METALLIC FIBER REINFORCED CONCRETE: EFFECT OF FIBER ASPECT RATIO ON THE FLEXURAL PROPERTIES

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ABSTRACT

Since many decades efforts have been made to reduce the brittleness of cementitious materials by the use of micro and macro fibers of different mechanical, geometrical and physical properties. This contribution presents the results of an experimental investigation carried out to study the effect of fiber aspect ratio on the flexural properties of metallic fiber reinforced concrete (MFRC). The flexural properties, which have been studied, include maximum load bearing capacity (peak load), post-crack strength and flexural toughness. High performance metallic fibers of different aspect ratios were used. The dosage of fibers was kept 20 kg/m^3 (0.25% by volume fraction) for all the fibered concrete mixtures. Three point bending tests were performed on both control (without fibers) and fibered notched prismatic concrete specimens of cross section 100 x 100mm and clear span of 450mm. The results showed that the flexural properties of concrete matrix are significantly improved by the addition of high performance metallic fibers. Moreover, it was found that the level of improvement in flexural properties of MFRC varies with the aspect ratio of fibers. Out of the two different aspect ratios of metallic fibers used in this study, the fibers with larger aspect ratio showed better efficiency in improving the flexural response of MFRC.

Keywords: fiber reinforced concrete, metallic fibers, aspect ratio, flexural properties.

1. INTRODUCTION

Concrete being a brittle material has low tensile strength and low strain capacity, as a result, the mechanical behaviour of the concrete is critically influenced by crack propagation. Concrete in service may exhibit failure through cracks which are developed due to brittleness [1, 2, 3]. To improve properties of concrete like low tensile and low strain capacity, fiber reinforced concrete (FRC) has been developed which is defined as concrete containing dispersed randomly oriented fibers [4]. Fibers had been used to reinforce cementitious material since ancient times, sun-backed bricks were reinforced by using straw as fiber and masonry mortar and plaster were reinforced using horsehair. Experimental investigation involving the use of discontinuous fibers to improve the properties of concrete was started in 1910 [5]. During the early 1960, the first major investigation was made to evaluate the potential of steel fibers as reinforcement of the concrete [6].

The properties of concrete matrix and of the fibers greatly influence the character and performance of FRC. The properties of fibers which are of interest include fiber stiffness, bond between fiber and concrete matrix, fiber concentration, fiber geometry, fiber orientation, fiber distribution and fiber aspect ratio [7]. The mixture-stiffening or workability effect is a major factor limiting the type, aspect ratio and amount of fibers that can be uniformly distributed throughout a particular cementitious matrix, which in turn determine the degree of improvement in the mechanical properties of composites in hardened state. Ideally the amount of fibers and aspect ratio should be as large as possible to maximise the improvements in the mechanical properties. On the other hand, both should be as small as possible (but compatible with aggregate size) to minimise the mixture-stiffening effect of fibers and associated difficulties in fabricating components from FRC [8].

Metallic fiber reinforced concrete has been extensively studied in last five decades. Powerful characterisation method of FRC properties have to be used in order to get pertinent data required by the structural engineers to design structural elements [9]. Currently, several methods are available which are used to characterise the concrete. These methods are ASTM [10], JSCE standard SF-4 [11], RILEM recommendations [12] and post crack strength (PCS) method [13].

In the construction market, since same fibers are available with different dimensions and the price is paid as per kilogram of fibers, it is important to select fibers with such dimensions which give maximum degree of performance for a particular application. In this contribution, as a case study, high performance metallic fibers of different aspect ratios (ratio of length to equivalent diameter) have been studied.

The objective of the present study was to investigate the effect of aspect ratio of commercially available metallic fibers on the flexural properties of FRC. For this purpose, concrete mixes containing metallic fibers of same mechanical and physical properties but different aspect ratio (125 and 105) at a constant dosage rate of 20 kg/m^3 (low dosage taking into account the high price of fibers) were tested in flexure. The results were analysed using post crack strength (PCS) method [13].

2. MATERIALS AND METHODS

2.1. Materials

The materials used for all concrete mixtures consisted of CEM I 52.5R cement, the coarse aggregates having size range of 4 to 10mm, and the locally available

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natural river sand of maximum particle size of 4 mm. A super-plasticizer was used as an admixture in order to improve the fresh properties of concrete in the presence of metallic fibers. Table-1 show the control concrete mix proportion (MCONT) and Table-2 show different concrete mix proportions used in this study. Each concrete mix has been given a name according to quantity and length of fibers. For example, M20F30, where 'M' stands for mix, 20 is quantity of fibers in kg/m^3, 'F' stands for fibers and 30 is length of fiber in mm.

Table-1. Control concrete mix proportion.

Material	**Quantity** (kg/m^3)
Cement (CEM I 52.5 R)	322
Sand	872
Coarse aggregate	967
Water	193
Super-plasticizer	1.61

Table-2. Different concrete mix proportions.

Concrete mixes	**Designation**	**Fiber quantity (kg/m^3)**
MIX 1	MCONT	-
MIX 2	M20F30	20
MIX 3	M20F20	20

Figure-1 shows the metallic fibers. These fibers are made of amorphous metal (Fe, Cr) 80 (P, C, Si) 20. Tensile strength and modulus of elasticity of fibers are 2000 MPa and 140000 MPa respectively. Rough surface and large specific surface area of these fibers result in high performance with regard to bond strength with matrix. Due to high bond strength with concrete matrix, fibers do not slide from the matrix when micro-cracks appear. At the time of initiation of micro-crack, fibers are immediately tensioned and try to arrest the micro-crack mechanism. Moreover, this fiber is stainless and suitable for use in aggressive environment such as concrete drainage pipe [19]. The geometrical properties of each fiber are given in Table-3.

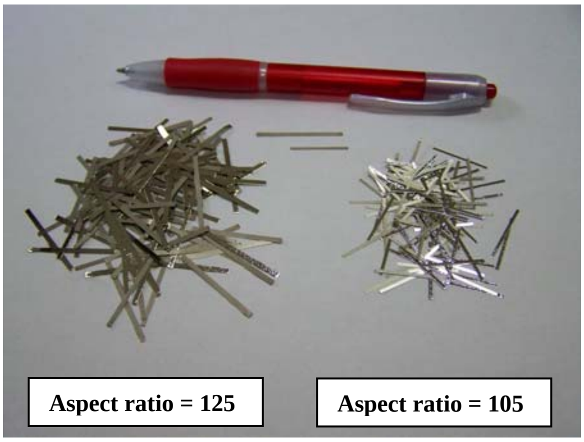

Figure-1. Metallic fibers with different aspect ratio.

Table-3. Geometrical properties of fibers.

Dimension	**Metallic Fiber** (Aspect ratio = 125)	**Metallic Fiber** (Aspect ratio = 105)
Length (mm)	30	20
Thickness (µm)	29	29
Width (mm)	1.6	1.0

2.2. Testing procedure

Three point bending tests were performed on notched beams of cross section 100x100mm with a clear span of 450mm. For each concrete mix, three specimens were tested. The tests were controlled by crack mouth opening displacement (CMOD) at a loading rate of 0.01mm/min up to CMOD value of 0.1mm and then at 0.1mm/min up to completion of test. During each test followings were measured using LVDT as shown in Figure-2a and recorded using computer based data acquisition system (Figure-2b).

- CMOD values
- Mid span deflection

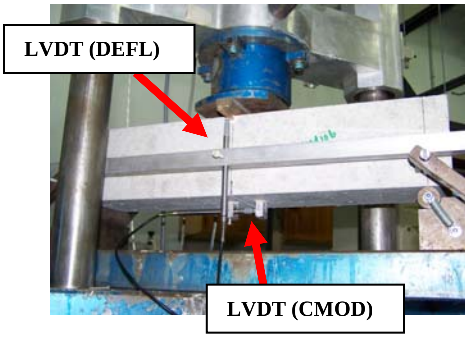

Figure-2a. CMOD and deflection measurement.

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Figure -2b. Complete assembly of the flexural test.

3. RESULTS

3.1. Maximum load bearing capacity (Peak load)

Comparison of the load deflection curves for all mixes is shown in Figure-3, where it can be observed that concrete containing fibers of aspect ratio 125 (M20F30) exhibits high performance in term of maximum load bearing capacity (peak load). Maximum Load carried by M20F30 was 80% more than the control concrete and 27% more than the M20F20. Careful study of the curves also shows that fibers with larger aspect ratio delay the occurrence of peak load (Figure-4) which enables the matrix to bear large deformations before the occurrence of peak load.

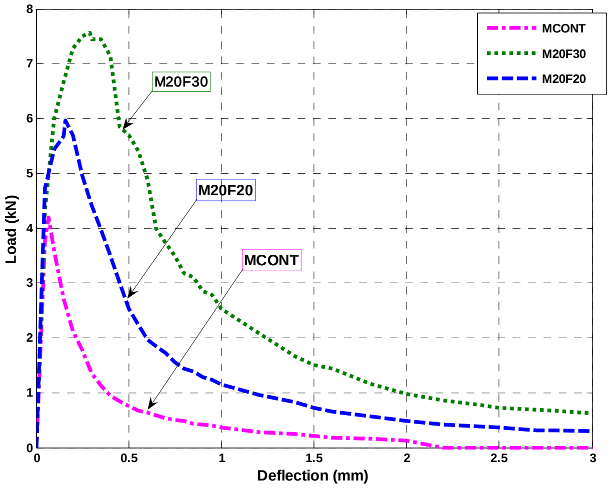

Figure-3. Comparison of load-deflection curves.

3.2. Post-crack strength

In order to study the effect of fiber aspect ratio on the post-peak flexural behaviour, post-crack strength values have been calculated using post-crack strength method [13].

3.2.1 Post-crack strength (PCS) method

The PCS method is a method of converting load-deflection curve into an equivalent flexural strength curve using simple energy equivalence [14]. The procedure of this method [15] is given bellow:

- Locate the peak load and divide the curve into two regions: the pre-peak region before the occurrence of the peak load and the post-peak region after the peak load. Note the value of the load at the peak and measure the area under the curve up to the peak load. This measure of energy is termed as pre-peak energy and denoted as E_{pre} (Figure-5).
- Locate points on the curve in the post-peak region with specimen deflections equal to various fractions of the span L/m1, L/m2, etc. The suggested fractions are between L/3000 and L/150. Measure the areas under the curve up to these deflections, denoted as E total,m (measured at a deflection of L/m).
- Subtract the pre-peak energy E_{pre} from the various values of $E_{total,m}$ to obtain the post-peak energy $E_{post,m}$ values to a deflection of L/m,.
- Calculate the post-crack strength (PCSm) in the post peak region at the various deflections. The PCSm at a deflection of L/m, is defined as Eq. (1):

$$PCS_m = \frac{(E_{post,m})L}{(\frac{L}{m} - \delta_{peak})bh^2} \quad (1)$$

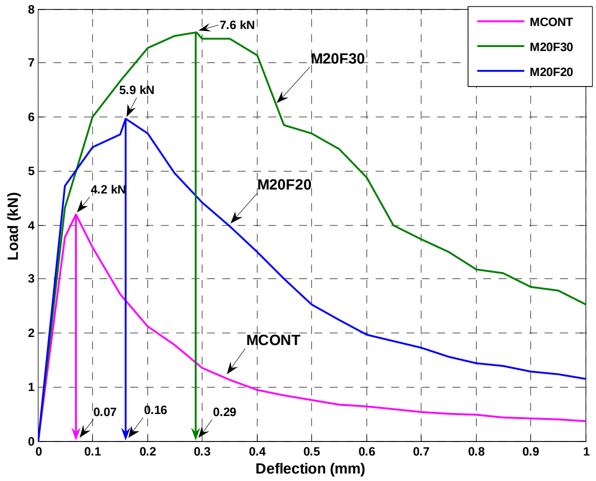

Figure-4. Load-deflection curves (blow up of Figure-3 up to 1mm deflection).

The value of PCS is actually an average residual flexural strength between two deflection points, first is the deflection corresponding to peak load and second is the selected value after the peak load between L/3000 and L/150 as mentioned in the procedure.

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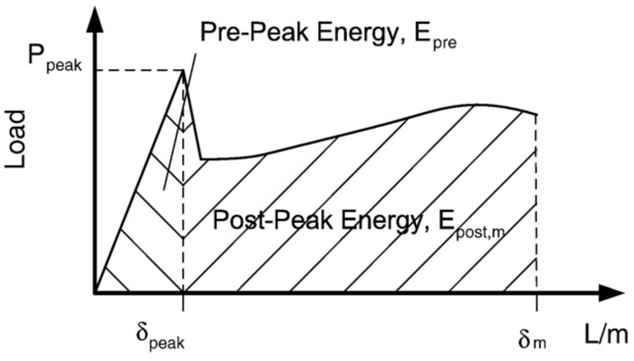

Figure-5. PCS analysis on a FRC beam [13].

Regarding the peak load identification, for some composites with higher volume fraction of fibers, two load peaks may occur, one at the end of matrix contribution and second when fibers reach their ultimate capacity. In such a case, the first peak load corresponding to the end of matrix contribution should be considered [15].

The values of post-crack strength (PCS), calculated at L/1500, L/643, L/450, L/300, L/225, L/180 and L/150, where L is the span of prism, are shown in Figure-6, where, it can observed that post-crack strength is increased appreciably in the presence of metallic fibers. Regarding the aspect ratio of fibers, the mix containing fibers with larger aspect ratio (M20F30) exhibited maximum value of post crack strength at all deflection values. Strength effectiveness of M20F30 compared to unreinforced concrete after the peak was 3 to 4.4 times and with M20F20; it was 2.1 to 2.5 times.

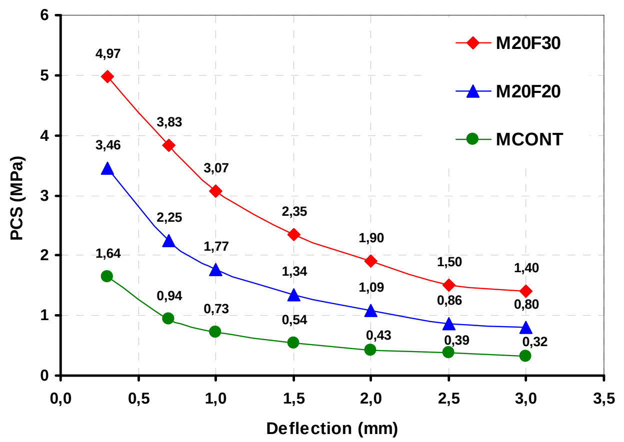

Figure-6. Post Crack Strength (PCS) versus deflection.

3.3. Reduced brittleness and flexural toughness

Area under the load deflection curve is flexural toughness which demonstrates the ductile behaviour of material. In Figure-3, it was observed that in the presence of fibers, the rapid decrease in load bearing capacity after the peak is reduced and relatively flattered curve is obtained over a small range of deflection. Among the two aspect ratios, fibers with larger aspect ratio showed more improved behaviour in term of reduced brittleness after peak and more flattered curve. In this study, flexural toughness has been calculated up to deflection of 3 mm and values are presented in Figure-7. Flexural toughness of M20F30 was found to be 5.1 times high compared to MCONT and 2.8 times high compared to M20F20.

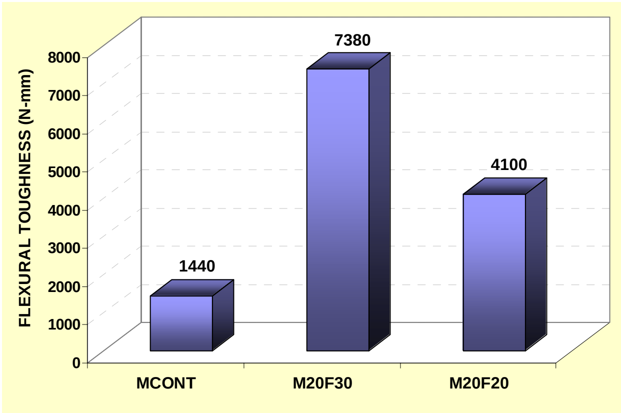

Figure-7. Flexural toughness of un-reinforced and reinforced matrices.

4. DISCUSSIONS

Crack development and propagation of brittle matrix is significantly affected by the presence of metallic fibers. The effectiveness of fibers on the mechanical properties of brittle matrix varies with the geometrical, mechanical and physical properties of fibers. The fibers which have been used in this study develop good bond with he matrix due to surface roughness and large specific surface area, as a results, micro-cracking mechanism before the occurrence of peak load [16] is arrested in the presence of fibers and fibered concrete exhibits high value of peak load compared to control concrete. This is evident from the results obtained in this study about the peak load. When the micro-cracks are developed, the stress in fiber increases gradually with the increase of crack opening and a stage comes when the stress in fiber exceeds its tensile strength capacity resulting in breakage of fiber instead of pulling out from the matrix.

To develop bond with matrix, specific surface area and surface conditions of fiber play an important role. On the other hand, to transfer the stress across the crack edges (bridging action of fibers), length of fiber compatible with maximum aggregate size d_{max} is important. Interfacial transition zone (ITZ) between the aggregate and the cement paste is the weakest phase in the concrete. In order to bridge this zone and to get highest effect of fibers, length of the fiber and the diameter of the aggregate must be coherent with each other [17]. To develop an efficient bridging action, fiber must be embedded into the matrix on both ends beyond the aggregate particles. For that fiber length must be at least greater than 2 times d_{max}, where d_{max} is maximum aggregate size. It has also been stated by Rossi P [18] that to get better efficiency, fiber length should be 2 to 3 times the maximum size of the coarse aggregate (d_{max}). In this study, M20F30 contains fibers with length equal to 3 times the $d_{max,}$ where d_{max} is 10 mm and M20F20 contains fiber with length equal to 2 times the $d_{max.}$ The results obtained showed that despite of less numbers of fibers for a given quantity, fibers of length 3 times the d_{max} are more efficient than fibers of length 2 times the $d_{max.}$

The curves of PCS for three different compositions are shown in Figure-6, where material property has been generated from a structural curve and this property can then be used in analysis, comparative assessment and in design [14]. It can be observed that for the same dosage, among the two different aspect ratios of fibers, the fibers with larger aspect ratio are more effective in strengthening and toughening the plain concrete. For instant, at 0.3mm deflection, PCS value of M20F30 is 3 times the control concrete and for M20F20, PCS value is almost 2 times the control concrete. Similarly at a deflection of 2mm, PCS value of M20F30 is 4.5 times more the PCS value of control concrete and for M20F20, PCS value is almost 2.5 times more the control concrete value.

From this discussion it can be concluded that incorporation of high performance metallic fibers in the plain concrete increases the peak load, residual flexural strength and energy absorption capacity. Moreover, regarding the two aspect ratios of fibers studied, fibers with larger aspect ratio are more effective than the fibers with smaller aspect ratio because of the larger specific surface area and enough anchorage length beyond the crack edges.

5. CONCLUSIONS

Study of the effect of aspect ratio of the metallic fiber on the maximum load bearing capacity (peak load) , residual flexural strength and flexural toughness (energy absorption capacity) of FRC made it possible to draw following conclusions limited to type, dosage and aspect ratio of the fibers used in this study:

- Maximum load bearing capacity (peak load), residual flexural strength and flexural toughness unreinforced matrix are significantly increased by the addition of metallic fibers.
- For a given contents, fibers with larger aspect ratio showed better efficiency in increasing the load bearing capacity (strengthening effect), residual flexural strength and area under the load-deflection curve (toughening effect) despite of the fact that number of fibers are less compared to fibers with smaller aspect ratio.
- For effective bridging action across the crack, the fiber aspect ratio must be selected taking into account the maximum aggregate size.
- At 2 mm deflection (considerably large value of deflection for span of 450mm), residual flexural strength of mix containing fibers of aspect ratio 125 was 4.5 times higher than the value with control mix and with mix containing fibers of aspect ratio 105, it was 2.5 times high compared to control mix.
- In the post-peak region of FRC, PCS method is useful tool to study the contribution of fibers in improving the residual flexural strength and energy absorption capacity of FRC.

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