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Experimental study on behaviors of polypropylene fibrous concrete beams

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Abstract: Synthetic fibers made from nylon or polypropylene have gained application when loose and woven into geo textile form although no information on the matrix's mechanical performance is obtained so that more understanding of their structural contribution to resist cracking can be determined. This paper presents the results of an experimental investigation to determine the performance characteristics of concrete reinforced with a polypropylene structural fiber. In this investigation "Fiber mesh" brand of fibers manufactured by SL Concrete System, Tennessee, USA and marketed by M/S Millennium Building System, Inc., Bangalore, India are used. The lengths of the fibers used were 24 mm. Fiber dosages used were 0.9, 1.8, 2.7 kg/m^3. A total of three mixtures, one for each fiber dosage were made. A standard slump cone test was conducted on the fresh concrete mix with and without fibers to determine the workability of the mix. The test program included the evaluation of hardened concrete properties such as compressive, split tensile, modulus of rupture and flexural strengths. The increase in compressive strength is about 36.25%, 26.20%, and 23.75% respectively that of plain concrete. This increase in strength was directly proportional to amount of fibers present in the mix. The increase in flexural strength for Mixes I~III is about 21%, 16.6%, and 23% respectively that of plain concrete specimens. An experimental investigation was also made to study the behaviors of reinforced fibers concrete beams (with longitudinal reinforcements) under two-point loading. The deflection and crack patterns were also studied. The improvements in strength and ductility characteristics were discussed.

Key words: Fiber, Reinforcement, Concrete, Mechanical properties, Polypropylene Fibre Reinforced Concrete (PFRC)
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INTRODUCTION

Addition of fibers in cement or cement concrete may be of current interest, but this is not a new idea or concept. Fibers of any material and form (shape) play an important role in improving the strength and deformation characteristics of the cement matrix in which they are incorporated. The new concept and technology reveal that the engineering advantages of putting fiber in concrete may improve the fracture toughness, fatigue resistance, impact resistance, flexural strength, compressive strength, thermal crack resistance, rebound loss, and so on. The magnitude of the improvement depends upon both the amount and the type of fibers used.

A number of studies have been reported on the flexural behavior of steel fiber reinforced concrete (SFRC) elements with particular reference to improvements in cracking resistance, stiffness and ductility. Improvements in shear capacity, impact resistance, resistance to abrasion and energy absorption with the addition of steel fibers have also been studied by several investigators (Cox, 1952; Craig, 1987; Dwarakanath and Nagaraj, 1987; Henager and Doherty, 1976; Kukreja *et al.*, 1980; Swamy and Al-Ta'an, 1981; Shah and Rangan, 1971). Not much work has been done in the country on the use of polypropylene fibers in making Polypropylene Fiber Reinforced Concrete (PFRC). Very few literature is available in the field of PFRC with the aim of developing some pre-cast concrete components like manhole covers and frames (Gracia *et al*., 2005).

Fibrillated polypropylene fibers have gained acceptance for use as concrete reinforcement. A fiber type is fibrillated with a patterned wheel to produce a main and cross fibril network. The tape is then cut transversely to reduce collated fibrillated polypropylene fibers. In this fashion fibers are added to concrete. During mixing and upon friction with aggregate, the fibrils are broken resulting in individual fibers with extending arms that help to enhance the bond to concrete. Polypropylene is hydrophobic and does not absorb water or bond chemically to cement paste. Therefore mechanical bonding achieved by fibrillation is useful (ACI Committee 318, 1989). The typical volume percent of fibrillated polypropylene fibers ranges from 0.1% to 0.3%. Some advantages of fibrillated polypropylene fibers include improved toughness and crack control properties and impact resistance.

RESEARCH SIGNIFICANCE

Concentration of reinforcement in tension zone in reinforced cement concrete (RCC) cannot resist diagonal tension developed because of shear stress and also cannot provide ductility in the entire cross-section of the member which leads to introduction of Fiber Reinforced Cement Concrete (FRCC). By adding fibers while mixing the concrete, a so-called homogeneous reinforcement is created. This slightly increases the mechanical properties before failure and also governs the post failure behavior. Thus plain concrete which is quasi brittle material is converted into pseudo ductile fiber reinforced concrete. This study aimed at conducting experimental investigation of the various mechanical properties of PFRC.

MATERIALS

The description of the materials used is given below.

(1) Cement: Ordinary Portland pozzolana cement 53 Grade with specific gravity of 3.15 as per IS 1489 (1976).

(2) Coarse aggregate: Crushed blue granite was passed through 20 mm sieve and meets gradation requirements of IS 2386 (1963). The apparent specific gravity is 2.95 and fineness modulus is 7.1.

(3) Fine aggregate: Natural river sand with fineness modulus of 2.64. Its gradation meets zone II of IS 383 (1970) requirements. Specific gravity is 2.63.

(4) Fiber: Fiber mesh brand of (Fibrillated polypropylene) fibers 24 mm in length, manufactured by SL Concrete System, Tennessee, USA and marketed by M/S Millennium Building System, Inc., Bangalore, India.

(5) Water: Potable water.

The physical properties of cement and fiber used for the investigation are given in Table 1 and Table 2 respectively.

Table 1 Physical properties of cement (53 Grade PPC)

Properties	Values
Normal consistency (%)	30.0
Fineness (m^2/g)	285.5
Soundness (mm)	1.0
Setting time	
Initial setting time (min)	80
Final setting time (min)	615
Compressive strength (MPa)	
3-day	30.0
7-day	37.0
28-day	55.0

Table 2 Properties of fibers

Properties	Values
Fiber type	Graded fibrillated polypropylene fibers
Length (mm)	12~24
Specific gravity	0.9
Tensile strength (MPa)	550~760
Young's modulus (GPa)	3.5
Density (kg/m^3)	910
Thermal conductivity	Low
Electrical conductivity	Low
Acid and salt resistance	High
Absorption	Nil

EXPERIMENTAL WORK

Three mix proportions were used in the experimental programme. The details of mix proportions are given in Table 3. The aggregates, cement, and water were batched by weight and mixed in a drum mixer of

Table 3 Mix proportioning details of PFRC for 1 m^3 of concrete

Types	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg)	Ratio
Mix I	383.16	571.850	1161.64	191.58	1:1.49:3.03:0.50
Mix II	430.52	540.423	1153.54	191.58	1:1.26:2.63:0.45
Mix III	497.61	503.150	1135.99	191.58	1:1.01:2.28:0.39

capacity 0.06 m^3. Water was added gradually until all the materials were mixed to a uniform colour. The fibers were introduced last and dispersed manually. Batching of fibers was by weight. Although the fibrous mixes were less workable than the plain concrete, they proved generally satisfactory in that the dispersion of fibers was found to be uniform and there was no significant balling. The following control specimens were cast from each mix: (1) three 100 mm plain concrete cubes for each type of mix for compressive test; (2) nine 100 mm fiber concrete cubes for compression test; (3) nine 150 mm diameter, 300 mm high cylinders for split cylinder tests (Three for each fiber fraction); (4) nine 100 mm×100 mm×500 mm prism beams for modulus of rupture test. The test programme also consisted of fabricating 12 beams having identical rectangular cross sections of 100 mm×200 mm, and testing them under two symmetrically placed concentrated loads. For each of the mixes, one beam was cast without fibers as control specimen and one beam each was cast for different volume fractions of fibers (0.1%, 0.2%, 0.3%) thus making a total of twelve beam specimens. In all the beams two number of 10 mm diameter bars were used in the tension zone and two numbers of 8 mm diameter bars were used in the compression zone as longitudinal reinforcement. Two legged 6 mm diameter stirrups at 130 mm centre to centre were used as shear reinforcement to prevent premature shear failure. A typical cross section of the beam specimens is shown in Fig.1. All the tests were conducted as per IS specifications.

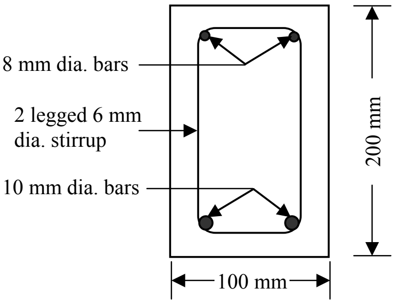


Fig.1 Cross-section of beam specimen

TEST RESULTS AND DISCUSSIONS

Compressive strength

The compressive strength of test cubes was measured for PCC and PFRC cubes after 28 d of moist curing. The average compressive strength values observed after 28 d are given in Table 4. The strength increment was directly proportional to increasing amount of fibers in concrete. The maximum 28 d average cube compressive strength for Mixes I~III was 48, 52 and 57.11 MPa respectively, all corresponding to a volume percentage of 0.3. The increase in compressive strength was about 36.25%, 26.2%, and 23.75% respectively that of plain concrete. While testing it was also observed that the pieces of concrete did not spall off as they were held intact by the fibers. The incorporation of the fibers in the concrete had, in general no significant effect on the compression strengths, although there were a few exceptions. These included some of the fiber concrete that had relatively low cement content for which the compressive strength was observed to be significantly inferior to that of the corresponding plain mixes. Such results have not been explained. However it is believed that proper fiber dispersion and full compaction of concrete may not be readily achieved with high

Table 4 Experimental results of PCC and PFRC

Types	v_f (%)	Compressive strength (MPa)	Split tensile strength (MPa)	Modulus of rupture (MPa)
Mix I	0.0	35.23	3.54	5.23
	0.1	39.50	4.42	5.47
	0.2	41.00	4.88	5.65
	0.3	48.00	4.95	6.35
Mix II	0.0	41.22	3.72	5.35
	0.1	49.78	4.53	5.99
	0.2	50.22	4.67	6.12
	0.3	52.00	4.74	6.24
Mix III	0.0	46.15	3.89	5.56
	0.1	50.67	4.88	5.70
	0.2	55.33	5.09	6.40
	0.3	57.11	5.52	6.84

v_f: volume fraction of fibers

dosages of fibers unless the cement content is kept over a certain minimum level.

Split tensile strength

Tests were carried out conforming to IS 5816 (1976) to obtain the splitting tensile strengths for various concrete mixtures. The strength in this case was similar to that of the cubes. The increase in strength for Mixes I~III was about 39.83%, 27.42%, and 41.90% respectively that of plain concrete specimens. A possible reason for this difference is that the fiber dispersion is more uniform because of the decreased amount of coarse aggregate. In the specimens containing fibers the split half of the cylinders were held together showing that the tensile strength and binding of fibers to concrete is superior. The results of the experiments are listed in Table 4.

Flexural strength

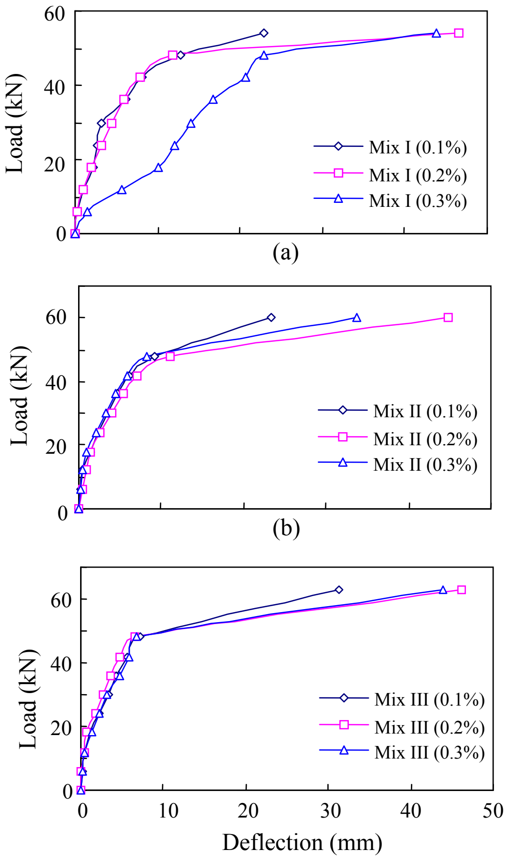
Tests were carried out conforming to IS 516 (1959) to obtain the flexural strength of various concrete mixtures. Nine beams of 100 mm×100 mm×500 mm were cast (three beams for each mixture and corresponded to one fiber fraction). The beams were tested using two point loading. The experimental results of flexural strength are shown in Table 4. The average maximum flexural strength tested at the age of 28 d for Mixes I~III is 6.35, 6.24 and 6.84 MPa respectively. The presence of fibers had little influence on the flexural strength of all the three concrete mixes; the exceptions noted were the same as those observed for the compressive strength though in these cases; the effect was much less noticeable. The fiber content with high compressive strength was also observed to produce the highest flexural strengths.

Young's modulus of elasticity

Young's modulus of elasticity *E* for the concrete investigated was determined at 28 d. The modulus of elasticity of fibers used in this study is 3.5 GPa (Table 2). It is very much less while comparing with steel fibers. Hence the *E* value of the composite using synthetic fibers is very much less than that of the concrete using steel fibers. The *E* value ranged from 174.2 to 1247.24 MPa. The results were to a large extent a function of the corresponding compressive strengths and this is in agreement with what is generally observed for conventional concrete. The presence of fibers again had little effect on the test results. Among the values of all the three mixes, Mix I containing 0.2% volume fraction of fibers showed highest value. One possible reason may be the greater addition of coarse aggregate in the Mix I compared with Mix II and Mix III.

Flexural behaviour of beam with longitudinal reinforcement

Beams of the size 100 mm×200 mm×1800 mm were tested under two point loading. All the beams were reinforced with 0.98% steel with a specified minimum yield stress of 415 N/mm^2. Figs.2a~Fig.2c show the deflection behaviour of the beams at mid span at all stages of loading up to failure. Fig.3 shows the crack patterns of the beams (Mix II) tested in the present work. Figs.4a~4c show the moment curvature curve for all the beams tested in the study. The curvatures were calculated from the concrete strains measured at various sections along the beam. The control beams (without fibers) cast for different mixes (Mix I, Mix II and Mix III) failed by flexure at the



(a)

(b)

(c)

Fig.2 Load vs deflection. (a) Mix I; (b) Mix II; (c) Mix III

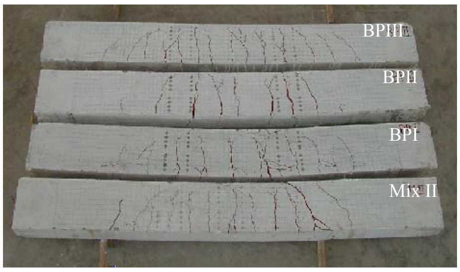
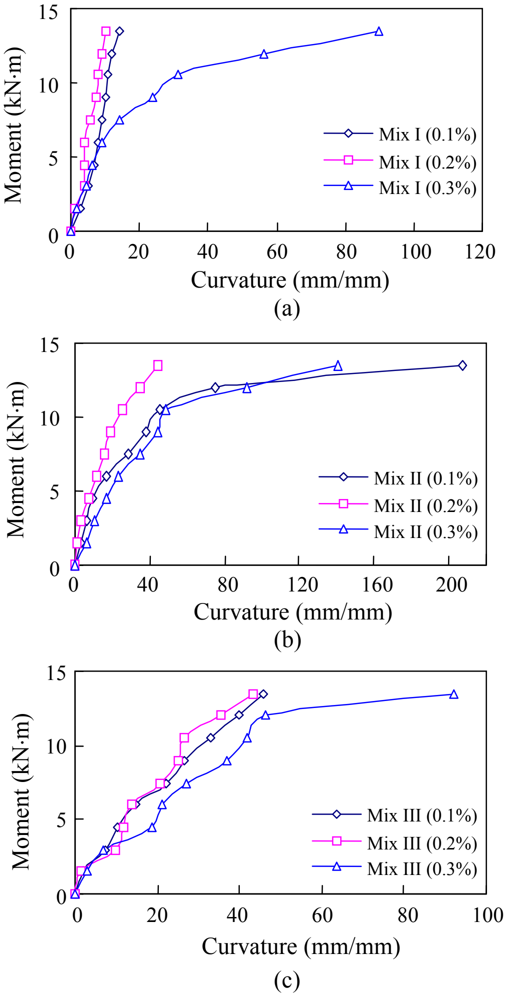


Fig.3 Crack patterns for beams of Mix II



(a)

(b)

(c)

Fig.4 Moment vs curvature. (a) Mix I; (b) Mix II; (c) Mix III

ultimate loads and maximum deflection values were observed to be nominal. Observations of the beam specimens with and without fibers are listed in Table 5. In all the specimens initial cracks were observed at an average of 15 kN to 20 kN, nearer to the mid-span. Further cracks, which appeared, were propagation of the initial cracks from the tension zone into the compression zone. All the cracks appeared between the point loads, showing that they were flexural ones.

Table 5 Test results for RC beams containing different fiber volumes

Beam designation	Mix type	v_f (%)	Fiber addition (kg/m^3)	Ultimate load (kN)	Initial crack load (kN)	Maximum mid-span deflection (mm)
AC	I	0.0	–	51	18	11.51
API	I	0.1	0.9	54	19	22.80
APII	I	0.2	1.8	57	21	46.44
APIII	I	0.3	2.7	60	20	43.81
BC	II	0.0	–	57	19	16.68
BPI	II	0.1	0.9	60	18	23.41
BPII	II	0.2	1.8	60	20	44.79
BPIII	II	0.3	2.7	61	21	33.68
CC	III	0.0	–	67	20	29.93
CPI	III	0.1	0.9	63	19	31.39
CPII	III	0.2	1.8	67	21	46.09
CPIII	III	0.3	2.7	64	20	27.01

In the beams containing various volume fractions (0.1%, 0.2% and 0.3%) of fibers, only minor increments in the ultimate load carrying capacity were noticed. There were significant increments in the deflection values for these beams, especially the beams with 0.2% volume fraction of fibers showed higher values of deflections than all the other beams tested. Fibrous concrete beam showed approximately the same stiffness as the conventional beam up to the first cracking load. After that the fibrous concrete beam showed greater stiffness. It was also observed that the cracks were more closely spaced in all the fiber concrete beams as shown in Fig.3 and that the crack widths were consequently less in these beams compared to those in conventional beams. All the fiber concrete beams showed increased neutral axis depth to their comparison beams without fibers. The effectiveness of the fibers in resisting external loads was thus evident right up to failure.

Deformations at first crack

The deformations at this stage of loading are only a fraction of those occurring at the design service loads, but the results showed that the fibers are effective even when the extent of cracking is very slight. Table 5 shows that the visible first crack loads of the beams varied from 30% to 35% of the experimental failure loads.

Table 6 shows the deformation characteristics of beams AP to CPIII tested in this study at the first flexural crack load. The flexural rigidity *EI* at the point of maximum moment was calculated by dividing the bending moment by the curvature obtained from the concrete strain readings in the compression zone.

Deformations at failure

Table 7 shows the deformations at failure of all beams without fibers and with fibers for Mixes I to III. All the beams failed by yielding of tension steel. After yielding the beams exhibited significant inelastic deformations (Fig.2a to Fig.2c) before the ultimate load was reached. The fiber concrete beams were thus as ductile as the conventional beams and in some cases more so. The concrete strain at the compression face at loads prior to failure varied from 0.0032 mm/mm to 0.028 mm/mm for plain concrete beams and from 0.00524mm/mm (Mix I: 0.2%) to 0.0295 mm/mm (Mix II: 0.3%) for fiber concrete beams.

The flexural rigidity of the fiber beams were higher for all the beams except for few cases which

Table 6 Deformation characteristics at first crack

Mix type		Properties								
		Deflection (mm)	Span/ deflection	Steel strain ($\times10^{-3}$ mm)	Concrete compressive strain ($\times10^{-3}$ mm)	Neutral axis depth (mm)	Curvature ($\times10^{-5}$ mm^{-1})	*EI* (kN/m^2)	*EI** (calculated) (kN/m^2)	*EI*/*EI**
I	0%	2.13	704.23	0.0416	3.88	78.00	4.96	90.70	2225.80	0.04
	0.1%	2.62	572.51	2.24	5.35	110.00	4.86	97.70	14.94	6.54
	0.2%	2.61	575.81	3.03	2.98	79.50	3.75	140.18	86.78	1.62
	0.3%	14.48	103.59	6.37	4.06	66.00	6.09	81.84	51.50	1.59
II	0%	1.77	847.46	0.040	3.20	65.00	4.92	81.63	2421.11	0.03
	0.1%	1.31	1145.03	9.71	4.40	47.00	9.36	48.07	32.54	1.48
	0.2%	2.04	735.30	5.83	6.28	89.00	7.05	70.92	81.62	0.87
	0.3%	1.58	949.36	22.22	6.42	37.00	17.36	30.24	15.59	1.94
III	0%	1.33	1127.82	12.00	28.00	112.00	25.00	45.00	2530.50	0.02
	0.1%	2.23	672.64	5.52	11.14	107.16	10.39	45.71	41.02	1.11
	0.2%	1.35	1111.11	8.40	3.78	31.50	11.98	43.82	42.07	1.04
	0.3%	1.28	1171.88	21.44	5.59	30.00	18.63	24.15	42.06	0.57

I^*=un-cracked transformed moment of inertia

Table 7 Deformation characteristics at ultimate failure

Mix type		Properties								
		Deflection (mm)	Span/ deflection	Steel strain ($\times10^{-3}$ mm)	Concrete compressive strain ($\times10^{-3}$ mm)	Neutral axis depth (mm)	Curvature ($\times10^{-5}$ mm^{-1})	*EI* (kN/m^2)	*EI*** (calculated) (kN/m^2)	*EI*/*EI***
I	0%	11.51	130.32	9.30	5.38	53.00	10.15	86.20	1012.40	0.09
	0.1%	22.80	65.97	11.20	6.00	42.00	14.28	94.53	6.92	13.66
	0.2%	46.44	32.30	11.52	5.24	50.00	10.48	135.97	17.57	7.74
	0.3%	43.81	34.24	135.00	9.00	10.00	90.00	16.66	14.35	1.16
II	0%	16.68	89.93	60.00	24.80	46.80	53.00	28.30	1038.28	0.03
	0.1%	23.41	64.08	320.00	20.71	10.00	207.10	7.24	8.49	0.85
	0.2%	44.79	33.49	47.99	23.06	52.00	44.34	33.82	10.35	3.27
	0.3%	33.68	44.54	164.00	29.05	21.00	140.47	10.85	5.04	2.15
III	0%	29.93	50.12	57.70	24.70	48.00	51.50	32.50	1068.96	0.03
	0.1%	31.39	47.79	50.00	23.00	50.00	46.00	34.23	8.60	3.98
	0.2%	46.09	32.55	52.50	13.00	30.00	43.33	38.65	12.39	3.12
	0.3%	44.00	34.10	113.67	21.27	23.00	92.00	16.30	6.43	2.53

I^{**}=second moment of area of cracked transformed section may be due to the experimental errors while measuring the strain readings. The propagation of cracks in the tension zone which crosses the steel level makes the strain gages inoperative in some beams and a few results are non-conforming with others. The observed flexural rigidity is more for APII (Mix I: 0.2%). The contribution of the higher aggregate content of the mix compared with other mixes may be the reason for the increasing flexural rigidity in some beams.

ULTIMATE FLEXURAL STRENGTH

The ultimate flexural strength analysis presented in this paper is based on the conventional compatibility and equilibrium conditions used for normal reinforced concrete except that the contribution of the fibers in the tension is recognized. The analysis is based on the following assumptions: (1) Plane sections remain plane after bending; (2) The compressive force equals the tensile force; (3) The internal moment equals the applied bending moment.

The actual and assumed stress and strain distributions at failure are shown in Fig.5. The stress block is assumed to be a parabolic one with the compressive stress of concrete being taken as $0.85f_c'$. The neutral axis depth is taken as k_1D. The stress variation from the top fiber is assumed to be a straight line up to a depth of $0.85k_1D$ thereby dividing the stress block into rectangular and parabolic portions. The depth of the parabolic portion is assumed as $0.15k_1D$. The height e of the elastic un-cracked zone of concrete is very small compared to the neutral axis depth and it is therefore assumed that the tensile contribution of fibers is represented by a rectangular stress block over the whole of the tensile zone.

The area and the neutral axis depth of the stress block are calculated as:

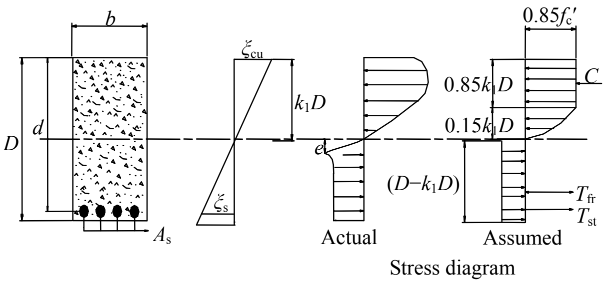


Fig.5 Stress and strain distributions

Area of rectangular portion of stress block,

$$A_1 = 0.85f_c' \times 0.85k_1D = 0.7225f_c'k_1D. \tag{1}$$

Distance of centroid of this rectangular portion from top,

$$y_1 = 0.85k_1D/2 = 0.425k_1D. \tag{2}$$

Area of parabolic portion of stress block,

$$A_2 = \frac{2}{3}\left[0.85f_c' \times 0.15k_1D\right] = 0.085f_c'k_1D. \tag{3}$$

Distance of centroid of this parabolic portion from top,

$$y_2 = 0.85k_1D + \left(\frac{3}{8} \times 0.15k_1D\right) = 0.906k_1D. \tag{4}$$

Total area,

$$A_1 + A_2 = 0.8075f_c'k_1D. \tag{5}$$

Distance of common centroid from top,

$$\bar{y} = \frac{A_1y_1 + A_2y_2}{\sum A} = \bar{y} = 0.475k_1D. \tag{6}$$

Distance of lever arm,

$$Z = d - \bar{y}. \tag{7}$$

Total compressive force in concrete,

$$C = 0.8075f_c'bk_1D. \tag{8}$$

Total tensile force,

$$T = T_{fr} + T_{st}, \tag{9}$$

$$T_{fr} = (\sigma_{fu}v_f) \times b \times (D - k_1D), \tag{10}$$

$$T_{st} = A_sf_y, \tag{11}$$

where σ_{fu} is the stress at the fracture of the fiber and v_f is the volume fraction of fiber. Since the orientation, length, and bonding characteristics of fibers will influence the strength of fiber-reinforced concrete, these parameters must be incorporated in Eq.(10).

$$\sigma_{\mathrm{u}} = \alpha_0 \alpha_1 \alpha_b \sigma_{\mathrm{f_u}} v_{\mathrm{f}}\ , \tag{12}$$

in which, α_0, α_1 and α_{b} are orientation factor, length-efficiency factor and bond efficiency factor of fibers respectively. The fiber strength σ_{fu} may be derived from bonding characteristics of fibers as Eq.(13):

$$\sigma_{\mathrm{fu}} = 2\tau(l_{\mathrm{f}} / d_{\mathrm{f}})\ , \tag{13}$$

in which τ=bond strength of matrix.

The ultimate strength σ_{u} of fiber-reinforced concrete is now summarized as

$$\sigma_{\mathrm{u}} = 2\alpha_0 \alpha_1 \alpha_{\mathrm{b}} v_{\mathrm{f}} \tau (l_{\mathrm{f}} / d_{\mathrm{f}})\ . \tag{14}$$

The orientation factor α_0 is known to be about 0.41 for uniformly distributed fiber-reinforced concrete (Oh, 1992), and the bond efficiency factor α_{b} is about 1.0 for straight fibers (Henager and Doherty, 1976). The present study exploits Cox (1952)'s results for length-efficiency factor as follows:

$$\alpha_1 = 1 - \frac{\tanh\ (\beta l_{\mathrm{f}} / 2)}{\beta l_{\mathrm{f}} / 2}\ , \tag{15}$$

where,

$$\beta = \sqrt{\frac{2\pi G_{\mathrm{m}}}{E_{\mathrm{f}} A_{\mathrm{f}} l_{\mathrm{n}} (s / r_{\mathrm{f}})}}\ , \tag{16}$$

$$s = 25\sqrt{\frac{d_{\mathrm{f}}}{V_{\mathrm{f}} l_{\mathrm{f}}}}\ , \tag{17}$$

in which G_{m}=shear modulus of concrete matrix; E_{f}=elastic modulus of fiber; A_{f}=cross sectional area of fiber; s=average spacing of fiber; r_{f}=radius of fiber; d_{f}=diameter of fiber; l_{f}=length of fiber, and v_{f}=volume ratio of fiber. Eq.(14) of fiber-reinforced composite may now be employed to derive the flexural capacity of concrete beams containing steel fibers. The strain profile as shown in Fig.5 has been assumed for a cracked section in pure bending. The concrete has reached its ultimate compressive strain ξ_{c}. The stress block in the compression zone is the one commonly assumed in ultimate strength calculations. It has been adopted under the assumption that the behavior of the fiber-reinforced compression zone is similar to that of one without fiber-reinforcement. Hence k_1 can be obtained from equilibrium conditions.

Equating the total compressive and tensile force, T=C

$$k_1 = \frac{\sigma_{\mathrm{u}} \times b \times (D - k_1 D) + A_{\mathrm{s}} f_{\mathrm{y}}}{0.8075 f_{\mathrm{c}}' bD}\ , \tag{18}$$

in which f_{c}'=cylinder compressive strength of concrete; b=width of the beam; D=overall depth of the beam; v_{f}=volume fraction of the fibers; σ_{u}=$2\alpha_0\alpha_1\alpha_{\mathrm{b}}\tau(l_{\mathrm{f}}/d_{\mathrm{f}})$=ultimate fiber strength incorporating orientation, length and bond efficiency factor; f_{y}=yield strength of tensile steel; A_{s}=area of tensile steel. The flexural capacity is then derived as follows:

Ultimate theoretical moment,

$$\begin{aligned} M_{\mathrm{uth}} &= T \times Z \\ &= (\sigma_{\mathrm{u}} b (D - k_1 D) + A_{\mathrm{s}} f_{\mathrm{y}}) \times (d - 0.475 k_1 D). \end{aligned} \tag{19}$$

This theoretical value is checked for its validity with the experimental results. The ratio of theoretical moment to experimental moment is verified for all the reinforced concrete beams containing fibers. The results given in Table 8 indicate that the conventional flexural theory under-estimates the ultimate flexural capacity of PFRC beams when contribution of fibers is not considered. These estimates are considered reasonably close, in view of the difficulty in establishing the peak load before an abrupt drop is recorded in their experiment. One possible reason for these conservative estimates is the uncertainty in the value of τ. It can be seen that the ultimate bond strength σ_{fu} is expressed in terms of fiber volume concentration v_{f},

Table 8 Comparison of theoretical moment with experimental moment

Beam designation	v_{f} (%)	M_{uth} (kN·m)	M_{uexp} (kN·m)	Ratio ($M_{\mathrm{uth}}/M_{\mathrm{uexp}}$)
API	0.1	10.9888	13.50	0.81
APII	0.2	10.9889	14.25	0.77
APIII	0.3	10.9890	15.00	0.73
BPI	0.1	10.9888	15.00	0.73
BPII	0.2	10.9889	15.00	0.73
BPIII	0.3	10.9890	15.25	0.72
CPI	0.1	10.9888	15.75	0.70
CPII	0.2	10.9889	16.75	0.66
CPIII	0.3	10.9890	16.00	0.69

M_{uth}: theoretical moment; M_{uexp}: experimental moment dynamic bond stress τ, and fiber aspect ratio l_f/d_f. Experimental studies undertaken by many investigators show the wide disparity of bond stress values, with the values depending on the response stage, concrete properties, fiber type and other characteristics. Tests confirmed that different values of τ resulting from various types of fibers could significantly modify the flexural behavior of FRC.

CONCLUSION

The following conclusions were arrived at in the above investigation:

(1) For all the mixes considered in this investigation, there was about 18.6% to 34.39% increase in the ultimate load carrying capacity of the beams containing fibers when compared to the control beam specimens without fibers. This fact concludes that the contribution of fibers in increasing the ultimate load carrying capacity is less.

(2) For all the mixes, the beams with fibers showed significant increase in the deflection values when compared to the control beams. The beams containing 0.2%v_f of the fibers showed the maximum deflections, this was seen for all the three mixes. This phenomenon of increased deflections lays emphasis on the fact that the addition of fibers enhances ductility, with 0.2%v_f of fibers being the optimum dosage to obtain that.

(3) The increase in compressive strength is about 36.25%, 26.20%, and 23.75% respectively that of plain concrete. This increase in strength is directly proportional to amount of fibers present in the mix.

(4) The increase in flexural strength for Mix I, Mix II and Mix III is about 21%, 16.6%, and 23% respectively that of plain concrete specimens.

(5) The addition of fibers does not change the crack pattern as such but there were reduced crack widths, which were observed.

(6) The comparisons of theoretical moment to experimental moment showed that the equation proposed for a reinforced concrete beam containing fibers, is on the conservative side.

(7) The flexural rigidity of the fiber concrete beams is more than their companion beams except for a few cases and the increases are found to be higher for beam AP II (Mix I: 0.2%). The contribution of the fibers to flexural strength is very minimal.

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