor, total energy and toughness index. The replacement of single length of fibers with graded length fibers at higher volume fraction in HyFRC is useful in improving workability, thereby providing better fiber dispersion and thus enhances both the pre-peak and post-peak performance of the concrete. From this investigation, it can be inferred that grading of fibers improved the mechanical behaviour of HyFRC by exhibiting positive synergy from both fiber geometry and fiber type.

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NOMENCLATURE

PM	Plain Mix	GrFRC	Graded Fiber Reinforced Concrete
HSC	High Strength Concrete	HyFR-HSC	Hybrid Fiber Reinforced High Strength Concrete
FRC	Fiber Reinforced Concrete	HyGrFR-HSC	Hybrid Graded Fiber Reinforced High Strength Concrete (HSC)

1. INTRODUCTION

Due to the higher strength and dense microstructure of High Strength Concrete (HSC), its application in diversified structures reduces the overall dimensions of the structural element with reduced dead weight, making it technically and economically viable solution in large scale infrastructure projects. At larger stress levels, HSC materials have performed effectively [1]. Despite abundant advantages of High Strength Concrete (HSC) over normal strength concrete, HSC was considered to be brittle material due to its minor fracture process zone [2]. So there is a need to enhance the strength and ductility of HSC by adding fibers, which

*Corresponding Author Email: *praviteja@student.nitw.ac.in* (S. R. R. Teja Prathipati)

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can control crack coalescence and propagation in concrete.

The mechanism of fiber action in the formation and propagation of crack growth in conventional FRCs is that after the formation of the first crack, the presence of fiber will prevent sudden failure and allows the load transfer across the crack [3,4]. The utilisation of discontinuous steel fibers into composite has improved the load-carrying capacity [5-7]. Addition of glass fibers in HSC was proved to be efficient in changing the failure mode of the composite from brittle to ductile [8]. Fiber-reinforced concretes produced today consist of a single fiber type that is only effective up to a limited level [9]. Reinforcing concrete with more than one fiber has been proved to be efficient in improving the strength and ductility of the composite [10].

Hybrid Fibre Reinforced concrete (HyFRC) is one of the versatile kinds of composite that uses more than one fiber, which improves the mechanical properties and arrests the multi-scale cracking in the concrete [11,12]. The use of steel fibers and glass fibers in the concrete under uniaxial stress will eliminate sudden failure as well as improves strength and toughness [13,14]. Fiber synergy can be achieved by combining different lengths, different diameters, and different Young's modulus of the fibers [15]. The inclusion of fibers of different lengths into the concrete will be useful in arresting cack at different levels, thereby improving the pre-peak and post-peak performance of the composite. The mechanical properties and the workability of the concrete will be enhanced by blending two different lengths of fibers instead of adding single length fiber at higher volume fraction [16]. The blending of different length fibers into concrete is termed as Graded Fiber Reinforced Concrete (GrFRC) [17]. GrFRC is a sub-classification of HyFRC. The strength and deformation behaviour under uniaxial stress was significantly improved by adding graded glass fibers into the concrete [17]. Addition of graded fibers into the concrete was proved to be advantageous and therefore, in this study hybridisation of graded steel fibers and graded glass fibers for use in concrete was attempted.

The majority of the research work was carried out on Hybrid Fiber Reinforced High Strength Concrete (HyFR-HSC) using different Young's modulus of the fibers and different geometries of fibers individually. According to some researchers, addition of fibers at lower volume is not much effective in enhancing the properties of concrete. But at higher volume fraction, due to the workability issues caused by higher relative surface area, there was not much improvement in the mechanical properties of the HyFRC. Therefore a new type of Hybrid FR-HSC called Hybrid Graded Fibre Reinforced High Strength Concrete (HyGrFR-HSC) in which different types of fibers are added in different lengths into the concrete was developed to overcome the problem of lower workability and improve the mechanical behaviour. A limited amount of research work was carried out on the behaviour of HyFR-HSC obtained by combining different types of fibers in graded form. In this study, the strength and uniaxial compressive behaviour of HyGrFR-HSC was investigated and reported. In this research work, crimped steel fibers 25mm and 50mm with aspect ratio 50 and 100 respectively and AR glass fibers 6 mm and 12 mm with aspect ratio 428 and 856 were used, and they are graded independently at first, and then they are hybridised to form HyGrFR-HSC. The objective of this research work is to study the behaviour of HyFR-HSC and HyGrFR-HSC under uniaxial stress.

Following the introduction section, the structure of the manuscript is designed as follows: Materials, mixing and curing, and testing methodology are described in section 2. Results and discussions are given in section 3 and finally concluding remarks are reported in section 4.

2. EXPERIMENTAL PROGRAM

Figure 1 represents the research methodology used in this study.

2. 1. Materials Ordinary Portland Cement (OPC) having a compressive strength of 53 Mpa with a specific gravity of 3.11, standard consistency of 33%, initial setting time is 48 mins, and final setting time is 125 mins was used in the mix. Fine aggregate from a nearby river source with a specific gravity of 2.68 and fineness modulus of 3.44 was used. Crushed granite of 10 mm nominal size as coarse aggregate with a specific gravity of 2.78 and fineness modulus of 7.1 was used. The water used for mixing and curing is Potable water. Superplasticizer used in the mix is Conplast SP430. Class F fly ash conforming to ASTM C618 [19] was used in the study. The fibers used in the study were

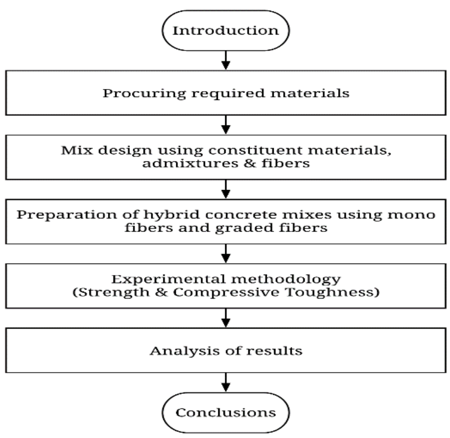

Figure 1. Research Methodology Flow chart

crimped steel fiber of length 25mm and 50mm with a constant diameter 0.5mm and Alkali Resistant glass fiber of length 6mm and 12mm with filament diameter 13.5 μ was used in the study. Table 1 provides information about the properties of fibers used in the study.

2. 2. Mix Proportions High strength concrete mix was designed as per ASTMC192 [20], and the mix proportions are tabulated in Table 2.

2. 3. Volume Proportions of Fibers Used In this investigation, alkali-resistant glass fibers of two different lengths and crimped steel fibers of two different lengths with a total fiber volume fraction of 1.65% were mixed in varying percentages and combinations to the concrete to obtain 13 HyFR-HSC and HyGrFR-HSC mixes. The first four HyFR-HSC mixes, Hy1 to Hy4 was obtained by blending glass and steel fiber in the mono form to the concrete. Mixes HyGr1 to HyGr9 mixes were obtained by hybridising graded glass and graded steel fibers into the concrete. Table 3 provides a schematic view of the experimental program used in this study.

2. 4. Mixing and Curing Fine and coarse aggregates were combined together into a homogeneous blend. Cement and fly ash were independently blended, and then glass fibres were scattered into the cement and fly ash blend. The contents were then placed into the pan mixer limit of 100 kg. Steel fiber was added to the mixer and mixed for another one minute. Finally, water was added along with superplasticiser and the contents thoroughly mixed. Proper homogeneous mixing was ensured by continuous mixing for 4-8 min. A slump test was conducted to ensure the workability of the plain concrete mix, HyFRC mixes and HyGrFRC mixes before casting. After the completion of the casting, all the specimens were kept to maintain the ambient conditions for 24 hours. The specimens were removed from the mould and were cured for 28 days.

TABLE 1. Fiber Properties

Property	Steel Fiber		Glass Fiber	
Length (mm)	25	50	6	12
Diameter (mm)	0.5	0.5	0.0135	0.0135
Aspect ratio	50	100	444	888
Elastic modulus (GPa)	200	200	73	73
Tensile strength (MPa)	1168	1168	1400	1400

TABLE 2. Mix Proportions

Cement (kg/m^3)	Flyash (kg/m^3)	Silica Fume (kg/m^3)	Water (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)
500	100	38	198	970	664

TABLE 3. Mix Designation

Specimen	Glass fiber length		Steel fiber length	
	6mm (G1)	12mm (G2)	25mm (S1)	50mm (S2)
	V_f (Glass) = 0.4%		V_f (Steel) = 1.25%	
PM	–	–	–	–
Hy1	100%	–	100%	–
Hy2	–	100%	100%	–
Hy3	100%	–	–	100%
Hy4	–	100%	–	100%
HyGr1	75%	25%	75%	25%
HyGr2	50%	50%	75%	25%
HyGr3	25%	75%	75%	25%
HyGr4	75%	25%	50%	50%
HyGr5	50%	50%	50%	50%
HyGr6	25%	75%	50%	50%
HyGr7	75%	25%	25%	75%
HyGr8	50%	50%	25%	75%
HyGr9	25%	75%	25%	75%

2. 5. Testing of Specimens A total number of forty-two cubical specimens (100 x 100 x 100 mm^3) and forty-two beam specimens (100 x 100 x 500 mm^3) for fourteen mixes were cast and tested for compressive strength and flexural strength. Forty-two cylindrical specimens (300mm height and 150mm diameter) were cast and tested to obtain stress-strain curves in compression. In this study, a 1000 kN servo-controlled test machine was used for testing specimens, which was shown in Figure 2.

3. RESULTS AND DISCUSSION

The uniaxial compressive and uniaxial tensile behaviour for the HyFR-HSC and HyGrFR-HSC specimens were discussed in the below sections.

3. 1. Compressive Strength For a total of 14 mixes, which include plain, hybrid, and hybrid graded mixes, the compressive strength values are given in Table 4. The compressive strength of the plain concrete mix was 78.65 Mpa. The compressive strength values for HyFR-HSC and HyGrFR-HSC are presented in Figure 3. The compressive strength improved marginally by using hybrid fibers at higher volume fraction. The percentage improvement of strength was

Figure 2. 1000kN servo-controlled test setup

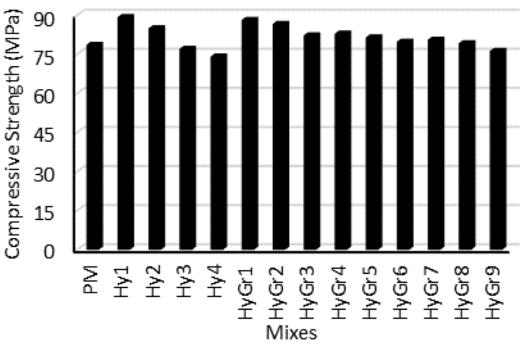

Figure 3. Compressive strength variation for different hybrid mixes

around 14%. The obtained values of compressive strength improvement were in good agreement with Vandewalle, L [11]. Among the hybrid mixes, the mixes which contain a higher amount of short fibers exhibited better performance in the enhancement of compressive strength, and this may be due to the better dispersion of short length fibers that arrest micro crack and improves the peak strength. In the hybrid combination, glass fiber with short length has contributed towards the increment of compressive strength, and this may be due to more number of fiber availability in the mix. Hy4 has the lowest compressive strength value among all the hybrid FR-HSC's, and this may be due to the balling effect of fibers, which was caused by using higher aspect ratio fibers at higher volume fraction.

3. 2. Flexural Strength The flexural strength of the plain concrete mix was 7.38 Mpa. The flexural strength values for HyFR-HSC and HyGrFR-HSC mixes are presented in Figure 4. The maximum improvement of flexural strength was 44% for the HyGr9 combination. Dawood et al. [10] also reported that similar improvement in flexural strength was observed with the addition of hybrid fibers. Hybrid fiber mixes exhibited a significant increase of flexural strength, and this may be due to the crack arresting mechanism by hybrid fiber, which delays the crack formation and propagation. It was evident that there was an apparent bridging effect provided by hybrid fibers, which reduced the crack widths and improved the flexural strength. The mixes which contain the longer fibers were much useful in the improvement of flexural strength, and this may be due to the enhanced bridging effect of larger cracks by longer fibers.

3. 3. Stress-Strain Behavior in Compression The uni-axial compressive stress-strain curves for plain concrete, HyFR-HSC, and HyGrFR-HSC specimens were drawn in Figure 5 for each mix by taking an average of three specimens. Addition of glass/steel fibers to the concrete exhibited a large number of cracks

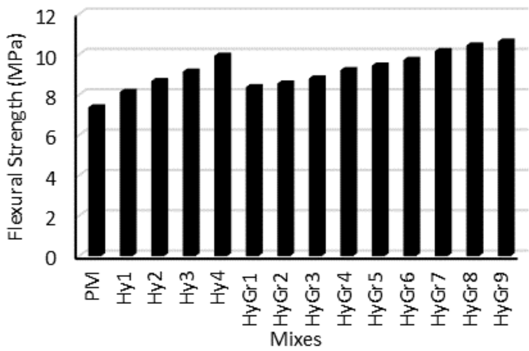

Figure 4. Flexural strength variation for different hybrid mixes

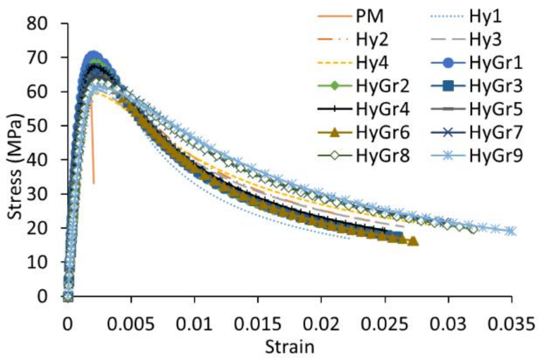

Figure 5. Uniaxial compressive stress-strain curve for hybrid mixes

before failure, thereby modifying the brittle failure pattern of the plain concrete. The softening part of the stress-strain curve of FR-HSC was improved with the addition of steel fiber/glass fiber.

The initial portion of the ascending part of the stress-strain curve of FRC was linear, and after reaching the peak stress, the stress values gradually decreased in the descending part at higher strain values. The salient properties that represent the uniaxial compressive stress-strain behaviour are peak stress, peak strain, ductility factor, and energy absorption capacity. From the stress-strain curves, for both the HyFR-HSC and HyGrFR-HSC specimens, the before said properties were extracted and presented in Table 4.

Plain concrete specimens without fibers exhibited brittle failure without any improvement in post-peak toughness. Both HyFR-HSC and HyGrFR-HSC specimens have shown ductile failure due to the bridging effect which was provided by hybrid fiber. Similar findings were given by Lihua Xu et al. [15], in which they stated that reinforcing concrete with hybrid fiber has a favorable effect in the improvement of the ductility. Glass fibers that were present in the hybrid FR-HSC were useful in the pre-peak zone by contributing towards the improvement of the peak stress of concrete by arresting the micro-cracks and the steel fibers will be effective in the post-peak behavior of concrete by capturing macro crack and by increasing toughness of the composite. Both the HyFR-HSC and HyGrFR-HSC specimens obtained by blending steel and glass fibers into the concrete arrested the cracks at different levels and improved both the strength and toughness of the composite.

With the addition of hybrid fiber into the concrete, the maximum improvement of peak stress was about 17% whereas the improvement of peak strain was 25%. By reinforcing hybrid fibers and hybrid graded fibers into the concrete, there was a significant improvement in the ductility factor, energy absorption and toughness index. Similar behaviour was observed by Ahmed et al. [18], in which they reported that hybrid fiber has a favorable reinforcement effect on uniaxial compression.

From Figure 6, it was clearly understood that the post-peak part of the stress-strain curve of HyGrFR-HSC specimens was significantly improved by hybridizing the graded fibers, which were not exhibited by HyFR-HSC specimens and the similar behaviour was reported by Kasagani, Hanuma et al. [16] . This was attributed to the multiple cracking failure pattern (formation of microcracks in the vicinity of the macro crack) of HyGrFR-HSC specimens. Among all the hybrid combinations, HyGr9 performed much better in terms of ductility factor, energy absorbed, and toughness index values.

TABLE 4. Salient Properties of Stress-Strain curve of Hybrid FRC under uniaxial compression

Mix	Peak Stress	Peak Strain	Ductility Factor	Total Energy (kJ/m^3)	Tough-ness Index
PM	60.73	0.00208	-	84.01	-
Hy1	70.85	0.02228	3.44	77 7.84	9.26
Hy2	67.79	0.02454	4.63	949.48	10.31
Hy3	60.74	0.02645	5.01	968.58	11.25
Hy4	59.41	0.02857	5.35	1018.18	12.12
HyGr1	69.61	0.02385	3.81	867.29	10.32
HyGr2	68.33	0.02385	3.89	906.67	10.79
HyGr3	66.93	0.02599	4.21	950.21	11.31
HyGr4	68.44	0.02498	4.25	942.27	11.22
HyGr5	67.27	0.02567	4.47	974.78	11.63
HyGr6	65.87	0.02730	4.54	1048.27	12.48
HyGr7	67.48	0.02985	4.94	1171.18	13.94
HyGr8	66.41	0.03212	5.52	1285.82	15.31
HyGr9	66.24	0.03558	5.82	1468.81	17.48

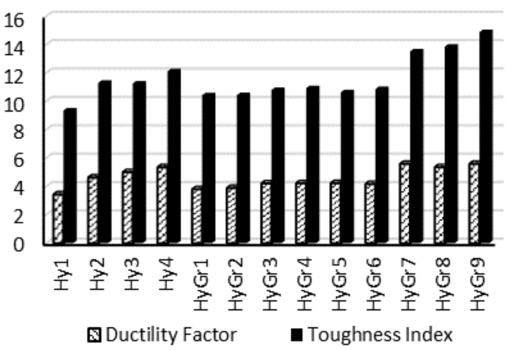

Figure 6. Ductility Factor and Toughness Index for different hybrid mixes

4. CONCLUSIONS

With an increasing in frequency of the applications of HyFRC in the present days, an understanding of the effect of different types of graded fibers on the properties of HyFRC is needed. In this paper, the mechanical behaviour of high strength concrete incorporating graded steel fiber and graded glass fiber in hybrid form was evaluated in terms of strength and toughness properties. Compressive strength, flexural strength, and uniaxial compressive stress-strain curves for HyFR-HSC and HyGrFR-HSC mixes have been investigated, and the following conclusions were drawn:

1. In both the HyFR-HSC and HyGrF-HSRC mixes, addition of short length glass fibers and short length

steel fibers have proved to be advantageous in the enhancement of peak stress, and this may be due to the more number of fiber availability with better dispersion in the composite.

2. HyGrFR-HSC mixes with a higher percentage of large fiber have exhibited significant improvement in flexural strength, and this may be due to the enhanced fiber bridging capacity of long-length fibers.

3. In HyFR-HSC and HyGrFR-HSC mixes, glass fibers improved the pre-peak behaviour of concrete by controlling the microcrack propagation and steel fiber is to enhance the post-peak response by seizing the broadening of macro crack.

4. Among the hybrid fiber mixes, HyGr9 performed much better in terms of failure strain, ductility factor, energy absorbed, and toughness index values performed better in all aspects.

5. The improvement in ductility, energy absorption, and toughness index of HyGrFR-HSC specimens was significant when compared to that of HyFR-HSC specimens at 1.65% fiber volume fraction, and this may be due to the advantage of hybridising the graded fibers.

Addition of graded steel and graded glass fibers into the high strength concrete have improved the ductility and toughness of the composite and thereby it can be used in the beam-column joints. Hybrid graded fiber-reinforced beam-column joints could be an excellent choice in the high seismic zones where high energy absorption capacity is required. From the above study, it can be deduced that utilisation of graded steel fibers and graded glass fibers in the HyFRC has proven to be a promising beneficial alternative to the use of mono fibers in the HyFRC.

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Persian Abstract

چکیده

شکنندگی، که ضعف ذاتی در بتن با مقاومت بالا (HSC) بوده ، با تقویت بتن با الیاف ناپیوسته می توان از آن جلوگیری کرد. تقویت HSC با بیش از یک فیبر در بهبود کلی عملکرد مکانیکی کامپوزیت سودمند است. در این مطالعه تجربی ، مخلوط بتن با مقاومت بالا از جنس فیبر ترکیبی (HyFR-HSC) با مخلوط کردن الیاف شیشه ای تک طول و الیاف فولادی تک طول با کسری از حجم ۱.۶۵ به داخل بتن و بتن با مقاومت بالا تقویت شده با فیبر ترکیبی تشکیل شد مخلوط (HyGrFR-HSC) با مخلوط کردن طول های مختلف الیاف شیشه ای با طول های مختلف الیاف فولادی در کسری از حجم کلی ۱.۶۵٪ در بتن بدست آمد. یک مطالعه مقایسه ای بین نمونه های HyFR-HSC و HyGrFR-HSC برای بررسی تأثیر درجه بندی فیبر بر خواص مقاومت و رفتار فشاری یک محوره HSC با الیاف ترکیبی انجام شد. در هر دو مخلوط HyFRC و HyGrFRC ، الیاف شیشه ای رفتار پیش از اوج را بهبود بخشیده و الیاف فولادی رفتار پس از اوج بتن را بهبود بخشیده و از این طریق یک هم افزایی مثبت در ترکیب شیشه و فیبر فولادی در بتن به نمایش می گذارند. در میان FRC دو هیبریدی ، HyGrFRC از پیشرفت HyFRC با پیشرفت چشمگیر در قدرت و انعطاف پذیری بالاتر عمل کرده است. در بین تمام مخلوط های HyGrFRC ، مخلوط HyGr9 ، که حاوی مقدار بیشتری از الیاف با طول طولانی است ، پیشرفت بهتری در کرنش اوج ، ضریب انعطاف پذیری ، کل انرژی و شاخص چقرمگی نشان می دهد. جایگزینی الیاف طول یکنواخت با الیاف طول درجه بندی شده در کسر حجمی بالاتر در HyFRC در بهبود کارآیی مفید است ، از این طریق پراکندگی بهتر فیبر را فراهم می کند و بدین ترتیب عملکرد قبل از اوج و پس از اوج بتن را افزایش می دهد. از این تحقیق ، می توان نتیجه گرفت که درجه بندی الیاف با نشان دادن هم افزایی مثبت از هر دو هندسه فیبر و نوع فیبر ، رفتار مکانیکی HyFRC را بهبود بخشیده است.