



Effect of Glass Fiber on Fracture Energy of Plain Concrete

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Abstract. Concrete has a very low fracture energy and due to this, it cracks at very low load in brittle mode. The main objective of this study was to determine the effect of the addition of glass fiber on the fracture energy of plain concrete of grade C20/25 and C25/30. The percentage of glass fiber added ranges from 0% to 0.6% by volume with a constant increasing interval of 0.2%. The glass fiber are placed in three layers with equal amount placed at uniform interval. The test is performed according to RILEM TC 50 FMC recommendation following the Work of Fracture Method (WFM). It has been observed that addition of glass fiber increases the fracture energy of plain concrete very significantly and change the failure mode from brittle to ductile.

Keywords: Fracture energy · Glass fiber · Plain concrete

1 Introduction

Concrete is a composite material made up of fine and/or coarse aggregates, cementitious materials and water combined together to give artificial hardened material. Due to this nature of concrete, it usually fails in a brittle manner, which is undesirable characteristics in the use of concrete as a structural element. It cracks at a very small tensile load compared to its compressive capacity. During this early formation of crack, there will be a release of energy from the concrete. This release of energy from cracked surface is expressed in terms of the fracture energy of the material.

Fracture energy is defined as the amount of energy necessary to create a unit area of crack. The area of a crack is defined as the projected area on a plane parallel to the main crack direction. (RILEM TC 50- FMC Fracture Mechanics of Concrete 1985) It is found to increase around the crack tip, and is generally a function of displacement and not strain. It plays a significant role in determining the amount of ductility a structure exhibits.

Fiber is a natural or synthetic material that has significant length compared to its thickness. Glass fiber is a material consisting of numerous extremely fine fibers of glass, which has very high tensile strength (3000–5000 MPa) and compressive strength (1000–1600 MPa).

Fiber reinforced concrete is defined as concrete made with hydraulic cement, containing fine or fine and coarse aggregate and discontinuous discrete fibers. The

fibers can be made from natural materials (e.g., asbestos, sisal, cellulose) or from manufactured products such as glass, steel, carbon, and polymer (e.g. polypropylenes, Kevlar). (ACI committee 544 2002).

The purpose of reinforcing the cement based matrix with fibers is to increase the tensile strength by delaying the growth of cracks, and to increase the toughness by transmitting stress across a cracked section so that much larger deformation is possible beyond the peak stress than without fiber reinforcement. Fiber reinforcement is observed to improve the impact and fatigue strength, and reduce shrinkage. (A.M. Neville 2010).

The orientation of the fiber relative to the plane of a crack in concrete influence the reinforcing capacity of the fiber. The maximum benefit occurs when the fiber is uni-directional and parallel to the applied tensile stress, and the fibers are of less benefit when randomly oriented in three dimensions (A.M. Neville 2010).

Fracture energy was significantly enhanced by using basalt fiber. As the basalt fiber content increased, the concrete showed higher ultimate loads, larger deflections before failure and higher fracture energy values. (Kabay 2013) A slight increase in fracture energy was observed for basalt and glass fiber reinforced concrete at the dosage of 0.25%. However, significant increase was observed beyond this dosage, fracture energy increased by more than 50% at 1.0% fiber inclusion for both basalt and glass fibers. (Ahmet B. Kizilkanat 2015) Basalt and glass fiber addition increase the fracture energy of ordinary concrete almost by 35%, this indicates the increase in ductility and energy dissipation capacity of ordinary concrete. (Arslan 2016).

The main objective of this study is to show the combined effect of plain concrete with glass fiber added in the tensile region in layers on the improvement of fracture energy of plain concrete grades with C20/25 and C25/30.

The most direct way of determining fracture energy is by means of a uniaxial tensile test, where the complete stress-deformation curve is measured. The test has to be stable, which means the deformation is increased slowly, without any sudden jumps.

Unfortunately, it is difficult to perform stable tensile tests. However, it is much easier to perform stable bending tests on notched specimens. The simplest test of this type is the three-point bend test on a notched beam. Therefore, this test has been chosen for the proposed RILEM recommendations.

The specimens shall be beams with a central notch according to Fig. 1. The depth of the beam as tested shall be horizontal during casting and the size of the beam shall depend on the maximum size of the aggregate, D_{max} , according to Table 1. The notch shall always have a depth, which is equal to half of beam depth ± 5 mm, and the notch width at the tip should be less than 10 mm.

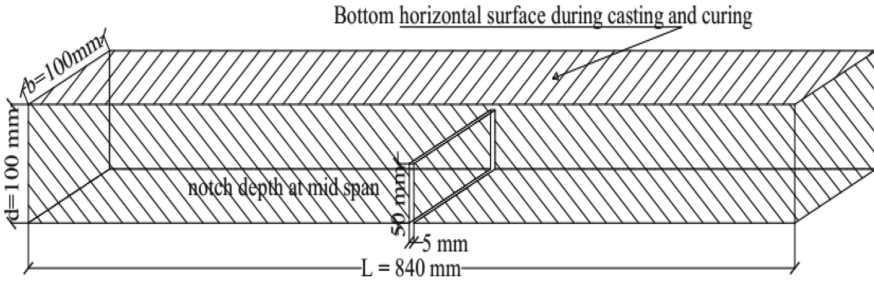


Fig. 1. The geometry of the beam to be used for the test. (RILEM TC 50- FMC Fracture Mechanics of Concrete 1985)

Table 1. Recommended sizes of test beams. (RILEM TC 50- FMC Fracture Mechanics of Concrete 1985)

D_{max} (mm)	Depth d (mm)	Width b (mm)	Length L (mm)	Span l (mm)
1–16	100 ± 5	100 ± 5	840 ± 10	800 ± 5
16.1–32	200 ± 5	100 ± 5	$1,190 \pm 10$	$1,130 \pm 5$
32.1–48	300 ± 5	150 ± 5	$1,450 \pm 10$	$1,385 \pm 5$
48.1–64	400 ± 5	200 ± 5	$1,640 \pm 10$	$1,600 \pm 5$

The supports and loading arrangements shall be such that the force acting on the beam are statically determinate, as shown in Fig. 2.

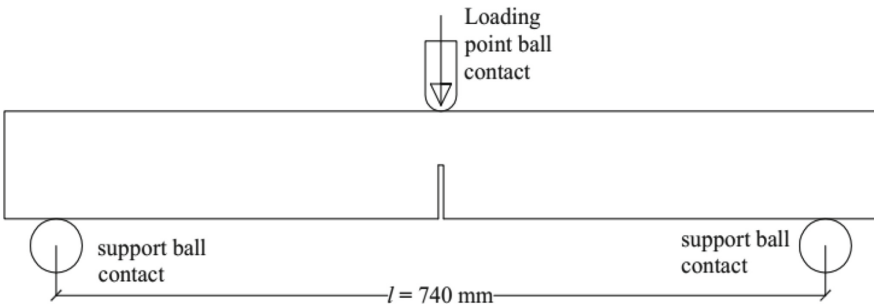


Fig. 2. Support and loading arrangement for the test. (RILEM TC 50- FMC Fracture Mechanics of Concrete 1985)

The deformation of the center of the beam shall be determined with regard to a line between two points on the beam above the supports. The deformation shall be measured with an accuracy of at least 0.01 mm.

The load-deformation curve is corrected for eventual non-linearities at low loads. The energy W_o , represented by the area under the curve is measured as well as the deformation δ_o at final Fracture.

The fracture energy is calculated from the equation:

$$G_f = (W_o + mg\delta_o) / A_{lig} \text{ [N/m]} \tag{1}$$

Where: W_o = area according to Fig. 3. [N.m]

$$m = m_1 + 2m_2$$

m_1 = weight of the beam between the supports, calculated as the beam weight multiplied by l/L [Kg]. m_2 = weight of the part of the loading arrangement which is not attached to the machine, but follows the beam until failure [Kg].

g = acceleration due to gravity, 9.81 m/s^2

δ = deformation at the final failure of the beam (m);

A_{lig} = area of the ligament, defined as the projection of the fracture zone on a plane perpendicular to the beam axis [m^2].

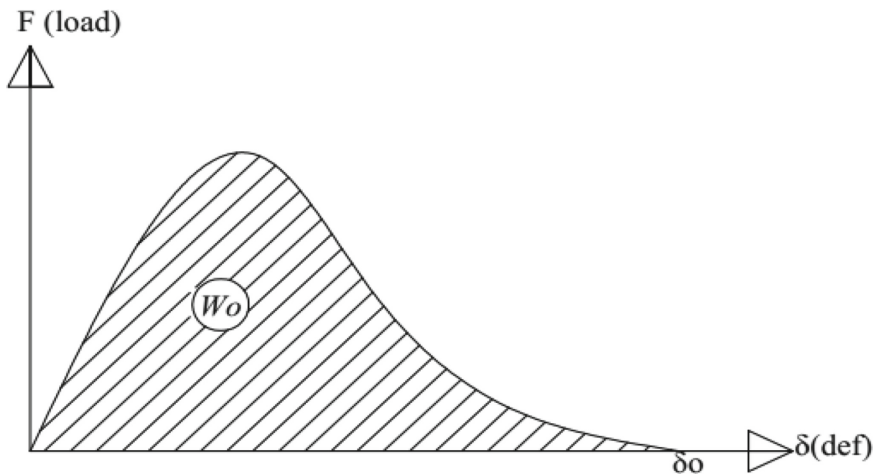


Fig. 3. Load vs beam’s center deflection curve. (RILEM TC 50- FMC Fracture Mechanics of Concrete 1985)

2 Methodology

2.1 Materials

The following materials were used to conduct the experiments on this study:

- Glass Fiber- fiber type E-glass with tensile strength of 3445 Mpa and Density 2580 kg/m^3 .
- Cement (Dangote PPC)

- Fine and coarse aggregates
- Water
- Different types of Molds
- Metal plate to create Notch beam
- Mixer
- Universal testing machine

2.2 Procedures

First, the appropriate mix-designs are prepared and the amount of glass fibers to be added is determined.

Mix-design for C20/25 and C25/30 grade concrete based on ACI method (ACI).

Material Properties:

- Specified compressive strength = 25 Mpa and 30 Mpa respectively
- Ordinary Portland cement specific gravity = 3.15
- Maximum aggregate size = 9.5 mm
- Dry unit weight of aggregate = 1373.73 kg/m³
- Moisture content of aggregate = 1.336%
- Fineness modulus of fine aggregate = 2.97
- Unit weight of fine aggregate = 1675.76 kg/m³
- Density of glass fiber = 2580 kg/m³ (Tables 2 and 3)

Table 2. Mix design results per 1 m³ of concrete

Components	C20/25	C25/30
Water (kg/m ³)	205	205
Cement (kg/m ³)	420	488
Coarse Aggregate (kg/m ³)	604.44	604.44
Fine Aggregate (kg/m ³)	1055.56	987.56
Total	2285	2285

Table 3. Amount of glass fiber added per one beam sample (0.0084 m³)

Glass fiber (% by volume)	Per 0.0084 m ³ (one test sample volume)
0.20%	43.9 gm (14.4 gm per layer)
0.40%	86.6 gm (28.8 gm per layer)
0.60%	130.0 gm (43.3 gm per layer)

Then, the test samples were prepared for each test parameters combination as shown below in table of parameters combination. Test samples without glass fiber were casted and tested for reference purpose.

There are six parameters combination used for this study, each with three samples. Therefore, there are eighteen test beam samples (Tables 4 and 5).

Table 4. Parameter combinations for three point bending test

Test parameters	Levels	Parameters combination applied for 3 point bending tests					
		1	2	3	4	5	6
Concrete grades	1	x	x	x			
	2				x	x	x
% of glass fiber	1	x			x		
	2		x			x	
	3			x			x
Fiber layer	1	x	x	x	x	x	x

Table 5. Legends

Legend		
Test parameters	Levels	Description
Concrete grades	1	C20/25 ^a
	2	C25/30 ^b
% of glass fiber	1	0.20% by total volume of the sample
	2	0.40% by total volume of the sample
	3	0.60% by total volume of the sample
Fiber layers	1	3 layers at uniform interval starting from the end of notched depth

^a C20/25 – refers to a concrete with 20 Mpa cylindrical and 25 Mpa cubic compressive strength.

^b C25/30 – refers to a concrete with 25 Mpa cylindrical and 30 Mpa cubic compressive strength.

Three Point Bending Test

This test is performed to determine the fracture energy of concrete by using notched beams test specimens. This test are performed according to RILEM TC 50-FMC Recommendation (Work of Fracture Method).

The following procedures are followed:

- Prepare $100 \times 100 \times 840$ mm³ beam sample with notch at the middle of the beam

Glass fibers are added in three layer after the concrete is mixed separately in the mixer and casted in the beam mold with the given dimensions. The number of glass fiber layer is constant for all samples, but the amount in each layer is different for different samples based on the percentage of glass fiber used.

First, place 15 mm of concrete then place the first layer of glass fiber, then place the next 15 mm of concrete then place the second layer of glass fiber, then place the next 15 mm of concrete then place the third layer of glass fiber. After the third layer of glass fiber is placed, fill the rest of the sample beam with concrete by placing the notch making plate at the middle (Fig. 4).



Fig. 4. Glass fiber in layer, casted beam with notch plate & notch plate removed

- Cure the sample for 28 days

The test samples are cured in open water tanker after they are removed from the mold until 3–4 h to test (Fig. 5).



Fig. 5. Sample curing for 28 days.

- Perform 3-point bending test using universal testing machine

The test is performed with an approximately constant rate of deformation, which is chosen so that the maximum load is reached within about 30–60 s after the start of the test. The testing machine records the deformation of the center of the beam and the corresponding load until the beam is completely separated into two halves.

The load shall be measured with an accuracy of at least 2% of the maximum value in the test. The area of the ligament, A_{lig} , shall be measured.

The length L of the beam as well as the span l during the test shall be measured with an accuracy of at least 1 mm.

- Record the load vs deflection results (Table 6)

Table 6. Test result format for 3- point bending test

Type of test	Test samples	Test results for 3 point bending test parameters combination					
		1	2	3	4	5	6
3–point bending test	1	x	x	x	x	x	x
	2	x	x	x	x	x	x
	3	x	x	x	x	x	x

3 Results and Discussion

The fracture energy of concrete is calculate using the RILEM TC 50-FMC Recommendation (Work of Fracture Method). As it has shown in the literature review, to calculate the fracture energy first the load vs displacement curve from the three point bending test must be drawn and the area under the curve must be calculated. Then using the given analytical formula from the RILEM TC 50-FMC Recommendation, the fracture energy is calculated.^{1,2}

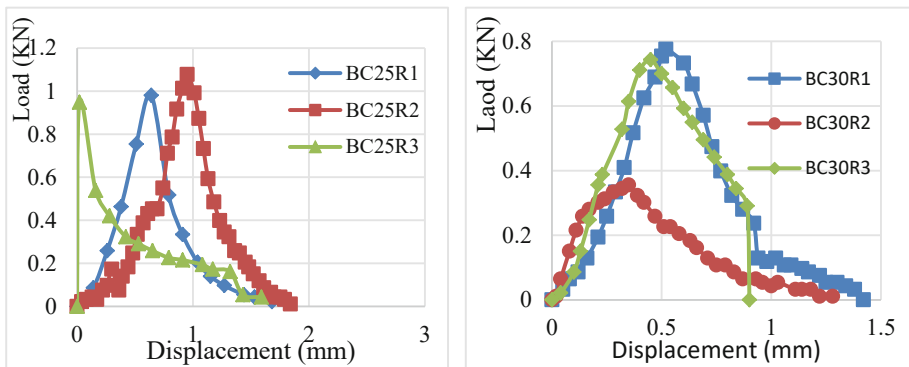


Fig. 6. Load vs Displacement curves for 0% glass fiber for grade C20/25 & C25/30 design concrete respectively.

Figure 6 shows that plain concrete of grade of C20/25 and C25/30 with no addition of glass fiber respectively. It shows very brittle failure with a maximum

¹ BC25R1, 2, 3 – refers to beam sample with 25 Mpa cubic compressive strength cast without addition of glass fiber as reference test sample 1, 2 & 3.

² BC30R1, 2, 3 - refers to beam sample with 30 Mpa cubic compressive strength cast without addition of glass fiber as reference test sample 1, 2 & 3.

displacement less than 2 mm at the central notched section of the beam (Fig. 7).^{3,4}

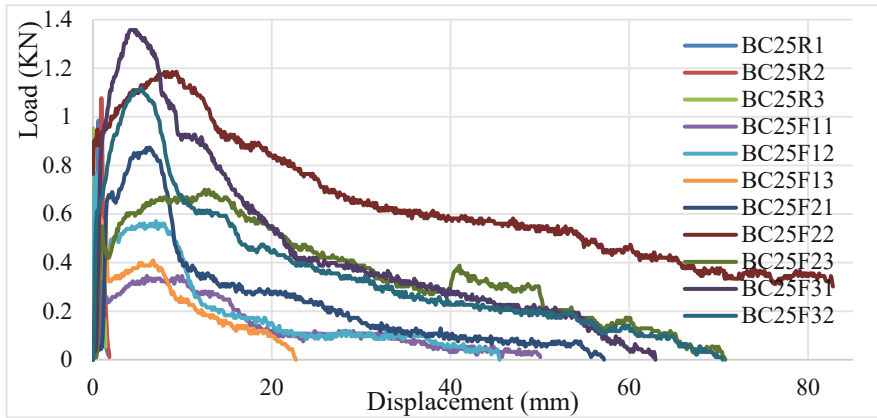


Fig. 7. Load vs Displacement curves for different percentage of glass fiber for grade C20/25 design concrete.

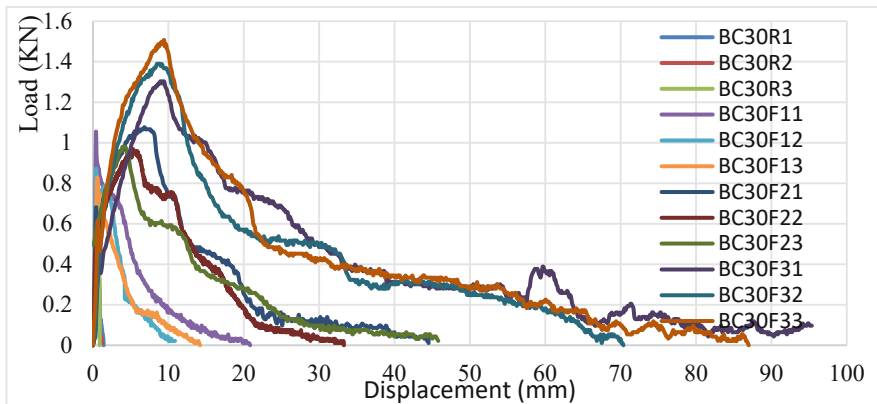


Fig. 8. Load vs Displacement curves for different percentage of glass fiber for grade C25/30 design concrete.

³ BC25F11, 2, 3 – refers to beam with 25 Mpa cubic compressive strength cast with 0.2% by volume addition of glass fiber as test sample 1, 2 & 3.

BC25F21, 2, 3 – refers to beam with 25 Mpa cubic compressive strength cast with 0.4% by volume addition of glass fiber as test sample 1, 2 & 3.

BC25F31, 2 – refers to beam with 25 Mpa cubic compressive strength cast with 0.6% by volume addition of glass fiber as test sample 1 & 2.

⁴ BC30F11, 2, 3 – refers to beam with 30 Mpa cubic compressive strength cast with 0.2% by volume addition of glass fiber as test sample 1, 2 & 3.

BC30F21, 2, 3 – refers to beam with 30 Mpa cubic compressive strength cast with 0.4% by volume addition of glass fiber as test sample 1, 2 & 3.

BC30F31, 2, 3 – refers to beam with 30 Mpa cubic compressive strength cast with 0.6% by volume addition of glass fiber as test sample 1, 2 & 3.

Figures 7 and 8 shows that the maximum displacement of the notched beam for C20/25 & C25/30 grade concrete respectively. It shows the maximum displacement increase significantly with the addition of glass fiber, which change the failure mode from very brittle (0% glass fiber) to very ductile (0.6% glass fiber addition by volume). The figure also shows there is an increase in the maximum load carried by the beam as the percentage of glass fiber addition increases.

The effects of the addition of glass fiber on fracture energy of plain concrete is presented in table format below.

Table 7. Experimental results for fracture energy by three point bending test

No.	Sample code	Mass (Kg)	mI (//L) Kg	Area of ligament (m ²)	Final disp. (m)	Area under load vs Disp. curve (N.m)	Fracture energy (N/m)	Average fracture energy (N/m)	Max. load (KN)	Avg. Max. Load (KN)	Avg. Max. Disp. (m)
1	BC30R1	19.3	17.13	0.0048	0.00142	0.416	136.381	111.08	0.776	0.625	0.00120
2	BC30R2	19.3	17.13	0.00474	0.00128	0.2	87.611		0.355		
3	BC30R3	19.4	17.26	0.00499	0.0009	0.393	109.252		0.743		
4	BC30F11	18.8	16.73	0.00479	0.02085	5.713	1,905.321	1,413.49	1.056	0.890	0.01532
5	BC30F12	18.7	16.60	0.00459	0.01089	3.355	1,117.242		0.786		
6	BC30F13	19.2	17.06	0.0047	0.01421	3.3457	1,217.892		0.829		
7	BC30F21	19.3	17.15	0.00469	0.04452	16.297	5,069.761	4,363.01	1.077	1.009	0.04121
8	BC30F22	19	16.86	0.0049	0.03329	12.876	3,751.700		0.969		
9	BC30F23	19	16.90	0.00504	0.04581	13.912	4,267.570		0.980		
10	BC30F31	19.1	16.99	0.0052	0.09537	39.19	10,593.884	10,205.8	1.303	1.400	0.08424
11	BC30F32	19.1	16.95	0.00515	0.07037	33.902	8,863.931		1.390		
12	BC30F33	18.8	16.73	0.0047	0.08699	38.176	11,159.464		1.508		
13	BC25R1	19.1	16.92	0.0047	0.00168	0.5154	168.996	172.885	0.980	1.002	0.00170
14	BC25R2	18.9	16.79	0.0047	0.00184	0.635	199.596		1.077		
15	BC25R3	19.2	17.08	0.00475	0.00159	0.446	150.063		0.948		
16	BC25F11	17.5	15.57	0.00489	0.05004	7.214	3,039.464	2,746.31	0.345	0.499	0.03941
17	BC25F12	17.3	15.37	0.0049	0.04549	9.614	3,362.124		0.571		
18	BC25F13	18.2	16.15	0.0048	0.0227	5.222	1,837.344		0.582		
19	BC25F21	18.8	16.71	0.0048	0.05718	14.169	4,904.184	8,586.60	0.873	0.919	0.07024
20	BC25F22	18.7	16.62	0.005	0.08278	52.909	13,280.688		1.185		
21	BC25F23	18.7	16.55	0.00485	0.07075	25.257	7,574.915		0.700		
22	BC25F31	19.3	17.16	0.00475	0.06293	29.707	8,479.261	8,148.08	1.357	1.239	0.06669
23	BC25F32	19.3	17.13	0.00475	0.07045	25.313	7,816.892		1.120		

Table 8. Comparison of fracture energy test results between C20/25 & C25/30 grade concretes for different percentage of glass fiber addition by volume ratio.

Concrete Grades	Fracture energy for different percentage of Glass fiber by volume (N/m)			
	0%	0.20%	0.40%	0.60%
C20/25	172.885	2,746.310	8,586.596	8,148.076
C25/30	111.081	1,413.485	4,363.010	10,205.760

Table 9. Comparison of maximum load carried test results between C20/25 & C25/30 grade concretes for different percentage of glass fiber addition by volume ratio.

Concrete Grades	Maximum load for different percentage of Glass fiber by volume (KN)			
	0%	0.20%	0.40%	0.60%
C20/25	1.002	0.499	0.919	1.239
C25/30	0.625	0.890	1.009	1.400

Table 10. Comparison of maximum displacement recorded results between C20/25 & C25/30 grade concretes for different percentage of glass fiber addition by volume ratio.

Concrete Grades	Maximum displacement for different percentage of glass fiber by volume (mm)			
	0%	0.20%	0.40%	0.60%
C20/25	1.703	39.410	70.237	66.690
C25/30	1.200	15.317	41.207	84.243

As it is shown in Tables 7, 8, 9 and 10 the fracture energy of plain concrete increases with the addition of glass fiber and this effect is greater for C20/25 design grade concrete than C25/30 design grade concrete. The above results shows that C20/25 design grade concrete have higher fracture energy due to the larger center of beam displacement than C25/30 design grade concrete. However, the C25/30 design grade concrete have better maximum load carrying capacity as the content of glass fiber increase.

3.1 Effects Observed During the Experimental Periods

During the conduct of tests, the following effects were observed due to the addition of glass fiber:-

For C25/30, grade concrete:

- With 0% glass fiber (Reference), the samples breaks instantly in brittle manner without showing any crack pattern.
- With 0.2% glass fiber by volume, the samples break in brittle manner, but there are visible crack patterns lines and crack width and the crack growth very fast to the upper end of the beam breaks suddenly.



Fig. 9. Crack patterns at 0.2% glass fiber addition for C25/30 design grade concrete just before failure.

- With 0.4% glass fiber by volume, the samples shows ductile behavior before failure after a very noticeable crack patterns lines and crack width and finally breaks into two halves (Fig. 10).



Fig. 10. Crack patterns at 0.4% glass fiber addition for C25/30 design grade concrete just before failure.

- With 0.6% glass fiber by volume, sample shows very ductile behavior and the samples do not breaks into two halves (Fig, 11).



Fig. 11. Crack patterns at 0.6% glass fiber addition for C25/30 design grade concrete.

For C20/25, grade concrete:

- With 0% glass fiber (Reference), the samples breaks instantly in brittle manner without showing any crack pattern.
- With 0.2% glass fiber by volume, the sample shows little ductile behavior and noticeable crack patterns and crack width and this crack patterns are similar to the 0.4% by volume of glass fiber for C25/30 grade concrete samples, and the sample breaks into two halves (Fig. 12).



Fig. 12. Crack patterns at 0.2% glass fiber addition for C20/25 design grade concrete just before failure.

- With 0.4% glass fiber by volume, the sample shows very ductile behavior and very noticeable crack patterns and crack width and this crack patterns are similar to the 0.6% glass fiber by volume for C25/30 grade concrete samples, and the sample breaks into two halves (Fig. 13).



Fig. 13. Crack patterns at 0.4% glass fiber addition for C20/25 design grade concrete just before failure.

- With 0.6% glass fiber by volume, the sample shows very ductile behavior with very noticeable crack patterns and crack width (Fig. 14).



Fig. 14. Crack patterns at 0.6% glass fiber addition for C20/25 design grade concrete just before failure.

4 Conclusions

- Addition of glass fiber increases the fracture energy of plain concrete for both C20/25 and C25/30 design grade concrete, and it has more effect for C20/25 design grade concrete than C25/30 design grade concrete.
- Addition of glass fiber increases the crack width for both C20/25 and C25/30 design grade concretes.
- The fracture energy increases for both C20/25 and C25/30 design grade concretes with the increases of glass fiber content. But after 0.4% by volume addition of glass fiber, it shows that the glass fiber layer slips on one other, so for higher percentage of glass fiber the fiber must be distributed in thin layers to create strong contact bond with the concrete.
- The maximum displacement of the center of the beam increases with the increases of glass fiber content and the increase for C20/25 design grade concrete is more than the C25/30 design grade concrete.
- Addition of glass fiber increase the maximum load carried by the test beam and its effect for C25/30 design grade concrete is greater than for C20/25 design grade concrete.

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