Influence of Fibre Content on Crack Propagation Rate in Fibre-Reinforced Concrete Beams

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Amir M. Alani, Morteza Aboutalebi, and Martin J. King

Abstract**—**Experimental study on the influence of fibre content on crack behaviour and propagation in synthetic-fibre reinforced beams has been reported in this paper. The tensile behaviour of metallic fibre concrete is evaluated in terms of residual flexural tensile strength values determined from the load-crack mouth opening displacement curve or load-deflection curve obtained by applying a centre-point load on a simply supported notched prism. The results achieved demonstrate that an increase in fibre content has an almost negligible effect on compressive and tensile splitting properties, causes a marginal increment in flexural tensile strength and increasesthe Re3 value.

Keywords**—**Fibre-Reinforced Concrete, Crack, Flexural Test, Ductility, Fibre Content, Experimental Study.

I. INTRODUCTION

THIS paper aims to investigate the mechanical properties of synthetic fibre reinforced concrete beams. The effect of varying volumes of fibre on the post-crack behaviour of beams is reported. The rapid increase in the use of steel and synthetic fibre reinforced concrete in civil and engineering applications in recent decades is due to the numerous benefits. Improved toughness, resistance to crack propagation, and light weight are just examples of the benefits.

The gap in knowledge relating to the behaviour of synthetic fibres (e.g. polypropylene and nylon) and its effect on concrete as reinforcement has restricted its application mainly to control the early cracking (plastic-shrinkage cracks) in slabs [1]. Unfortunately, even the experimental results reported conflict. Some researches such as Bentur and Mindness [2], Tchrakian, O'Dwyer and West [3] and Kazemi and Lubell [4] report a significant improving effect on the peak strength and post-peak ductility in compression, flexure and direct shear as the fibre volume fraction increases. The information provided by other studies such asCasanova and Rossi [5], Zhang and Stang [6], Lok and Xiao [7] and Dhir et al. [8] indicates that the influence mentioned previously is negligible. Also, as explained in the 2007 edition of Technical Report No. 65 [9], the use of macro synthetic fibres does not have any significant structural effect on the concrete, which would be expected of traditional steel bar or fabric reinforcement. Various research papers have looked at how the introduction and dosage of fibres in a concrete mix affect the compressive strength of the hardened concrete. Richardson [10] suggested that a higher dosage of polypropylene fibres would lower the compressive strength. Hasan, Afroz and Mahmud [11] found a mild increase in compressive strength in relation to fibre content and Richardson, Coventry and Landless [12] found no effect on compressive strength to record. These conflictions, as alluded to earlier, reveal a critical gap in knowledge which will be studied further in this paper.

Unlike traditional concrete design with steel bar or fabric, which uses clearly set out design codes, there is little guidance on concrete design using fibre reinforcement. Design using synthetic fibres relies heavily upon manufacturer's guidance, whereas steel fibres have better developed independent design guides available to assist in their correct use [9]. Specifications of the synthetic fibres themselves have been set out in BS EN 14889-2 [13] but these only cover properties of the reinforcing material and not its use.

II. THEORETICAL BACKGROUND

Fibre-reinforced concrete (FRC) is a cement-based composite material reinforced with discrete and usually randomly distributed fibres. Hsu et al. [14] showed that there are incipient microcracks at the surface of the larger coarse aggregate particles. These cracks exist in a zero load condition.

As concrete is stressed due to various loading conditions, including fatigue, the microcracks are propagated along the faces of the aggregate and under appropriate conditions propagate through the concrete matrix to adjacent coarse aggregate particles. These cracks exist in a zero load condition.

As the crack tip progresses through the matrix, as discussed above, the width of the propagating crack increases. For fibres passing through and resisting the microcrack widening, the development of the required stress in the fibre is provided by both:

- surface bond effects between the cement paste and the fibre; and
- mechanical anchorage mechanisms due to fibre shape, which enhance the effect of surface bond or act as an

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alternative should stress levels in the matrix exceed the surface bond effects, which have been estimated to be in the order of 3 MPa.

For straight fibres, the length of fibre required to provide a sufficient surface area for bond to develop the tensile strength of the fibre results in fibre length being excessive, in terms of adversely affecting the plastic state properties of the concrete. This can result in the undesirable 'balling' of fibres and / or difficulties in placing, compacting and finishing of the concrete.

Fibre manufacturers have addressed the challenges presented by straight fibres by providing various mechanical anchorages in the fibre shape. These can be classified into two distinct types: continuously deformed and end-anchored.

Continuously deformed fibres provide a defined mechanical anchorage mechanism close to the position of any propagating crack, leading to greater restraint and stress redistribution into the surrounding matrix.A number of fibre manufactures have elected to provide mechanical anchorage effects by the end anchorage technique by providing deformed ends.

These fibres, under the developing stress from the propagating microcrack, progressively lose surface bond dependent on the effectiveness of the end anchorage. They then bridge the developed crack over the length of the debondedfibre. The literature published by the purveyors of this type of fibre shows diagrams of cracks which have been bridged with the stressed fibre.

When the stress in the concrete exceeds this 'balanced' macro crack condition the end anchorage is lost and thedeformed ends either slide through the void cast into the cement paste in a straightening mode, or alternativelyslip by local crushing of the matrix as the end pulls through. The purveyors of these end anchorage fibres definethis as the preferred failure mechanism. The fibre stress, at which fibre pull-out occurs, relative to the tensilecapacity of the fibre, is not defined.

Other suppliers have taken the philosophy that it is more appropriate to restrain the propagating crack anddisperse the stress into the surrounding matrix by a combination of surface bond and closely spaced mechanicalanchorages along the length of the continuously deformed fibre.

The tensile behaviour of metallic fibre concrete is evaluated in terms of residual flexural tensile strength values determined from the load-crack mouth opening displacement curve or load-deflection curve obtained by applying a centre-point load on a simply supported notched prism as illustrated in Fig. 1.

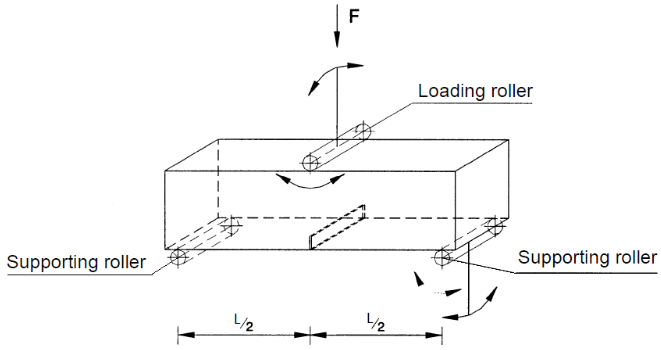

Fig. 1 Arrangement of loading of test specimen [15]

The test specimens shall be prisms conforming to EN 12390-1 with a nominal size (width and depth) of 150 mm and a length L so that 550 mm ≤ L ≤ 700 mm. The specified shape and size of test specimens are suitable for concrete with aggregate no larger than 32 mm and/or metallic fibres no longer than 60 mm.

Before testing can takeplace the beams should be notched. This involves cutting a 25mm deep, 5mm wide notch from thecentre of the beam on the underside. Thisencourages the beam to split at this point directlybelow where the load will be placed.

The flexural tensile strength test provides several important pieces of informationabout the samples. The Limit of Proportionality (LOP), the average residual flexuraltensile strength at a given crack mouth opening displacement (CMOD) and the Re3 are just samples.

The LOP is the load which can be applied until the beam departs from the initiallinear response. The Re3 "is a measure of ductility and is the average load applied as a beam deflects to 3mm expressed as a ratio of load to first crack" [16].

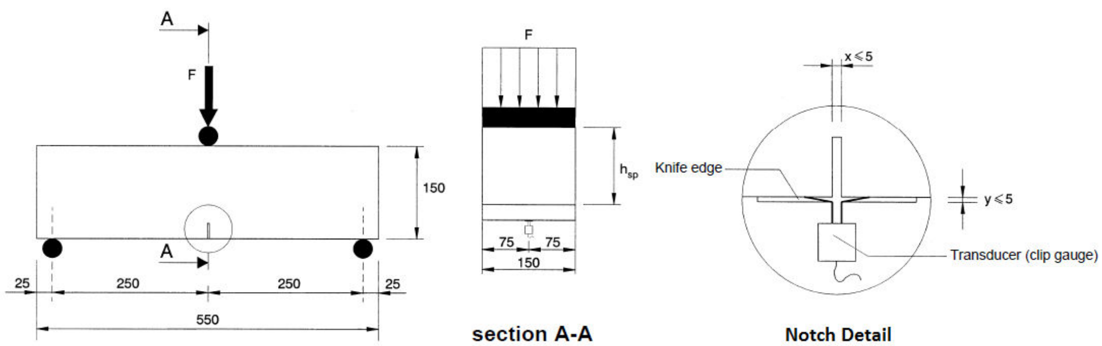

Fig. 2 Typical arrangement for measuring CMOD (all dimensions in mm, [15])

In Fig. 2, $h_{sp}$is the distance between the tip of the notch and the top of the specimen in the mid-span section.Much of the design of fibre reinforced concrete looks at the Re3 value of the fibres. When designing floor slabs, a major use of fibre reinforced concrete, the Re3 value isused to calculate the positive moment capacity. It is not used in the calculation ofnegative moment capacity as "it is assumed that the limiting criterion is the onset ofcracking at the top surface" ([16], p. 9.8.1) The Re3 value is provided by themanufacturer of the fibre and will normally be given for a specific strength concrete.The LOP is an important piece of information as it allows for calculations of firstcrack to be found. After the LOP has been reached the concrete has begun to crackand then behaves plastically.

Based on the beam and loading alignment in Fig. 1, the bending moment at mid-span of the test specimen corresponding to the centre-point load F is:

$$M = \frac{F}{2}\frac{L}{2} \quad (1)$$

where L is the span length.

Assuming a linear stress distribution as shown in Fig. 3, if the force and moment corresponding to Limit of Proportionality are respectively denoted as F-L and M-L then the LOP will be given by the expression:

$$f_{ct,L}^{f} = \frac{6M_L}{bh_{sp}^2} = \frac{3F_L L}{2bh_{sp}^2} \quad (2)$$

where b denotes the width of the beam specimen.

The load-CMOD diagram of the fibre reinforced concrete beams in the notched flexural tensile strength test might exhibit different patterns. To find the correct LOP and consequently to recognise the precise amounts for F-L and M-Lthe four common cases for the load-CMOD diagram are illustrated in Fig. 4.

There are four values for CMOD at which the residual tensile stress of the beam should be recorded. These values are 0.5mm, 1.5mm, 2.5mm and 3.5mm. They are called $CMOD_1$, $CMOD_2$,$CMOD_3$ and $CMOD_4$, respectively. They will be noted as $CMOD_j$(j=1,2,3,4) for the sake of convenience. The residual flexural tensile strength $f_{R,j}$ (j=1,2,3,4) indicating the corresponding stresses at $CMOD_j$(j=1,2,3,4) will then be found by the expression:

$$f_{R,j} = \frac{6M_j}{bh_{sp}^2} = \frac{3F_j L}{2bh_{sp}^2} \quad (3)$$

It is obvious that F_j and $M_j$in this equation describe the force and moment corresponding to $CMOD_j$ (j=1,2,3,4).

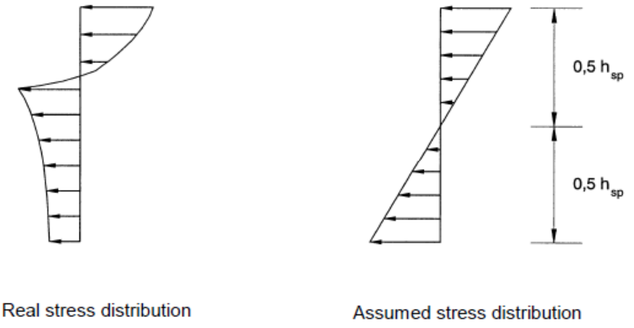

Fig. 3 Stress distribution in the specimen [15]

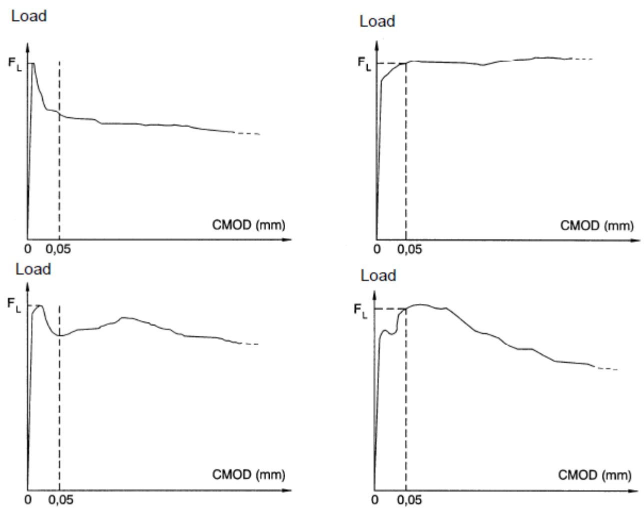

Fig. 4 Recognising $F_L$in load-CMOD diagram [15]

Fig. 5 illustrates a typical load-CMOD diagram and the four F_j corresponding to the values of $CMOD_j$(j=1,2,3,4).

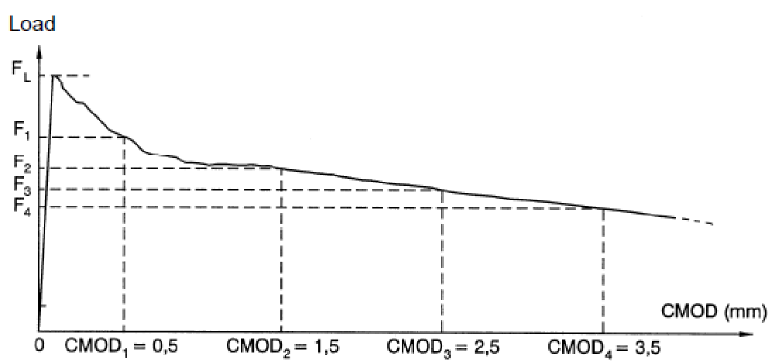

Fig. 5 Typicaldemonstration of $CMOD_j$ (j = 1,2,3,4) and corresponding F_j [15]

III. Experimental Procedure

The first stage in the testing process was the selection of a synthetic fibre and aconcrete mix.Previous research carried out at the University ofGreenwich [17] was aimedat fibre reinforced ground supported slabs. As one of the main commercial uses of fibre this scenario for the use of fibres seemed the most logical to apply. Theprevious testing carried out has included the testing of macro synthetic fibres and in order to continue adding to the research base it was decided to select the same fibre and mix design.

TABLE I
Concrete Mix Design Proportions (per m^3)

Material	Quantity	Unit
10/20mm gravel	747	Kg
4/10mm gravel	385	Kg
Sand	831	Kg
Cement (premium cement CEM ll/A-L)	153	Kg
GGBS (Hanson GGBS)	153	Kg
Water reducing agent(SikaTwinflow 05)	1.1	Lt
Total water	165	Lt

The fibre selected is produced by Elasto-Plastic Concrete (EPC) and is titled Barchip Shogun. It is a macro synthetic fibre; class II, as defined in [13]. The fibre was added to the mix in quantities of 6 kg/m^3, 7 kg/m^3 and 8kg/m3.Before production, all aggregates were kiln dried and stored in air tight containers to minimise any increase in water content and to controlthe water content in the concretemore effectively.

The following table gives the material properties as supplied by EPC.

TABLE II
Barchip Shogun Properties

Characteristic	Material property
Base resin	Modified Olefin
Length	48mm
Tensile strength	550Mpa
Surface texture	Continuously embossed
No. of fibres	35000 per kg
Specific gravity	0.90-0.92
Young's Modulus	10Gpa
Melting point	150°C-165°C
Ignition point	Greater than 450°C

The testing was designed to gather a range of the mechanical properties of the produced concrete.As a result the following tests were selected:

- Compressive cube strength (100x100x100mm cubes)

Test conducted in accordance withBS EN 12390-3at a rate of2.5kN/swith three tests being carried out at seven and 14 daysand four being carried out at 28 days for each mix design.

- Tensional splitting of cylinders (150mm diameter x 300mm)

Test performed at a loading rate of2.2kN/swith three tests being carried out at seven days and three being carried out at 28 days for each mix design.

- Flexural tensile strength (150mm x 150mm x 565mm)

Experiment was in accordance with [15]. Three beams were tested at seven, 14and 28 days.

Five beams were produced from each of the three batches, all being loaded in accordance with the Rilem testing method procedure. The beams were loaded onto a vibrating table toensure full compaction of the sample. Five cubes and three cylinders were produced using steel cube, cylinder and beam moulds. These moulds were all BS EN 12390-2 compliant and all samples were cast using thevibrating table to ensure full compaction. The moulds were stored in the concrete labat a temperature of 20°C +/- 5°C and were covered with damp hessian cloth andplastic to avoid dehydration of the samples.

IV. Numerical Results

As alluded to earlier, the compressive strength of the ten 100x100mm cubes for each mix design of 6kg/m^3, 7kg/m^3 and 8kg/m^3 added fibre was tested in accordance with BS EN 12390-3 using an AveryDenison 7226CB/T85234. Cubes were tested at seven, 14 and 28 days to show not only the final mechanical properties but also the development of these properties over time. The average compressive strength results are presented in Table III and the variations are illustrated in Fig. 6.

The last column in Table III gives the percentage difference of the compressive strength results for each mix to the corresponding amount for the mix design with 6kg/m3 added fibre. The compressive strength results show a small variation in compressive strengthbetween the three different mixes.

TABLE III
Average Compressive Strength Results

Mix	Age at test (Days)	Fibre content (kg/m^3)	Average stress at Fail (kN)	% Difference
1	7	6	33.39	0
2	7	7	32.73	-1.97
3	7	8	34.36	+2.91
1	14	6	40.18	0
2	14	7	41.88	+4.23
3	14	8	42.92	+6.82
1	28	6	49.17	0
2	28	7	47.37	-3.66
3	28	8	49.75	+1.18

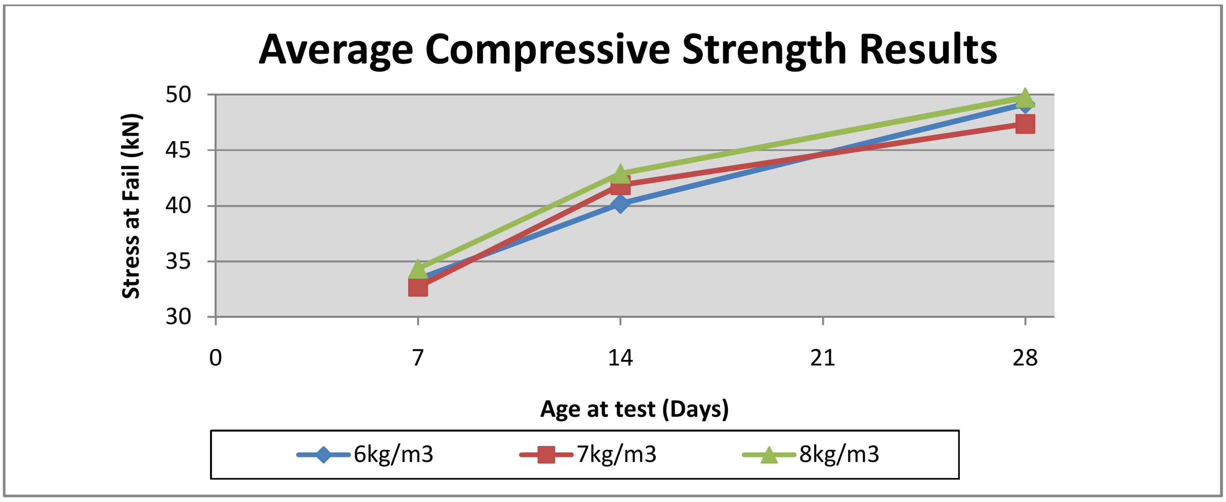

Fig. 6 Average compressive strength results

The results show both a positive and negative variation ranging from -3.66% to +6.82%. Due to the nature of the variations ranging between positive and negative values and of only small percentages it is sensible to assume that this variation is due to natural inconsistencies in a heterogeneous material such as concrete.

The concrete strength improved over the 28 day period as would have been expected. No significantly anomalous results were recorded. This indicates that the batching of the concrete was controlled effectively.

Six tensile splitting tests were completed for each mix design of 6kg/m3, 7 kg/m3 and8 kg/m3. Cylinders of 150mm diameter and 300mm length were tested at seven and 28days using the Avery Denison 7226CB/T85234.

As revealed in Table IV, the tensile splitting strength tests again showed both a positive and negative percentage difference when compared to the base mix of 6kg/m^3.

TABLE III
AVERAGE TENSILE SPLITTING STRENGTH

Mix	Age at test (Days)	Fibre content (kg/m^3)	Average splitting strength at fail (kN)	% Difference
1	7	6	2.89	0
2	7	7	2.87	-0.69
3	7	8	2.87	-0.69
1	28	6	3.84	0
2	28	7	3.77	-1.82
3	28	8	4.13	+7.55

A range of between-1.82% and + 7.55% was recorded as illustrated in Fig. 7. On the seven day tests a variation of only -0.69% was recorded for both mixes with 7kg/m^3 and 8kg/m3fibre contents. Again it is sensible to assumethat these variations are linked only to the nature of the concrete rather than specifically to the fibre content.

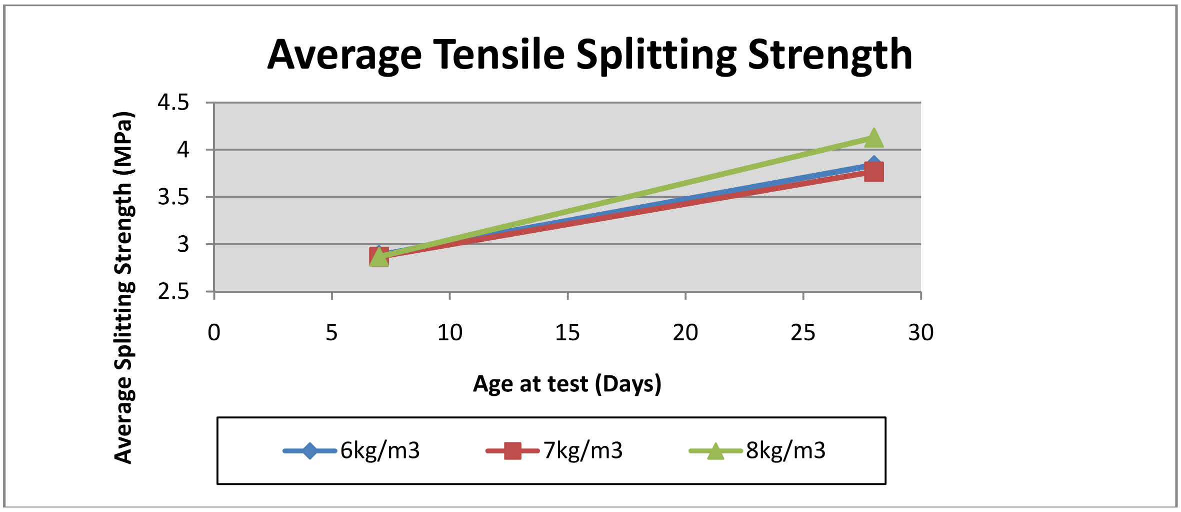

Fig. 7 Average tensile splitting strengthresults

Nine 560x150x150mm notched beams were tested using a DARTEC M100/2E testingapparatus, which were carried out in accordance with BS EN 14651. The beams weretested at seven, 14 and 28 days. The Limit of Proportionality (LOP), the average residual flexural tensile strength at a given crack mouth opening displacement (CMOD) andthe Re3% values were all obtained for the samples.

TABLE IV
AVERAGE FLEXURAL TENSILE STRENGTH RESULTS

Mix	Age at test (Days)	Fibre content (kg/m^3)	Average LOP (N/mm^2)	Average residual flexural tensile strength (MPa) at given CMOD values				Average Re3%
				CMOD= 0.5mm	CMOD= 1.5mm	CMOD= 2.5mm	CMOD= 3.5mm	
1	7	6	4.07	1.60	1.40	1.37	1.30	38
1	14	7	4.7	1.93	1.80	1.80	1.63	41.33
1	28	8	4.83	1.60	1.63	1.60	1.53	36.33
2	7	6	4.07	2.10	2.13	2.07	2.07	54.67
2	14	7	4.47	2.10	2.00	1.87	1.73	46
2	28	8	4.87	2.03	2.07	2.17	2.10	45.33
3	7	6	4.23	2.37	2.50	2.47	2.37	59
3	14	7	4.63	2.50	2.53	2.40	2.17	53.33
3	28	8	5.27	2.33	2.13	2.30	2.23	45

A sample of the notched beam flexural tensile strength result is illustrated in Fig. 8.

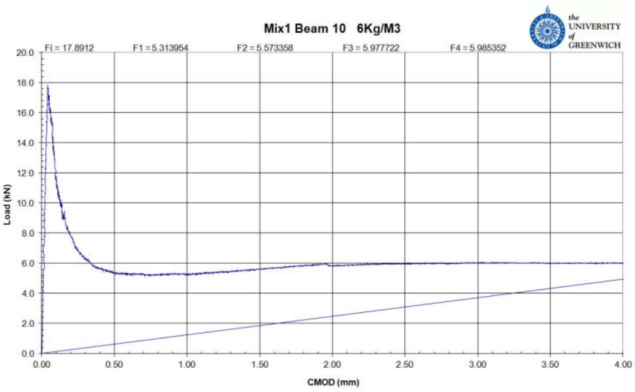

Fig. 8 6kg/m^3 28day notched beam flexural tensile strength

The LOP results ranged from -4.89% to + 9.11%variation from the 6kg/m^3 mix. Again due to the nature of the random variationsbetween positive and negative difference and due to the small magnitude of variationit is assumed that this result is simply due to the heterogeneous nature of concrete.

The residual flexure tensile strength provides data to show how much force the beam can resist at a given deflection. This is an important factor in situations such as ground supported floor slabs. The higher the residual flexural tensile strength the moreeffective the concrete will be at deformation under load. The results seen here show that the residual flexural tensile strength increased as the fibre content of concreteincreased. Atseven day tests this improvement was most obvious with an increase of 70.4% and 97.96% from the 6kg/m^3 mix for the 7kg/m^3 and 8kg/m^3 mixes respectively. At 28 days this difference dropped to 31.6% and 41.35% respectively.Taking an average of the seven, 14 and 28 day test results shows an improvement of 32.61% and 53.55% for the 7 kg/m^3 and 8 kg/m^3 mixes over the 6 kg/m^3 mix.

The Re3 value is perhaps the most important value here as it is this which is used in calculations for floor design. The Re3 value was seen to increase as the fibre contentincreased. Again this was most obvious at the seven day test with improvements of 43.87% and 55.26% recorded for the 7kg/m3 and 8 kg/m^3 mixes over the 6 kg/m^{3}mix. At 28 days this increase had dropped to 24.77% and 23.86% respectively.

The Re3 value decreases as the concrete ages and is assumed commercially to havereached its design value at 28 days. The 8 kg/m^3 mixes declined, following a clearlinear line when plotted against age, whereas the 6 kg/m^3 and 7 kg/m^3 mixes do not demonstrate such a linear decline.

V. CONCLUSIONS

This manuscript sets out to investigate the effect ofincreasing the volume of macro synthetic fibres on the mechanical properties of concrete. The literature review identified a gapin knowledge on the mechanical properties when fibre content was varied.

Compressive, tensile and flexural tests were carried out on samples containing three different volumes of fibre: 6kg/m^3, 7 kg/m^3 and 8 kg/m^3.

Compressive strength results from all three fibre volumes were seen to be similar. Nonoticeable effect on the compressive strength of the concrete was recorded. Minorvariations either positively or negatively were recorded but these are attributed to theheterogeneous nature of concrete.

Seven day tests showed almost identical results for the tensile splitting strength. 28 dayresults showed a mild increase for the 8kg/m^3 mix of 7.55% over the 6kg/m3 results.However the 7kg/m^3 mix showed a 1.82% decrease in strength compared to the6kg/m^3 mix. These variations could again be down to the heterogeneous nature of theconcrete.

The flexural tensile strength tests provide several important mechanical results. The LOP, residual flexural strength and Re3.The LOP results show a variation ranging between -4.89% and +9.11% from the basemix of 6kg/m^3. The variations shown do not suggest a notable effect from anincrease in the fibre volume. As the fibres are not designed to affect the elasticproperties of the concrete this behaviour was expected.

The residual flexural strength results show an increase as the fibre volume increases. This was most evident in the seven day tests. Increases of 47.62% and 71.25% were recorded for the 7kg/m^3 and 8kg/m3 mixes respectively. At 28 days this had decreasedto only a difference of 31.6% and 41.35% gain over the 6kg/m3 for the 7kg/m3 and8kg/m3 mixes.

The Re3 values also increased as the fibre volumes increased. At seven day tests the7kg/m3 and 8kg/m3 mixes had increased by 43.87% and 55.26% respectively. At 28days this increase had again decreased to only 24.77% and 23.86% respectively. It isimportant to note that the 28 day strength of the 7kg/m3 mix showed a higher Re3 value than the 8kg/m3 mix.

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