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TECHNICAL PAPER

A study on the uniaxial compressive behaviour of graded fiber reinforced concrete using glass fiber/steel fiber

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Abstract

Hybrid fiber reinforced concrete (HyFRC) effectively utilises the combined benefits of different fiber types present in it for enhancing its properties. The mechanical behaviour of HyFRC with varying lengths of fibers was not completely understood to date, and hence, this study focuses on the uniaxial compressive behaviour of HyFRC with two different fiber lengths. In the first phase of the study, fresh properties and the uniaxial compressive behaviour of M30 grade mono glass fiber reinforced concrete (MGFRC) reinforced with glass fibers of 6 mm and 12 mm length and M30 grade mono steel fiber reinforced concrete (MSFRC) using crimped steel fibers of 25 mm and 50 mm length were evaluated and reported. In the second phase of investigation, fresh properties and uniaxial compressive behaviour of graded fiber reinforced concrete (GrFRC), obtained by blending two different lengths of fibers (Glass Fiber/Steel Fiber) were evaluated and reported. From the results, the uniaxial compressive response of the concrete was improved by the addition of glass fiber or steel fiber to the concrete. Graded FRC exhibited better synergy compared to Mono FRC in uniaxial compression for both glass and steel fiber reinforced concrete. Among all the MGFRC and GrGFRC mixes, GrGI combination (75% short length glass fiber + 25% long length glass fiber) grading of glass fibers exhibited better performance, similarly, of all MSFRC and GrSFRC mixes, GrSIII combination (25% short length steel fiber + 75% long length steel fiber) grading of steel fibers exhibited better performance. The addition of graded glass fibers to the concrete enhances the pre peak behaviour of the stress–strain curve considerably, and the addition of graded steel fibers to the concrete improves the post peak behaviour of the stress–strain curve remarkably. From this study, we can conclude that adding graded fibers (glass fiber/steel fiber) has proved to be advantageous in enhancing the uniaxial compressive behaviour of concrete.

Keywords Hybrid fiber reinforced concrete · Graded fiber reinforced concrete · Alkali resistant glass fibers · Crimped steel fibers · Uniaxial compression · Compressive stress–strain behaviour

Introduction

Concrete, a composite material, is weak in tension, and thus, the tensile strength of concrete in reinforced concrete structures is neglected. By adding fibers to the concrete, crack coalescence and propagation can be controlled, which helps in the improvement of its tensile strength, thereby making the concrete ductile. Concrete reinforced with the discontinuous fibers has been designated as fiber reinforced concrete (FRC) [1]. FRC, thus formed, has a considerable improvement in the tensile stress, flexural strength, absorption capacity and toughness as compared to plain concrete [2]. The role of fibers in the formation and propagation of cracks in conventional FRCs is that after the formation of the first crack, the presence of fiber at the crack will prevent sudden failure and allows the load transfer across the crack. In this process, crack widening is controlled, and the width is reduced by fiber bridging. Depending on the fiber volume fraction and fiber characteristics, further increase in the load leads to fiber pull-out or fiber rupture [3].

Many attempts were made to enhance the strength and toughness of the cement concrete by reinforcing it with different types of short and discrete fibers[3]. Different kinds of fibers such as metallic, polymeric or natural fibers are commonly used in cement composite matterials [4]. The addition of well dispersed and well oriented short length

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glass fibers improves the strength of the composite substantially [5, 6]. The introduction of steel fibers into the concrete significantly enhances its ductility and toughness [7–10]. Reinforcing the concrete with single type of fiber shows limited improvement in the mechanical properties of concrete. So, the inclusion of a single type of fiber to the composite improves either its strength or toughness but not both [11]. In comparison with Mono type FRC, HyFRC enhances the ductility, toughness, energy absorption and durability of the composite [12].

Fibers of different young's moduli, lengths and functions were blended into the concrete to form hybrid fiber reinforced concrete (HyFRC) [13–19]. The resulting composite uses the advantages from each fiber type and exhibits a positive synergy [20–22]. For example, reinforcing concrete with steel fiber provides better strengthening effect than reinforcing concrete with carbon fiber and in the same way reinforcing concrete with carbon fibers provides better toughness than reinforcing concrete with steel fibers. But when both steel fibers and carbon fibers are mixed into the concrete in hybrid form, there is a significant improvement in both the strength and toughness of the HyFRC [23]. HyFRC with steel and polypropylene fibers utilises the advantages of both the fiber types, where high modulus steel fibers improve the ultimate strength of the composite, and polypropylene fibers of lower modulus control the improvement in the ductility of concrete [24]. Yao, W et al. (2003) [25] investigated the mechanical properties of HyFRC (steel–polypropylene, polypropylene–carbon and steel–carbon) at low fiber volume fraction of 0.5%. HyFRC with the combination of carbon–steel fibers exhibited the best performance in terms of higher strength and flexural toughness among all the considered fiber combinations because of similar modulus, graded in length and synergetic interaction of the fibers. HyFRC with steel fibers and glass fibers exhibited better improvement in compressive strength, split tensile strength and load-failure characteristics among the HyFRC's with steel-glass, steel-basalt and glass-basalt fibers [26]. The majority of the researchers has worked in the area of HyFRC with fibers of different young's moduli, whereas work on HyFRC with varying lengths of fibers was limited.

Formation of the micro-cracks in concrete can be arrested by short randomly dispersed fibers, which improve the peak strength of the composite [27–29]. After the widening of micro-cracks into macro cracks, the short fibers will be pulled out, and then fibers with long lengths resist the growth of macro cracks by bridging them. With the increase in fiber length, enhancement in ductility and toughness was observed in the post-peak phase [30]. Concrete reinforced with single length fibers is termed as mono fiber reinforced concrete (MFRC). Adding single length fibers alone will not be sufficient in enhancing the strength and toughness of the composite [31]. Incorporation of fibers of different lengths into the concrete, mitigates the formation and propagation of cracks effectively, where short length fibers resist the formation of cracks and long length fibers bridge the macro cracks.

When fibers are added to the concrete in higher volume, mechanical properties can be improved significantly, but the uniform dispersion of fibers gets affected and leads to balling, which may not help in the overall improvement of mechanical properties. The problem of balling can be avoided with graded fibers. The mechanical properties and the workability of the concrete can be improved by blending two different lengths of fibers instead of adding single length fiber at higher volume fraction [32]. Concrete made with the addition of fibers of two or more different lengths is termed as graded fiber reinforced concrete (GrFRC), which will be beneficial in controlling different scales of cracking and contributing to increment in pre-peak strength and post-peak deformation [33].

Some of the previous investigations on the grading of fiber in concrete have been identified and presented in this paragraph. The addition of a combination of 4 mm length PVA fibers and 12 mm length PVA fibers into the concrete exhibited higher pre-crack strength, post-crack strength and strain capacity compared to that of composite with single fiber length [1]. Using a mixture of different lengths of polyvinyl alcohol fibers in various combinations of volume fractions improves average first crack stress and also enhances post-peak ductility of concrete compared to monotype fiber reinforced concrete [22]. Grading of glass fibers of different lengths into the concrete effectively controls different scales of cracking and thereby improving both the pre peak and post peak performance of the composite [5]. The workability of the concrete with long and short corrugated steel fibers at different volume fractions can be improved by increasing the percentage of short fibers [34]. Blending of steel fibers of short and long lengths into the concrete enhances the strength and ductility of the concrete significantly [35, 36]. In ultra-high performance concrete, which involves the mixing of different types of steel macro and micro fibers, it was reported that microfibers affect the strain hardening behaviour and multiple cracking, while the macro fiber type affects the shape of stress–strain curve [37].

Research significance

The effectiveness of adding graded glass fibers into the concrete for improving the mechanical properties was already established by other researchers, whereas studies on the impact of graded fibers on enhancing the toughness by improving the stress–strain behaviour were limited. In this investigation, the behaviour of the stress–strain curve for graded fiber reinforced concrete was studied and compared with mono fiber counterparts with the same volume fractions. Further, the effect of graded fibers on SFRC and GFRC was identified and reported.

In this investigation, glass fibers of 6 mm length and 12 mm length were added independently and combinedly to form mono glass fiber reinforced concrete (MGFRC) and graded glass fiber reinforced cconcrete (GrGFRC), respectively. Similarly, steel fiber of 25 mm length and 50 mm length were added independently and combinedly to form mono steel fiber reinforced concrete (MSFRC) and graded steel fiber reinforced concrete (GrSFRC), respectively. The uniaxial compressive behaviour of plain concrete, mono FRC and graded FRC was investigated by analysing the stress–strain curves in compression.

Experimental program

Materials

Ordinary portland cement (OPC) of 53 grade with a specific gravity of 3.11, standard consistency of 33% was used in the present study whose chemical composition is given in Table 1. The initial and final setting time of the cement were 48 min and 125 min, respectively, conforming to IS 12269 [38]. Fine aggregate from a nearby river source with a specific gravity of 2.68 and fineness modulus of 3.44, complying with IS 383 [39], was used. As coarse aggregate, crushed granite of 10 mm nominal size with a specific gravity of 2.78 and fineness modulus of 7.1 conforming to IS 383 [39] was used. Superplasticizer used for the mix was Conplast SP430. Grade II fly ash used in the present study in accordance with IS 3812-Part 1 [40]. Steel fibers (crimped) of length 25 mm and 50 mm with a diameter of 0.5 mm and Alkali Resistant (AR) glass fibers of length 6 mm and 12 mm with filament diameter of 13.5 µm were used. The fiber properties are presented in Table 2.

Mix proportions

The required concrete mix was obtained in accordance with IS10262-2009 [41], and the mix proportions for M30 grade concrete are given in Table 3.

Table 1 Chemical composition of cement

Chemical composition	OPC (%)
CaO	62.20
SiO_2	20.56
Al_2O_3	5.16
Fe_2O_3	3.6
MgO	2.5
Loss of Ignition (LOI)	3.58

Table 2 Properties of fibers

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

Volume proportion of fibers

Mono fiber reinforced concrete

Mono fiber reinforced concrete (MFRC) obtained by adding single length fibers into concrete was studied in the first phase of the experimental program. Glass fibers of two different lengths, 6 mm and 12 mm (represented as G1 and G2) were added to concrete in four different volume fractions 0.1%, 0.2%, 0.3% and 0.4% (represented as F1, F2, F3 and F4, respectively) to form eight mono glass fiber reinforced concrete (MGFRC) mixes. Steel fibers of two different lengths, 25 mm and 50 mm (represented as S1 and S2) were added to concrete in four different volume fractions 0.5%, 0.75%, 1% and 1.25% (represented as V1, V2, V3 and V4, respectively) to form eight mono steel fiber reinforced concrete (MSFRC) mixes. The mix designations and their respective volume proportions used for MFRC are given in Table 4.

Graded fiber reinforced concrete

Glass fibers of lengths G1 and G2 were mixed in three different combinations, i.e. (I: 75% (G1) + 25% (G2), II: 50% (G1) + 50% (G2) and III: 25% (G1) + 75% (G2) at two different fiber volume fractions 0.3% and 0.4% to the concrete to form six graded glass fiber reinforced concrete (GrGFRC) mixes. Similarly, steel fibers of lengths S1 and S2 were mixed in three different combinations, i.e. (I: 75% (S1) + 25% (S2), II: 50% (S1) + 50% (S2) and III: 25% (S1) + 75% (S2) at two different fiber volume fractions 1% and 1.25% to the concrete to form six graded steel fiber reinforced concrete (GrSFRC) mixes. The mix designations and their respective volume proportions used for GrFRC are given in Table 5.

Mixing and curing

The concrete was mixed in a pan mixer of 100 kg capacity. In the first stage of mixing, both the aggregates were added separately to the mixer and mixed for one minute. In the second stage, fly ash, cement and glass fibers/ steel fibers were added separately into the mixer and mixed

Table 3 Mix proportions for M30 grade of concrete

Mix	Cement (kg/m$^{3)}$	Fly ash (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	SP430 (kg/m^3)
M30	300	100	178	1450	764	1.0

Table 4 Volume proportions for MFRC

S. no	Mix designation	V_f (%)	Length of glass fiber		Length of steel fiber	
			6 mm	12 mm	25 mm	50 mm
1	Plain	0	–	–	–	–
2	MG1F1	0.1	100%	–	–	–
3	MG1F2	0.2				
4	MG1F3	0.3				
5	MG1F4	0.4				
6	MG2F1	0.1	–	100%	–	–
7	MG2F2	0.2				
8	MG2F3	0.3				
9	MG2F4	0.4				
10	MS1V1	0.5	–	–	100%	–
11	MS1V2	0.75				
12	MS1V3	1				
13	MS1V4	1.25				
14	MS2V1	0.5	–	–	–	100%
15	MS2V2	0.75				
16	MS2V3	1				
17	MS2V4	1.25				

Table 5 Volume proportions for GrFRC

S. no	Mix designation	V_f (%)	Length of glass fiber		Length of steel fiber	
			6 mm	12 mm	25 mm	50 mm
1	GrGI-0.3	0.3	75%	25%	–	
2	GrGII-0.3		50%	50%		
3	GrGIII-0.3		25%	75%		
4	GrGI-0.4	0.4	75%	25%	–	
5	GrGII-0.4		50%	50%		
6	GrGIII-0.4		25%	75%		
7	GrSI-1	1.00	–		75%	25%
8	GrSII-1				50%	50%
9	GrSIII-1				25%	75%
10	GrSI-1.25	1.25	–		75%	25%
11	GrSII-1.25				50%	50%
12	GrSIII-1.25				25%	75%

for one more minute. In the last step, water along with superplasticizer was added to the mixer and mixed thoroughly for another two minutes to obtain a homogeneous mix. Before placing the concrete into the moulds, the workability of each mix was measured by using the slump cone test. Moulds are filled with concrete and then compacted on the vibrating table. After 24 h of casting, the specimens were demoulded and were subjected to curing for 28 days. A total number of eighty seven cubical specimens ($100 \times 100 \times 100$ mm^3) was cast and tested for compressive strength. Also eighty seven cylindrical specimens (300 mm height and 150 mm dia) were cast and tested to obtain stress–strain curves in compression.

Testing methodology

Three concrete cubes for each concrete mix were tested under uniaxial compression as per IS: 516–1959 in 2000 KN Tinus-Olsen testing machine (TOTM) with loading rate of 14 N/mm^2/min and the compressive strength was obtained by taking an average of three specimens. Stress–strain curves for each mix were obtained by testing cylindrical specimens under uniaxial compression. Data acquisition system (DAC) with load cell and LVDTs were used to measure the load and corresponding displacements of the specimens (Fig. 1).

Fig. 1 LVDT's setup attached to the cylinder

Results and discussions

Results are discussed separately for both MFRC and GrFRC mixes in the below sections.

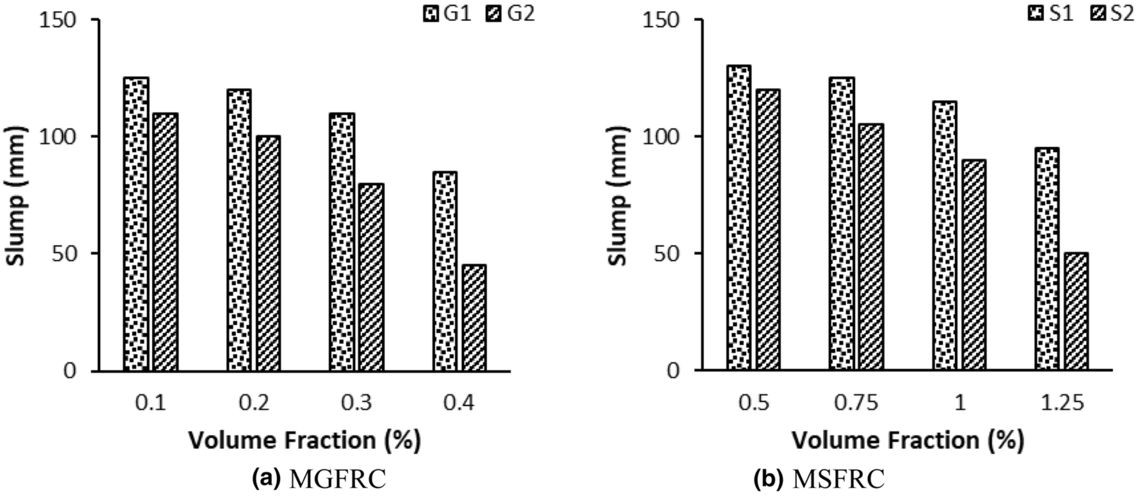
MFRC

The experimental results for both MGFRC and MSFRC specimens are discussed in the following sections.

Workability

The workability for each mix was measured during the time of casting by using a slump cone test apparatus, and the slump of the plain concrete was 165 mm. The slump values for MGFRC and MSFRC mixes are presented in Fig. 2.

With an increase in fiber volume from 0.1% to 0.4%, the workability of MGFRC decreased, and the slump values further reduced with the increase in fiber length from 6 to 12 mm. The workability was reduced with the increase in fiber length and fiber volume for MGFRC mixes, and this was more significant for the mix containing 12 mm glass fibers at a volume fraction of 0.4%. The workability of MSFRC reduced with increase in fiber percentage and fiber length, and this trend is similar to that of MGFRC. The loss of workability was substantial in the mix containing 50 mm steel fibers at a volume fraction of 1.25%. There seems to be an optimum fiber content for both MGFRC and MSFRC mixes upto which the workability increased and later on decreased and similar behaviour was observed by other researchers [2, 29]. Compared to MSFRC mixes, workability was slightly less for MGFRC mixes.



(a) MGFRC **(b)** MSFRC

Fig. 2 Workability of MFRC specimens

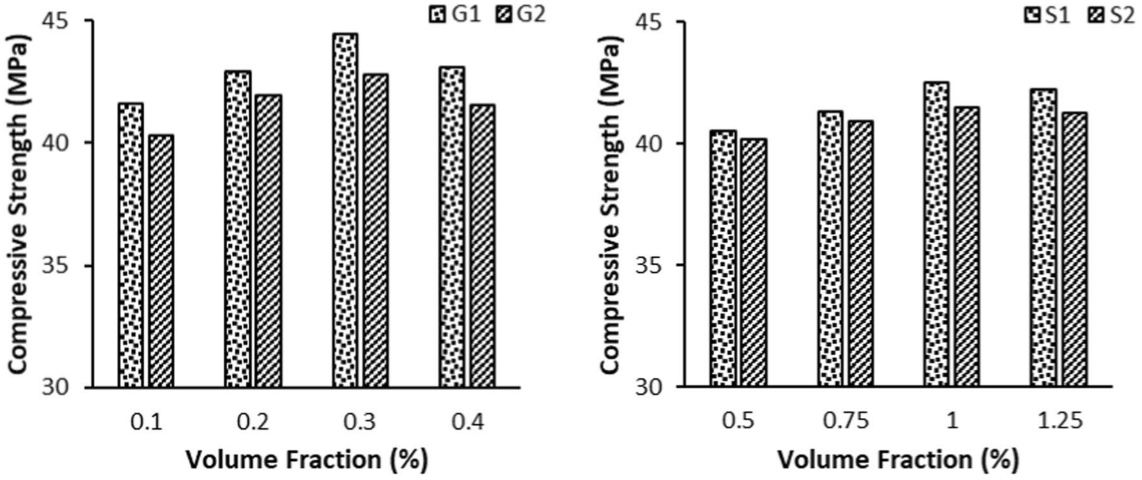
Compressive strength

The compressive strength of the plain concrete mix was 39.72 Mpa. The compressive strength values for MGFRC and MSFRC mixes are presented in Fig. 3. For MGFRC and MSFRC mixes, at lower fiber volume fraction, the improvement in the compressive strength was insignificant. The compressive strength for MGFRC mixes increased up to 0.3% fiber volume fraction and later decreased, and for MSFRC mixes, the compressive strength increased up to 1% fiber volume fraction and subsequently decreased. At higher fiber volume, there is a reduction in compressive strength which may be due to the balling of fibers as reported by other researchers [2, 15]. With an increase in the fiber length, the compressive strength values reduce for both MGFRC and MSFRC mixes irrespective of fiber volume fraction and similar research findings were reported by Betterman L et al. [1]. Compressive strength values of MGFRC mixes are on the higher side when compared to MSFRC mixes and this may be due to the availability of more number of well dispersed fibers in MGFRC mixes as described by Ali, B et al. [42].

Stress–strain behaviour in compression

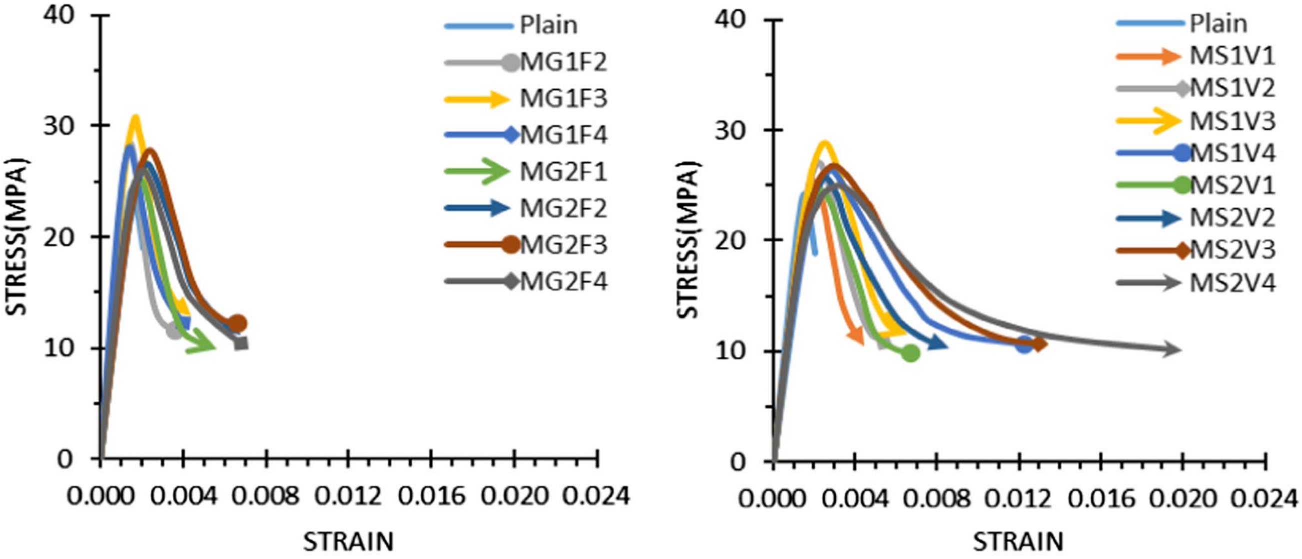
The uniaxial compressive stress–strain curves for MSFRC and MGFRC specimens are presented in Fig. 4 for each mix by taking an average of three specimens. The addition of glass/steel fibers to the concrete exhibited large number of cracks before failure, thereby modifying the brittle failure pattern of the plain concrete [15]. The softening part of the stress–strain curve of FRC was improved with the addition of glass/steel fibers. 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. MGFRC specimens have shown a rapid declination of stress in the post-peak softening region than MSFRC specimens. The salient properties that represent the uniaxial compressive stress–strain behaviour are initial slope, strengthening factor, ductility factor, strain softening slope and energy absorption capacity. From the stress–strain curves, for the MFRC specimens, the above mentioned salient properties were extracted and presented in Tables 6 and 7.

(a) Initial slope (E_i): The ratio of stress and strain in the linear portion of the stress–strain curve will give the Initial slope (E_i). For MGFRC specimens, E_i was computed and presented in column 3 of Table 6, and for MSFRC specimens, E_i is shown in column 3 of Table 7. Plain concrete reinforced with glass fibers enhances E_i values in contrary with the addition of steel fibers to the concrete. The improvement in E_i values may be attributed to the micro-crack arresting mechanism of glass fiber, which increased the stiffness of the material [42]. For both MGFRC and MSFRC specimens, E_i decreased with an increase in fiber length irrespective of fiber volume. The reason for the decrement in E_i for long length fiber was that with the increase in fiber length, there was a reduction in the number of fibers present at a section. With higher fiber volume, the initial slope decreased as the workability gets reduced, which in turn reduces the flowability of mix and thereby creating voids in the concrete matrix [43]. The decrement in initial stiffness was observed with long length fiber at higher fiber volume for both MGFRC and MSFRC specimens.



(a) MGFRC **(b)** MSFRC

Fig. 3 Compressive strength of MFRC specimens



(a) MGFRC **(b)** MSFRC

Fig. 4 Compressive stress–strain curve for MFRC

Table 6 Summary of test results of MGFRC in uniaxial compression

MIX (1)	V_f (%) (2)	E_i ($\times 10^4$) MPa (3)	STF (4)	DF (5)	E_{ss} ($\times 10^4$) MPa (6)	EA_{ssr} ($\times 10^{-2}$) N/mm (7)
Plain	0	1.81	1.00	1.311	1.074	0.011
MG1F1	0.1	2.51	1.09	1.600	1.595	0.016
MG1F2	0.2	2.41	1.18	1.712	1.307	0.024
MG1F3	0.3	2.27	1.27	1.794	1.056	0.032
MG1F4	0.4	1.94	1.16	1.871	0.912	0.036
MG2F1	0.1	1.61	1.04	1.638	0.663	0.037
MG2F2	0.2	1.54	1.10	1.759	0.598	0.045
MG2F3	0.3	1.53	1.15	1.866	0.557	0.048
MG2F4	0.4	1.24	1.08	2.029	0.518	0.052

Table 7 Summary of test results of MSFRC in uniaxial compression

MIX (1)	V_f (%) (2)	E_i ($\times 10^4$) MPa (3)	STF (4)	DF (5)	E_{ss} ($\times 10^4$) MPa (6)	EA_{ssr} ($\times 10^{-2}$) N/mm (7)
Plain	0	1.81	1.00	1.311	1.074	0.011
MS1V1	0.5	1.59	1.05	1.438	0.844	0.026
MS1V2	0.75	1.58	1.08	1.650	0.711	0.032
MS1V3	1	1.51	1.19	2.114	0.557	0.059
MS1V4	1.25	1.26	1.09	2.695	0.286	0.092
MS2V1	0.5	1.42	0.96	1.561	0.549	0.030
MS2V2	0.75	1.38	1.00	1.810	0.399	0.047
MS2V3	1	1.32	1.11	2.802	0.242	0.107
MS2V4	1.25	1.20	1.03	2.91	0.189	0.114

(b) Strengthening factor (STF): Strengthening factor (STF) is obtained by dividing the peak stress of FRC with plain concrete. For MGFRC and MSFRC specimens, STF was computed and reported in column 4 of Table 6 and column 4 of Table 7, respectively. MGFRC mixes exhibited higher STF values when compared with MSFRC mixes. For MGFRC mixes, STF increased with the increase in volume fraction upto 0.3%; thereafter, it decreased for any length of glass fiber. STF increased up to 1% volume fraction for MSFRC mixes, and after that it decreased for 1.25% fiber volume for any length of steel fiber. Balling of fibers at higher fiber volume, substantially lowers the workability, which inturn reduces the strength may be the reason for the decrement of STF [20]. For both the MFRC mixes with the increase in fiber length, STF decreases. This may be due to short length fibers, which helped to counter the macro crack opening by arresting the micro-cracks and enhancing the peak stress compared to long length fibers, and it leads to a higher strengthening factor.

(c) Ductility factor (DF): The ratio of the strain at an inflection point to the strain at peak stress is defined as Ductility Factor (DF). The inflection point was identified by the change in the slope in the descending potion of the stress–strain curve. The DF for MGFRC specimens were given in column 5 of Table 6, and DF for MSFRC were given in column 5 of Table 7. There was a significant improvement of DF values in MSFRC specimens when compared with MGFRC specimens. Long length fibers with higher fiber volume have higher DF values for both MGFRC and MSFRC specimens. Long length fibers and higher fiber volume fraction increased the DF by offering more resistance against lateral deformation [44]. MSFRC specimens exhibit higher DF compared to MGFRC specimens.

(d) Strain softening slope (E_{SS}): The ratio of change of stress to change of strain from peak point to the inflection point of strain softening region is called as strain softening slope (E_{SS}). E_{SS} values were calculated for MGFRC, and MSFRC specimens and are presented in column 6 of Table 6 and column 6 of Table 7, respectively. When compared with MSFRC specimens, MGFRC specimens have higher E_{SS} values because of the steepening of the curve. In the post-peak region, as the change of stress was more for short length fibers and the change of strain is more for long length fibers, E_{SS} decreases for long length fibers for both MSFRC and MGFRC specimens. E_{SS} values decrease for both MGFRC and MSFRC specimens at higher fiber volume, and this may be due to the flatter stress–strain curve in the descending portion. Hence, post peak deformations were observed to be more for concrete with long length fibers at higher volume fraction and hence have a lower E_{SS}.

(e) Energy absorption capacity (EA_{SSR}): Energy absorption capacity (EA_{SSR}) is calculated by measuring the area of the stress–strain diagram upto the inflection point, and EA_{SSR} for both the MGFRC and MSFRC were given in column 7 of Table 6 and column 7 of Table 7. MSFRC specimens have higher EA_{SSR} values than MGFRC mixes. As the length of fiber increased in the composite, it will control the macro crack propagation, and due to this, EA_{SSR} increased for both MGFRC and MSFRC and this agrees well with the findings of Bhargava P et al.[13]. Enhancement in EA_{SSR} values was observed for both MGFRC and MSFRC specimens at higher fiber volume. At higher volume fractions, the availability of fibers increased in the composite, and this will help to form dense mix and increased the energy absorption capacity of composite [32].

In brief, the discussion on the results obtained from MFRC specimens can be summarised as follows. The addition of mono steel fibers improved the descending portion of the stress–strain curve, and by adding mono glass fibers to the concrete, the ascending part of the stress–strain curve was enhanced. In MGFRC and MSFRC specimens, short length fibers exhibit higher strengthening factor and initial slope values, and long length fibers exhibit higher ductility factor and energy absorption capacity. From this, it can be observed that fibers with short length improved the peak strength of the FRC, and the inclusion of fibers with long length enhances the post-peak deformations of the FRC.

GrFRC

The results of the study for both GrGFRC and GrSFRC specimens are discussed as follows.

Workability

The slump values for GrGFRC and GrSFRC mixes are presented in Fig. 5. The addition of graded fibers to the concrete increased the slump values, thereby improving the workability of GrFRC mixes compared to MFRC mixes for their respective volume fractions and this agress well with the work done by other researchers [33, 34]. Also, the improvement in workability was more significant for GrGFRC mixes compared to GrSFRC mixes. From GrGI to GrGIII mixes and GrSI to GrSIII mixes, the slump values gradually decreased for their respective volume fractions, and this may be due to the increase in long length fiber volume from GrGI to GrGIII and GrSI to GrSIII.

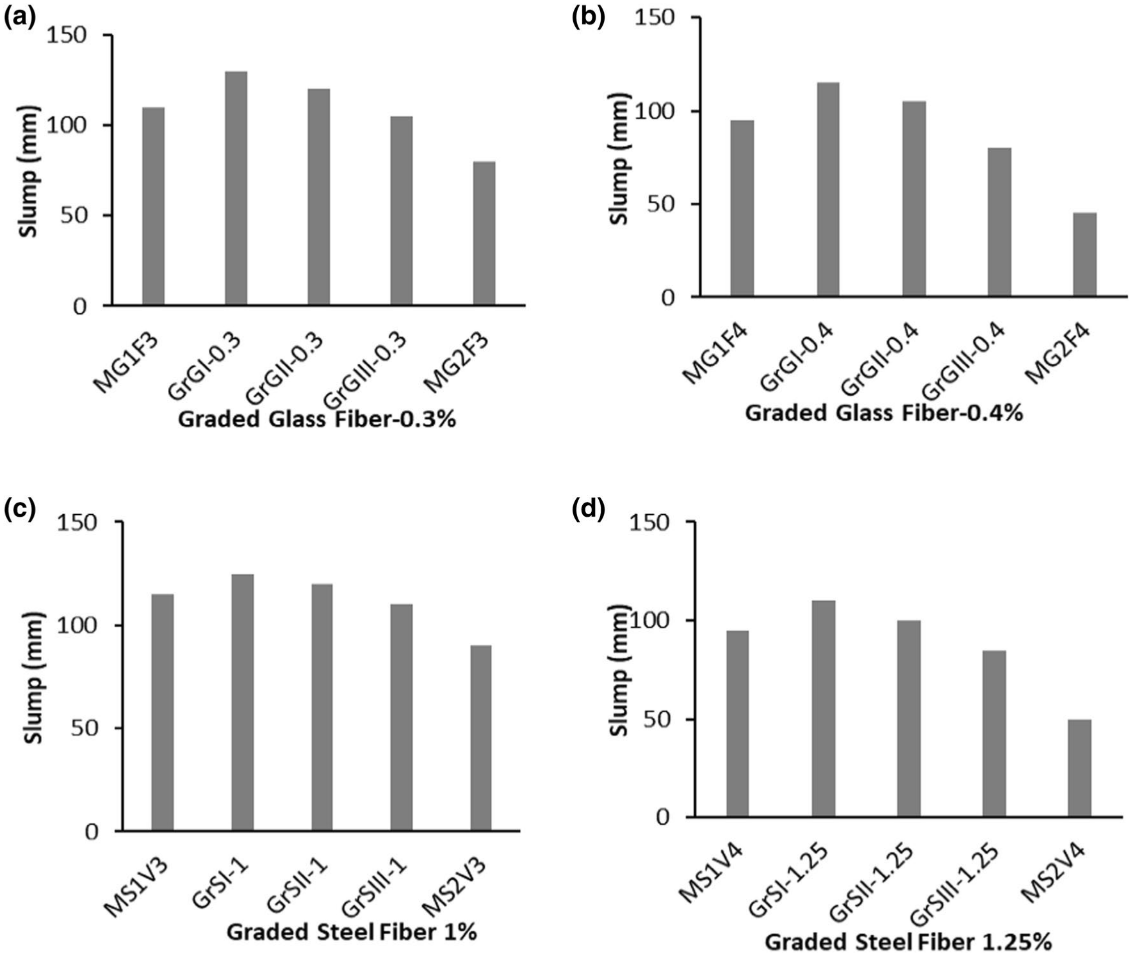


Fig. 5 Slump values for (**a**), (**b**) GrGFRC mixes—volume fraction 0.3% and 0.4% (**c**), (**d**) GrSFRC mixes—volume fraction 1% and 1.25%

Compressive strength

The compressive strength values for GrGFRC and GrSFRC are presented in Fig. 6. The compressive strength values of the composite increased by adding graded fibers. For GrGFRC, with the grading of glass fibers at 0.4% volume fraction slightly increased the compressive strength by 6% and for GrSFRC, the compressive strength improved slightly at 1.25% volume fraction. Mohammadi et al. [34] and Kasagani et al. [15] have also reported that grading of fibers into the concrete improved the compressive strength compared to addition of mono fibers into the concrete. The reason for the improvement may be due to fiber grading, which prevents the balling of fiber by the uniform distribution of fibers in the mix, and therefore, the formation of voids in the matrix was minimized in GrGFRC and GrSFRC specimens. Among GrGFRC and GrSFRC specimens, the improvement in compressive strength was substantial for GrGFRC specimens, and this is may be due to more number of glass fibers at the section. Among the three different combinations used in the grading, the combination I (75% short length fibers + 25% long length fibers) exhibit significant improvement in compressive strength for GrGFRC and GrSFRC specimens.

Stress–strain behaviour in compression

The stress–strain curves were plotted for GrFRC by taking average values of three specimens for each mix. The obtained stress–strain curves for graded fiber composites under uniaxial compression are presented in in Figs. 7 and 8, respectively. Uniaxial compressive behaviour of GrGFRC was compared with MGFRC for 0.3% and 0.4% volume fractions, and similarly, the compressive response of GrSFRC was compared with MSFRC for 1% and 1.25% volume fractions. The influence of graded glass fibers and graded steel fibers on the stress–strain curve in compression was studied. The values of Initial slope (E_i), Strengthening Factor (STF), Ductility Factor (DF), Strain Softening Slope (E_{ss}), and Energy Absorption (EA_{ssr}) of GrSFRC and GrGFRC were extracted and given in Tables 8 and 9.

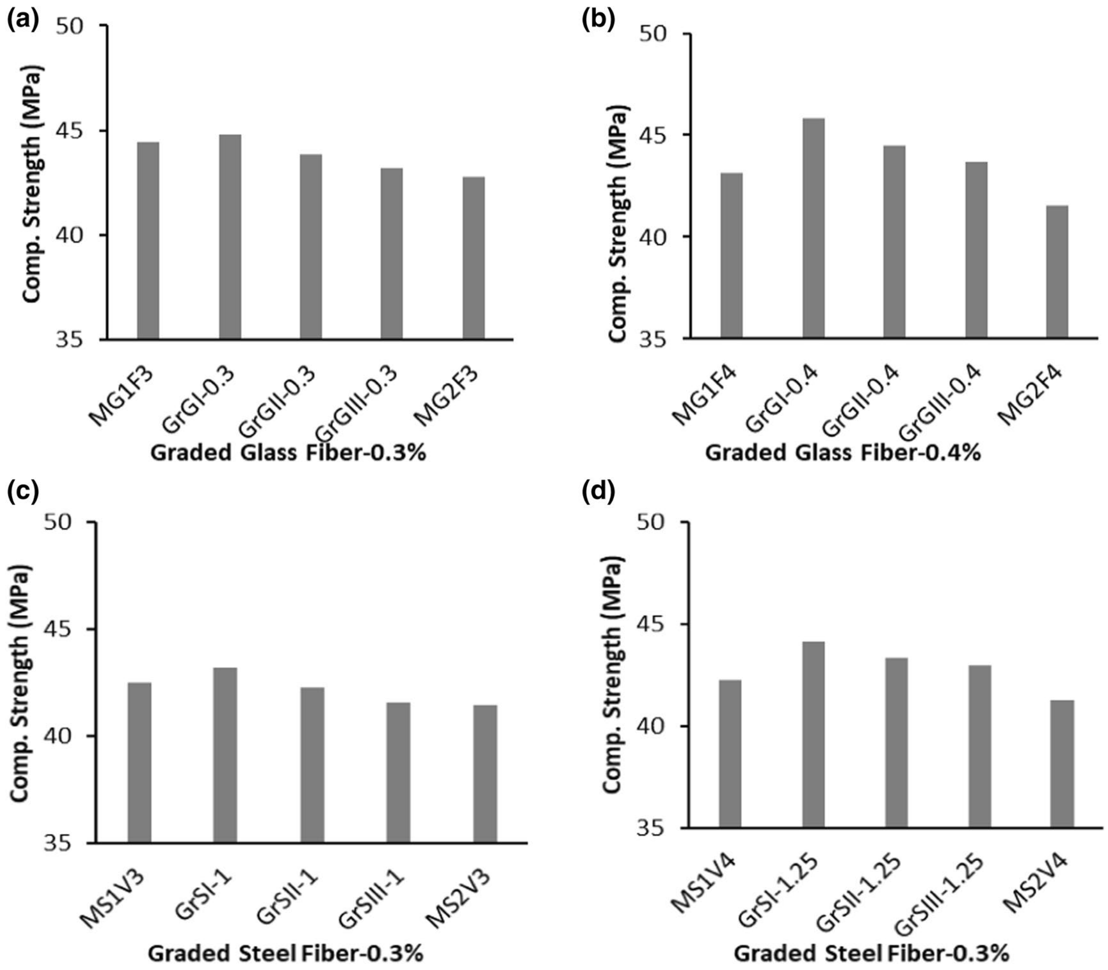


Fig. 6 Compressive strength values for GrFRC (**a**), (**b**) GrGFRC mixes—volume fraction 0.3% and 0.4% (**c**), (**d**) GrSFRC mixes—volume fraction 1% and 1.25

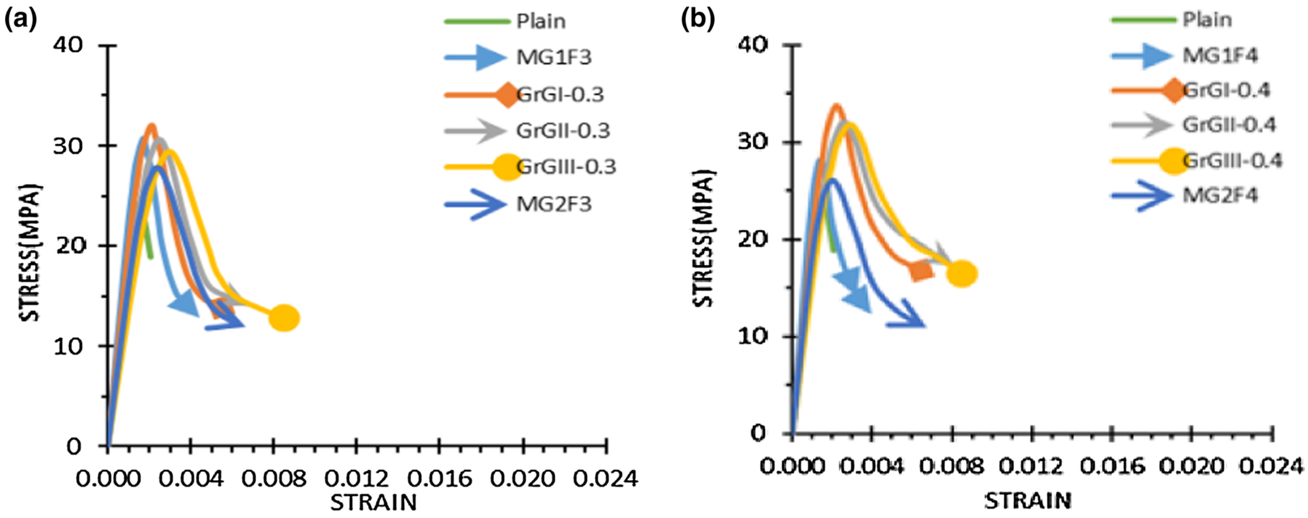


Fig. 7 Compressive stress–strain curve for (**a**), (**b**) GrGFRC specimens—volume fraction 0.3% and 0.4%

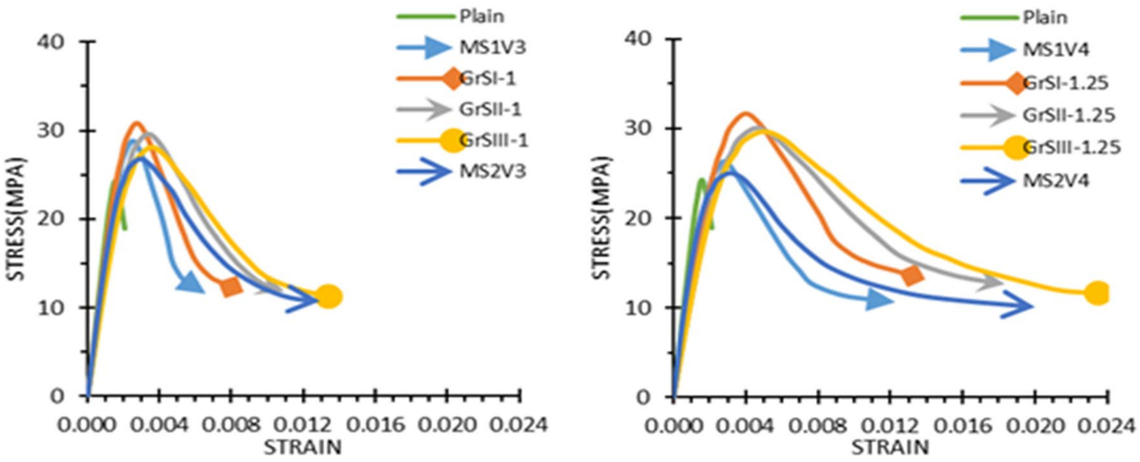


Fig. 8 Compressive stress–strain curve for (**a**), (**b**) GrSFRC specimens—volume fraction 1% and 1.25%

Table 8 Summary of test results of GrGFRC in uniaxial compression

MIX	V_f (%)	E_i ($\times 10^4$) Mpa	STF	DF	E_{ss} ($\times 10^4$) MPa	EA_{ssr} ($\times 10^{-2}$) N/mm
(1)	(2)	(3)	(4)	(5)	(6)	(7)
MG1F3	0.3	2.27	1.27	1.794	1.056	0.032
GrGI-0.3	0.3	1.93	1.32	1.882	0.837	0.045
GrGII-0.3	0.3	1.57	1.28	1.925	0.625	0.054
GrGIII-0.3	0.3	1.29	1.22	2.042	0.467	0.068
MG2F3	0.3	1.53	1.15	1.970	0.557	0.048
MG1F4	0.4	2.54	1.16	1.871	0.912	0.028
GrGI-0.4	0.4	1.96	1.40	1.919	0.619	0.058
GrGII-0.4	0.4	1.62	1.35	1.991	0.432	0.067
GrGIII-0.4	0.4	1.47	1.32	2.074	0.393	0.079
MG2F4	0.4	1.74	1.08	2.029	0.518	0.044

Table 9 Summary of test results of GrSFRC in uniaxial compression

	V_f (%)	E_i ($\times 10^4$) Mpa	STF	DF	E_{ss} ($\times 10^4$) MPa	EA_{ssr} ($\times 10^{-2}$) N/mm
(1)	(2)	(3)	(4)	(5)	(6)	(7)
MS1F3	1	1.51	1.19	2.114	0.557	0.059
GrSI-0.3	1	1.43	1.28	2.201	0.477	0.077
GrSII-0.3	1	1.22	1.22	2.485	0.294	0.111
GrSIII-0.3	1	1.18	1.16	2.876	0.233	0.133
MS2F3	1	1.32	1.11	2.802	0.242	0.107
MS1F4	1.25	1.26	1.09	2.695	0.286	0.092
GrSI-0.4	1.25	1.11	1.31	2.220	0.290	0.123
GrSII-0.4	1.25	0.98	1.25	2.802	0.217	0.189
GrSIII-0.4	1.25	0.94	1.23	3.404	0.159	0.230
MS2F4	1.25	1.20	1.03	2.802	0.189	0.110

(a) Initial slope (E_i): The Initial slope (E_i) values for GrGFRC and GrSFRC were computed and presented in column 3 of Table 8 and column 3 of Table 9, respectively. GrGFRC and GrSFRC specimens have shown E_i values lower than their respective mono FRC specimens. In GrGFRC specimens among the three combinations, 25% of 6 mm length + 75% of 12 mm length combination has given the lower initial slope values for both 0.3% and 0.4% volume fractions. Similarly, in the case of GrSFRC, specimens made of 25% of 25 mm length + 75% of 50 mm length combination has given the lower initial slope values compared to specimens made of other combinations for both 1% and 1.25% volume fractions. From this, we can conclude that the long length fibers present in GrGFRC and GrSFRC decreased the stiffness values and therby decreased the initial slope values [43]. GrGFRC specimens have higher E_i values than that of GrSFRC specimens, and this may be due to the confinement of the matrix with an increased number of glass fibers.

(b) Strengthening factor (STF): The values of Strengthening Factor (STF) for GrGFRC and GrSFRC were computed and presented in column 4 of Table 8 and column 4 of Table 9, respectively. In GrGFRC specimens, among the three combinations, 75% of 6-mm length + 25% of 12-mm length combination has given the highest STF than other GrGFRC and MGFRC specimens for both 0.3% and 0.4% volume fractions. Similarly, for GrSFRC, specimens made of 75% of 25-mm length + 25% of 50-mm length combination has given the highest STF compared to other GrSFRC and MSFRC specimens for both 1% and 1.25% volume fractions. GrGFRC specimens exhibited higher STF values than GrSFRC specimens, and this may be due to the micro-crack arresting mechanism of glass fiber, which enhanced the peak strength [15].

(c) Ductility factor (DF): The variation in Ductility Factor (DF) for GrGFRC and GrSFRC was computed and represented in column 5 of Table 8 and column 5 of Table 9, respectively. For GrGFRC specimens, among the three combinations, 25% of 6-mm length + 75% of 12-mm combination has given a considerable improvement in Ductility Factor values compared to other graded and mono glass FRC specimens for both 0.3% and 0.4% volume fractions. Similarly, in the case of GrSFRC, specimens of 25% of 25-mm length + 75% of 50-mm length combination have shown significant improvement in Ductility Factor values compared to other mono and graded steel FRC specimens for both 1% and 1.25% volume fractions. GrSFRC specimens exhibit higher DF values than GrGFRC specimens, and this may be due to the increment of post peak deformation for GrSFRC specimens.

(d) Strain softening slope (E_{SS}): The Strain Softening Slope (E_{SS}) values for GrGFRC and GrSFRC specimens were computed and presented in column 6 of Table 8 and column 6 of Table 9, respectively. In GrGFRC specimens, among the three combinations, 25% of 6 mm length + 75% of 12 mm length combination has shown the lower E_{SS} compared to other graded and mono glass FRC specimens for both 0.3% and 0.4% volume fractions. Similarly, in the case of GrSFRC, specimens made of 25% of 25 mm length + 75% of 50 mm length combination has given lower E_{SS} values than other graded and mono steel FRC specimens for both 1% and 1.25% volume fractions. In the strain softening region, the change in stress was more for GrGFRC specimens, and the change in strain was more for GrSFRC and due to this E_{SS} values were more significant for GrGFRC specimens.

(e) Energy absorption capacity (EA_{SSR}): The energy absorption capacity (EA_{SSR}) values in the strain softening region for the GrGFRC and GrSFRC specimens are given in column 7 of Table 8 and column 7 of Table 9, respectively. For the GrGFRC specimens, among the three combinations, 25% of 6 mm length + 75% of 12 mm length combination has given the higher EA_{SSR} compared to other mono and graded glass FRC specimens for both 0.3% and 0.4% volume fractions. Similarly, in the case of GrSFRC, specimens with 25% of 25 mm length + 75% of 50 mm length have given the higher EA_{SSR} compared to other mono and graded steel FRC specimens for both 1% and 1.25% volume fractions. This was due to less efficiency associated with short fiber in bridging macrocracks, which was completely pulled out from the matrix following the transformation of micro-cracks into macrocracks [45]. GrSFRC specimens exhibited significant improvement in EA_{SSR} than GrGFRC specimens, and this can be attributed to the improvement in the post-peak phase with a less steep slope for the GrSFRC specimens.

Comparison of GrGFRC and GrSFRC behaviour

Strength enhancement for graded glass fiber reinforced concrete specimens varied from 1.22 to 1.40, and for graded steel fiber reinforced concrete specimens, strength enhancement varied from 1.16 to 1.31. In GrGFRC and GrSFRC specimens, the specimens with more percentage of short length fiber have shown a substantial improvement in peak stress. Ductility values for GrGFRC were in the range of 1.882 to 2.074, and for GrSFRC, the ductility values were in the range of 2.201 to 3.404. In GrGFRC and GrSFRC specimens, the specimens with more percentage of long length fiber have shown a significant improvement in ductility. Therfore, the addition of graded glass fibers to the concrete exhibits better improvement of the pre-peak region, and inclusion of graded steel fibers to the concrete exhibits a better improvement of the post peak area of the stress strain curve.

Conclusions

The research results of Mono FRC and GrFRC were reported in this paper. Hybridisation of fibers consists of grading of different lengths of steel fiber and similarly that of glass fibers. The behaviour of Mono FRC and Graded FRC of glass and also of steel fibers in compression were compared. From the results of the experimental investigation, the following conclusions were drawn.

1. The addition of short length fibers, either glass fiber or steel fiber to the concrete, enhanced the stiffness and peak strength of the composite at higher fiber percentage, whereas the inclusion of long length fibers either steel fiber or glass fiber to the concrete enhanced the toughness and ductility of the composite.
2. Adding graded fibers (short and long length) to the concrete had shown the combined advantage of individual fibers, thereby improving the strength and toughness of the composite. In GrGFRC, (75% short length glass fiber + 25% long length glass fiber) combination of glass fibers exhibited better performance over other GFRC specimens, and in GrSFRC, (25% short length steel fiber + 75% long length steel fiber) combination of steel fibers exhibited improved performance over other SFRC specimens.
3. The workability of the concrete was reduced for MGFRC, and MSFRC mixes with an increase in fiber length and fiber volume, but for both the fiber types, the workability was improved when graded fibers were added to the composite, thereby improving its mechanical propeties.
4. Among GrGFRC and GrSFRC specimens, GrGFRC specimens have shown improvement in the ascending portion of the compressive stress–strain curve, thereby exhibiting significant improvement in the pre-peak region, whereas GrSFRC specimens have shown substantial improvement in the descending portion of the compressive stress–strain curve, thus exhibiting considerable improvement in the post-peak region.

From the above conclusions, utilisation of graded glass fibers and graded steel fibers in the FRC has proven to be a promising beneficial alternative to the use of mono fibers in the FRC.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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