Equating Steel And Synthetic Fibre Concrete Post Crack Performance

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Abstract**-- Establishing toughness performance in concrete using steel fibres is well understood and design guides are available to assist with this process. What is less readily understood is the use of Type 2 synthetic fibres to provide toughness. This problem is exacerbated by the wide range of synthetic fibres available, with each different fibre providing different structural/material properties.**

This paper examines the relative pull out values of two single fibre types, being steel and Type 2 synthetic fibres. The pull out test results have informed the doses of fibre additions to beams which have been used to equate near equal toughness performance for each fibre type. The results show that synthetic Type 2 fibres when used at a prescribed dose can provide equal toughness to steel fibre concrete. The residual loads analysed at crack mouth opening displacements were examined and conclusions were drawn. It was noted, using mean values, that a steel fibre dose of 30 kg/m^3 provided sufficient post crack residual flexural strength to exceed the minimum requirements of BS EN 14651:2005+A1:2007. A synthetic fibre dose of 7.44kg/m^3 also complied with the BS minimum requirements, albeit at a lower load transfer in the early stages of post crack performance, however the synthetic fibres performed equally as well as steel fibres at crack mouth opening displacement (CMOD) 3 and 4.

This test when compared to other research using synthetic fibres to provide post crack strength highlights the difference a synthetic fibre type can make in terms of structural performance.

Key words: Steel fibres, synthetic fibres, toughness, beam, load, residual strength

I. Introduction

The post crack performance of reinforced concrete can be improved with the use of steel rebar, steel fabric or fibres. The individual performance of synthetic and steel fibres vary considerably due to steel having an elastic modulus in region of 205,000 N/mm^2 whereas polypropylene has an elastic modulus of around 3500 N/mm^2. The individual load transfer capacity of steel and synthetic fibres, vary considerably due to the difference in cross sectional area of the fibre and the ability to bond to the concrete matrix. When all of these parameters are considered, it is very difficult to easily equate equal performance using very different materials with different shapes, aspect ratios, bond strength and tensile capacity.

Richardson et al. (2010) have shown that near equal performance can be achieved with suitable dosages of steel and synthetic fibres, allowing the designer to make an informed judgement. The previous work equated performance by examination of pull out values which in turn informed the relative fibre dose between synthetic and steel fibre types. This research extends the previous work by applying a different test method and using different fibre types.

Destrée (2007) reports that it is now possible in some applications to replace traditionally used reinforcement with concrete that is reinforced by fibres alone. Concrete is used widely because of its high compressive strength, however concrete has low tensile strength, cracking easily under tensile forces. Therefore in order to counteract this material deficiency; reinforcement is necessary to prevent cracks and failure of the material. Traditionally, reinforcing concrete is achieved by using rebar, or steel mesh, in quantities dependent upon the function and application of the concrete member or floor slab. Recent increases in the cost of steel plus the importance of sustainable design and construction are causing the industry to look toward to greener and more cost effective solutions and fibres may partially fulfil this role, particularly synthetic Type 2 fibres.

The recommended dosage for steel fibre addition to concrete is 15 to 45 kg/m^3 (Propex 2006), therefore a concrete design mix with fibre addition at a mid point between the minimum and maximum parameters was considered a good starting point for this work.

II. Concrete Mix Design

The concrete mix design used is in accordance with BS EN 14845-1:2007, reference concretes for fibre testing, where the maximum cement content was applied to the design mix. It was chosen to ensure adequate cement paste was available to coat the fibres, however the synthetic fibres will require more cement paste as they have a larger surface area and number when compared to steel fibres.

Table 1 below shows the relative proportion of batching quantities for the C35 mix design which is a structural grade concrete widely used in industry.

TABLE I
Concrete Mix Design per m^3.

Material	Quantity (kg)
Cement CEM 1 (42,5 N)	400
Sand (0-4mm)	680
Gravel (10 - 20 mm)	1090
Water cement ratio	0.55

The cement type is defined within BS EN 197 and the aggregates are UK sourced. The quality of the mixing water for production of concrete can influence the setting time, the strength development of concrete and the protection of reinforcement against corrosion. Potable water, described as water which is fit for human consumption is suitable to use according to BS EN 1008: 2002, was used in the batch production.

III. ATERIALS – FIBRES AND ORIENTATION

The fibres used in this research are steel and synthetic, and these are shown with the salient properties stated in Table 2 below.

TABLE II
Fibre data

	Steel fibres	**Synthetic fibres**
Length	50mm	45mm
Section	1mm Diameter	1mm x 0.5 mm
Aspect Ratio	50	45
Deformation	Offset hooked end	Crimped – along one axis
≈ Modulus	205000 N/mm^2	3500 N/mm^2

The steel fibres are cold drawn wire fibres that conform to BS EN 14889-1:2006 and the synthetic fibres are polypropylene macro fibres which conform to BS EN 14889-2:2006.

The number of effective fibres is not only dependent of the fibre dosage but also of the orientation factor and length efficiency factor (Dupont and Vandewall 2005). The fibre orientation is influenced by the boundary conditions where the faces of the beams encourage the fibres to lie parallel to them, thus providing enhanced reinforcement at the boundary for a distance from the boundary of half the fibre length. The corner of any mould boundary will exacerbate the orientation effect. The reason for this is that two boundaries affect the corner of a concrete sample to a distance of half the fibre length (Dupont and Vandewall 2005).

It is generally accepted the strength of the concrete has little effect on the failure load for the fibres, as it is the bond between the concrete and the fibre that breaks first (Bentur 1997). The final post crack load will be influenced by fibre direction, total number of fibres, fibre type and concrete type. Parviz and Cha-Don Lee (1990) concluded that, only 65% of the fibres should be considered for structural analysis, and from previous research (Richardson 2007) it should be considered that this figure may be slightly too high and caution should be exercised when establishing performance parameters.

IV. METHODOLOGY

Three main standard methods are available that analyse the post crack performance of concrete and these are British Standard EN 14851, ASTM (American Society for Testing and Materials) 1018 and JSCE SF – 4 (Japan Society Civil Engineers). The Japanese standard provides Re3 values that equate to 90% of the residual load divided into the maximum load at failure and these are used in TR 34 to calculate floor slab design. TR 34 is under revision to incorporate BS EN 14851 into the design code and new data is currently being sought regarding fibre performance.

ASTM 1018 was one of the previous methods for calculating toughness of concrete, which is no longer current. The results were in the form of dimensionless toughness indices to describe the toughness of a sample by analysing the load deflection curve. This however cannot easily be applied to industry, as the indices have no dimensional value to use in load calculations for manufacturers or designers. This has now been superseded by ASTM 1399 which operates a two point loading system that provides residual loads at specific deflections.
The BS EN 14851 method as chosen for this study uses load versus. Crack mouth opening displacement (CMOD) method to give a flexural strength value at multiple points of deflection as well as a value of the limit of proportionality (LOP) at first crack. This allows application of a dimension to results that are useable and easily understood by designers in industry when wishing to control structural and thermal cracking in structural concrete.

In order to equate the values of post crack toughness of the steel and the synthetic fibres when used in beams, pullout tests were used to establish the bond strength relationship between the two fibre types. Six concrete cubes were cast with six fibres embedded into the surface concrete to a depth of 22.5mm. Three cubes were used for steel fibres and three were used for synthetic fibres. After14 days of curing, pull out tests were carried out to determine the maximum load each fibre could sustain and then the bond strength in N/mm^2 per fibre was calculated. Weights were added to a hanger attached to the individual fibres until slippage was recorded at which point no further mass as added for the synthetic fibres and a small addition for the steel. Once the individual fibre performance had been evaluated, the steel and synthetic fibres were balanced to provide near equal performance using CMOD values as post crack performance indicators.

Six 150 x 150 x 650mm beams were cast of each fibre type and allowed to cure in water for 28 days. The beams were then subject to a flexural strength test. A load was applied to the beam through a three point loading frame at 0.05 mm/min. until the CMOD reached 0.5 mm then the rate was increased to 0.2 mm/min until ultimate limit state was achieved.

The test method was carried out to BS EN 14651:2005+A1:2007, and all of the load/deflection charts were converted to load/CMOD charts for every beam tested.

The charts were used to calculate the limit of proportionality (LOP) values and crack mouth opening deflection ($CMOD_j$) values. LOP describes the strength of a specimen at point of first crack while $CMOD_j$ describes the residual post crack flexural strength of a specimen at a given point. The four points of measurement are shown below:

- $CMOD_1$ = 0.5mm (minimum value of 1.5 N/mm^2
- $CMOD_2$ = 1.5mm
- $CMOD_3$ = 2.5mm
- $CMOD_4$ = 3.5mm (minimum value of 1.0 N/mm^2

The $CMOD_j$ values are units of flexural strength given as N/mm^2. This is distinctive to the British Standard method of interpretation and extremely useful to engineers. This is because the data gathered from load/CMOD graphs is the basis for calculating $CMOD_j$ values which an engineer can use for floor slab design.

V. Steel and Synthic Fiber pull outtest data

Pull out values depend upon the bond between fibre and concrete, when a constant dead load is applied. The mean compressive strength of the concrete as manufactured was 37 N/mm^2 at 14 days and the density was between 2354 and 2365 kg/m^3. The density is above the nominal value for normal concrete of 2307 kg/m^3 as shown in BS 648. Steel fibres failed at 6.6 N/mm^2 and synthetic fibres failed at 2.5 N/mm^2. The synthetic fibres failed due to creep and once the initial movement started, de-bonding was progressive and failure occurred without the need to add further weights. The steel fibres took on average an additional 10% to create failure conditions from the initial pull out. All of the steel fibres failed due to pull out and all but one of the synthetic fibres failed by breaking before pull out occurred. This mode of failure of the synthetic fibres showed the potential bond strength of the fibres relative to the bond strength of the concrete.

As expected the individual synthetic fibres failed at a load significantly lower to that of the steel fibres, as polypropylene has a much lower Young's modulus than that of steel. In order to balance the values of fibre performance for the flexural tests, the bond strength of both fibre types was established and a ratio of bond strength for steel and synthetic fibres was established for equal performance when used in beams. The average bond strength of steel fibres was 6.62N/mm^2 and the average bond strength of synthetic fibres was 2.53 N/mm^2

The bond strength ratio is 1:2.61. Ten fibres of each material were weighed; steel fibres weighed 3.232g and the synthetic fibres weighed 0.307g. Converting this to a ratio to show the number of synthetic fibres required to equate to the mass of one steel fibre provided a ratio of 1 : 10.528, steel to synthetic. This shows that steel fibres have approximately 10 times the mass of the synthetic. As batching demands a weight of fibres to be provided within the concrete mix to manufacture 1 m^3, the relative batching weights were required to equate the number of fibres used.

A steel fibre dosage for a concrete floor of 30kg/m^3 was used. To equate the number of synthetic fibres needed if the mass of steel fibres were 30kg, provides a value of 2.850 kg of synthetic fibres. $\frac{30}{10.528} = 2.85$ kg

As the steel fibres possessed a greater embedded bond strength than the synthetic fibres the fibre numbers were increased by multiplying the mass of fibres required by the bond strength ratio, as calculated earlier. (2.850 x 2.61 = 7.44 kg/m^3).

Using this method, the weight of the fibres and the bond strength of the fibres, have both been used to calculate the amount of synthetic fibres required to match the toughness values of the steel fibres at the steel fibre dosage of 30kg/m^3. Therefore as supported by the previous calculations, 30kg/m^3 of steel fibre reinforcement shall be tested against a dosage of 7.44kg/m^3 of synthetic fibres. The proportion of each fibre type will change with the type of fibres used as there are many permutations of length, aspect ratio, material composition and shape that will influence the fibre performance.

VI. Result steel LOP and CMODj values

There were no observations of fibre balling as identified by Richardson (2005:217) in any of the steel or synthetic beams during the process of manufacture. Testing of the beams took place at 28 days after casting and curing was in water. Displacement of CMOD was calculated using the Equation (1) taken from BS EN 14651:2005+A1: 2007.

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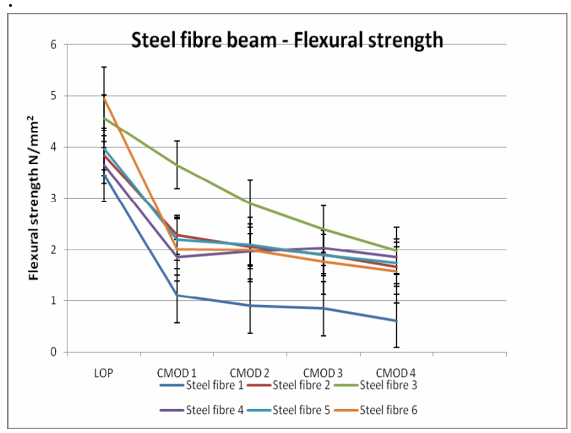

Fig. 1 Steel $CMOD_i$ Comparison of individual beam performance

Figure 1 shows the spread of the CMOD and LOP values calculated for the steel fibre beams which occurs over a large performance range. The random spread of fibres was identified by Richardson (2005) therefore the results are predictable with normal degrees of scatter.

The synthetic fibre beam suffered very large deflections beyond the CMOD 4 value and still was able to transfer a small load across the rupture plane. The findings are corroborated within earlier work by Richardson (2005) using a load sensitive cut out for fibre beam analysis, prior to the current BS EN 14651:2005+A1: 2007 being formulated.

Figure 2 shows the relative performance of the fibre beams and it was noted there was a larger degree of scatter in the post crack performance when comparing synthetic fibre with steel fibre. The fibres also increased the post crack load bearing capacity during the load application towards CMOD 2 and 3 in four out of the six beams. This performance was due to fibres being loaded at an angle across the rupture plane as identified by Hannant (1995) which created frictional forces between the fibre and the internal edge of the rupture plane.

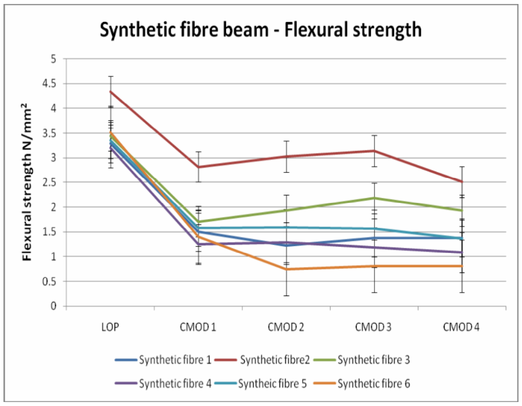

Fig. 2 Synthetic $CMOD_j$ - Comparison of individual beam performance

Synthetic fibres failed by pull out and snapping modes in equal number across the fracture plane, however the number of fibres across the rupture plane varied from 145 to 20 and this is reflected in the beams post crack flexural performance. There are many variables when using fibre concrete technology to take into account for a prescribed design method.

When the fibres had completed transmitting load across the fracture plane, it was noted that instead of stretching, they split lengthways into finer fibres and this was thought to be due to the fibre straightening and the original heat treatment when they were manufactured for this particular fibre type from an individual manufacturer.

When comparing the steel and synthetic fibre comparison, the aim of this research has been established in that very similar post crack performance can be achieved using synthetic fibres in place of steel fibres and this is shown in Figure 3.

Richardson et al (2010) showed equal performance could be achieved comparing 40 kg/m^3 of steel fibres with 6.88 kg/m^3 synthetic type 2 fibres. This test equated 30 kg/m^3 with 7.44 kg/m^3 synthetic type 2 fibres. The difference in performance of the synthetic fibres is markedly different. This test used a heavier fibre with a lower aspect ratio and this quality provided lower toughness performance per fibre than a lighter fibre. The relevance of the test is displayed when comparing the different performance values and synthetic fibre type should be chosen carefully as the above comparison shows a 30% difference in performance.

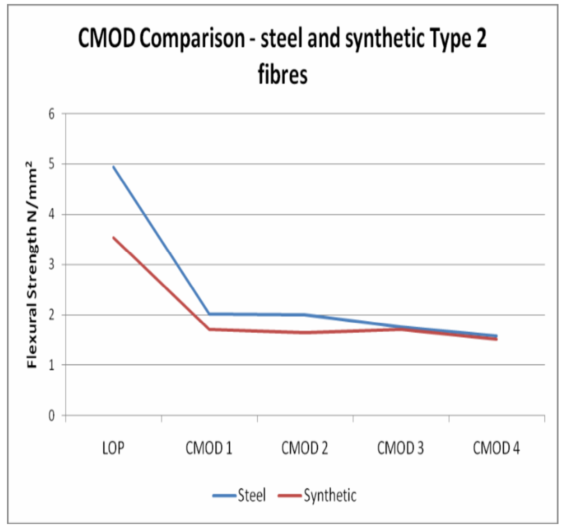

Fig. 3 CMOD comparison – steel and synthetic fibres

The steel fibres outperformed the synthetic fibres at LOP and CMOD 1 and 2, however the performance at CMOD 3 and 4 is very similar between the beams. The addition of more synthetic fibres or the reduction of steel fibres will bring the performance very close to each other in the early post crack stage of performance, however the sample size of six beams of each type may have skewed the results and a larger sample size would improve the consistency of the results. It was noted there was a small amount of synthetic fibres attached to the sides of the rotary drum mixer during the batching process and this may account for the lower values of the synthetic fibre performance. A larger batch size and mill mixer would assist in overcoming the problem of fibres sticking to the side of the drum once the mixing is complete as this has the effect of reducing the number of fibres within the beams.

To achieve a satisfactory performance in accordance with BS 14651, CMOD 1 must be either 1.5 N/mm^2 or above and CMOD 4 must achieve a minimum value of 1 N/mm^2. Both fibre types tested at the point of CMOD 1 exceeded the 1.5 N/mm^2 and CMOD 4 value of 1.0 N/mm^2. Synthetic fibres were 14% and 52% above CMOD 1 and CMOD 4 respectively. Steel fibres were 45% and 57% above CMOD 1 and CMOD 4 respectively.

VII. Conclusions

It has been shown that synthetic and steel fibres can perform equally, when used in balanced doses and tested to the current BS for fibre concrete. However further tests are required to balance the fibre dosage depending upon which CMOD value is most important for the designer.

Testing to the BS gives the structural engineer/designer more accuracy in controlling the forces in structural elements, when compared to area under load deflection curves as used previously in other research papers using different standards.

Synthetic fibre reinforcement would be suitable for applications where steel reinforcement may corrode, such as sea defences, dams or applications where there is a high electrical current and a necessity to control conduction of that current. Using pull out tests to establish relative synthetic fibre doses, allows the designer to control the post crack performance using synthetic fibre technology. However due to the individual large fibre performance variations that can be encountered when using synthetic fibre technology, this procedure should be used to provide a meaningful reference for structural design to enable comparisons to steel fibre performance.

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