Synthetic and steel fibres – a comparative study

This study is a comparative investigation into the bond and toughness effects of Type 2 Strux 90/40 synthetic fibres and Maccaferri Wirand FF1 steel fibres using bespoke pull-out tests to identify fibre bond strength and then to establish batching quantities by weight for manufacture of beams for testing to ASTM 1018[1]. The test programme provides an in-depth comparative examination of the effects of these fibres on the concrete beams.

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"This study has shown that equal performance can be achieved with suitable dosages of steel and synthetic fibres, allowing the designer to make an informed judgement."

Steel fibres are used in many engineering applications to great effect in controlling cracking of the concrete and enhancing toughness. Steel has a natural affinity with concrete as good bond strength can be developed and the coefficient of expansion for steel and concrete are virtually identical. The steel fibres selected for this study were 50mm long by 1mm diameter with a tensile strength of 1100MPa.

Macro-synthetic fibres have been added to concrete since the mid-1980s (see Concrete Society Technical Report 65[2]). However, there is still some debate as to the benefits that they can offer the designer and end user. Manufacturers are making claims for their products that would benefit from independent research to identify and quantify the properties and performance claimed. This view is supported by Technical Report 65, which states, "Much development of the use of Type 2 fibres has been by individual manufacturers, supported by a limited amount of published research. There are an increasing number of applications, and some projects have appeared in the trade and technical literature, although very little of this is peer reviewed".

Synthetic fibres for use in concrete are classified in BS EN 14889-2[3]. They fall into two categories: Type 1 (Monofilament < 0.3mm diameter); and, Type 2 (Macro Synthetic > 0.3mm diameter). The fibres as used in this study have a modulus of elasticity of 9.5GPa and a tensile strength of 620MPa.

According to Kiss[4], it is likely that the market would be more relaxed about expanding its usage (of fibres in concrete), if independent guidance were available to cover aspects such as design, construction and performance in service. This work goes some way in achieving this goal.

Methodology

Three test cubes, of each fibre type (six cubes in total) were formed with six fibres embedded to half of their length and cured for 28 days prior to pull-out testing to establish bond strength (see Figure 1). They were loaded until pull-out failure occurred and the final pull-out force was recorded. The procedure was to add weight by 0.1kg for synthetic samples and 1kg for steel samples, at 60 second intervals, until pull-out failure occurred.

Using the pull-out data for comparison purposes, the steel and synthetic fibre performance was examined to provide relative fibre dosage equating to equal toughness performance.

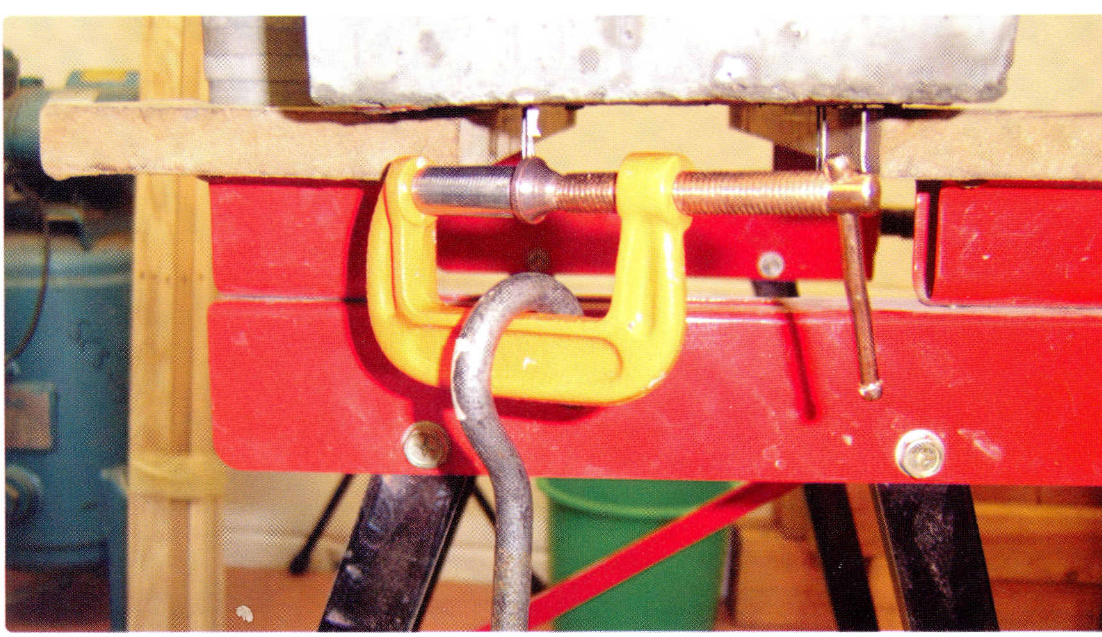
From the pull-out test results, it was calculated that steel fibres have increased pull-out strength when compared to synthetic fibres of 1:8.746.

For an equal weight of fibres there are 51 times more synthetic fibres than steel.

For the purpose of this comparison, a concrete containing 40kg of steel fibres per m^3 was selected. To provide an equal number of fibres per m^3, 0.784kg of synthetic fibres was needed. ($^{40}/_{51} = 0.784$)

The number of synthetic fibres was increased by the ratio of the pull-out strengths (8.746) to give a balanced fibre addition in terms of bond strength, weight and numbers: ($0.784 \times 8.746 = 6.86 kg/m^3$)

Figure 1: G clamp providing a plane clamp for fibre pull-out.



This approach suggests that equal performance can be achieved with $40 kg/m^3$ of steel fibres or $6.86 kg/m^3$ of synthetic fibres; the latter dosage falls within maximum of $7 kg/m^3$ recommended by the manufacturer[5].

Six 100 × 100 × 500mm beams were cast with each fibre type (12 in total) and they were tested to ASTM C1018 to provide flexural strength, first crack load and toughness data.

ASTM C1018 evaluates the flexural performance of toughness parameters derived from fibre-reinforced concrete, in terms of area under the load-deflection curve. This is obtained by testing a simply supported beam under third-point loading. The toughness determined in terms of area under the load-deflection curve is an indication of the energy absorption capability of the particular test specimen. Ultrasonic transducers were held at opposite ends of the specimen to allow direct transmission of ultrasonic pulses through the specimen. This was done to allow greater accuracy in the determination of the first crack load values.

Results

A compressive strength test was carried out on six 150mm × 150mm × 150mm pull-out cubes, to BS EN 12390-3[6]. The mean value of the compressive strength of the concrete was 53MPa and the standard deviation was 4.7.

Density was determined for the concrete and it was found to be a mean value of $2345 kg/m^3$. The standard deviation for density was 13 and this shows a consistent series of concrete batches.

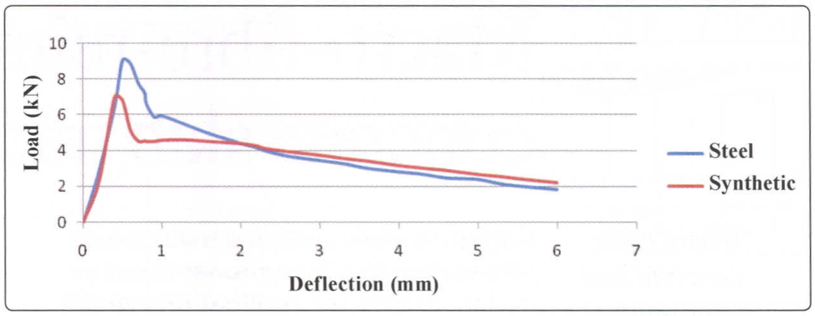
Examining the rupture plane during the test, specimens containing the synthetic fibres had an average of 163 fibres spanning the rupture plane, where specimens containing steel fibres had an average of 34 fibres. This is within 17% of the ratio of fibres added to each batch compared to the design quantities, which suggests a slightly uneven distribution throughout the specimens.

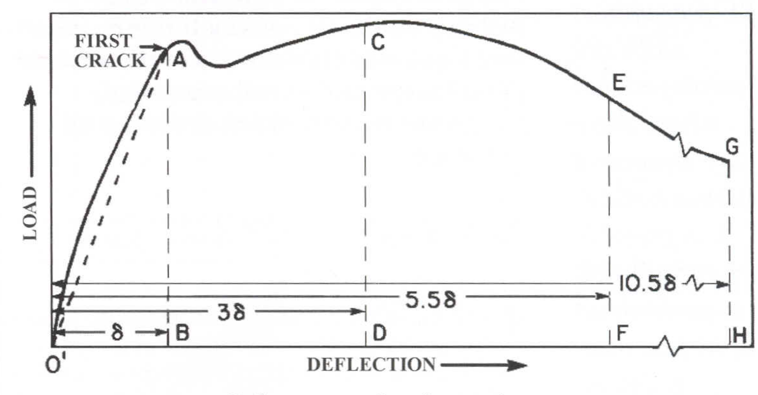
Comparing the performance of steel fibres and high modulus macro-synthetic fibres in concrete, with regards to toughness and strength, it was found that synthetic Type 2 fibres and steel fibres perform equally well.

The steel-fibre-reinforced concrete performed better in terms of first crack strength and in the take up of the force after the first crack has formed, as seen in Figure 2. However, two steel fibre beams had significantly higher flexural strength values than the other beams within the cohort and with a small population of six beams of each type it does skew the results in favour of the steel fibre beams.

In accordance with ASTM C1018[1], the Toughness indices (I) and residual strength values (R) are calculated as follows:

- Determine the first-crack deflection as the deflection corresponding to the length OB in Figure 3. Determine the area under the load-deflection curve up to the first-crack deflection, ie, the triangular area OAB.
- Determine the area under the load-deflection curve up to a deflection of 3.0 times the first-crack deflection. This corresponds to the area OACD where OD equals 3.0 times the first-crack deflection. Divide this area by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_5.
- Determine the area under the load-deflection curve up to a deflection of 5.5 times the first-crack deflection (area OAEF). Divide it by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_{10}.
- When required, determine the area under the load deflection curve up to a deflection of 10.5 times the first-crack deflection (area OAGH). Divide it by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_{20}.
- Determine the residual strength factor $R_{5,10}$ as $20(I_{10}-I_5)$, and, when required, the residual strength factor $R_{10,20}$ as $10(I_{20}-I_{10})$.





b) Convex upwards to first crack

Figure 2 top: Average results of steel and synthetic fibres after ASTM C1018 test.

Figure 3 above: Determination of toughness indices.
(Source ASTM C1018 - 1997).

This is also reflected in the values of I_5 that examine this area of post-crack toughness where I_5 for steel is 3.3 and 3.2 for synthetic fibres.

Synthetic fibres performed slightly better than steel for values of I_{10} and I_{20} where the values were 5.5 and 8.4 for steel and 6.0 and 10.4 for synthetic fibres, as a consequence of these values the residual strength values were proportionally higher for synthetic fibres.

Concluding remarks

This study has shown that equal performance can be achieved with suitable dosages of steel and synthetic fibres, allowing the designer to make an informed judgement. A larger sample size would reduce the scatter in the results and further research is required to refine the results. It is the authors' intention to repeat the test to BS EN 14845-2[7], using 150mm beams that are more representative of floor-slab thickness. ■

References:

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Bulk dosing of synthetic and steel fibres with the same system

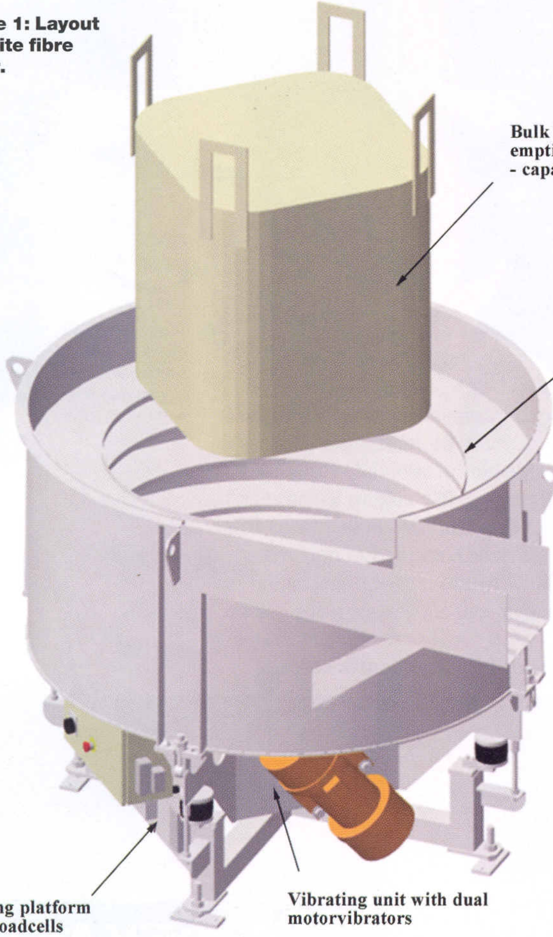

Figure 1: Layout of Incite fibre doser.

Figure 3: Batching plant at Tarmac Precast before installation of fibre dosing system.

Dispersing and transporting fibres by vibration is, by far, the best solution for bulk dosing of fibres into concrete.

Rikard Engblom, Incite

Incite is a Swedish-based mechanical engineering company manufacturer of fibre dosing systems for concrete products. It developed the first fibre-dosing system in 1993. Since the first successful installation was commissioned for a ready-mixed concrete company in Sweden in 1993, hundreds of fibre-dosing systems have now been installed in more than 20 countries, working in conjunction with producers of ready-mixed, precast, sprayed concrete, mining, tunnelling and refractory concrete.

The fibre dosers are designed (see Figures 1 and 2) for maximum flexibility and minimum maintenance. Bulk bags of fibres are emptied into the fibre container which sits on a vibration unit and a segregated weighing platform. The only moving parts on the fibre doser are well protected inside the dual vibrator motors, hence the fibre doser is, from a health and safety and maintenance point of view, extremely user-friendly.

The fibre container is removable and, as an option, several fibre containers can be used for quick changeover between different types of fibres.

A special spiral inside the fibre container effectively disperses and transports the fibres to an outlet. The major benefit is a concrete without 'fibre balls' and consequently, even distribution of fibres within the concrete.

Of equal importance, the amount of fibres added to the concrete are accurately weighed and recorded, ensuring the end user a quality controlled fibre concrete.

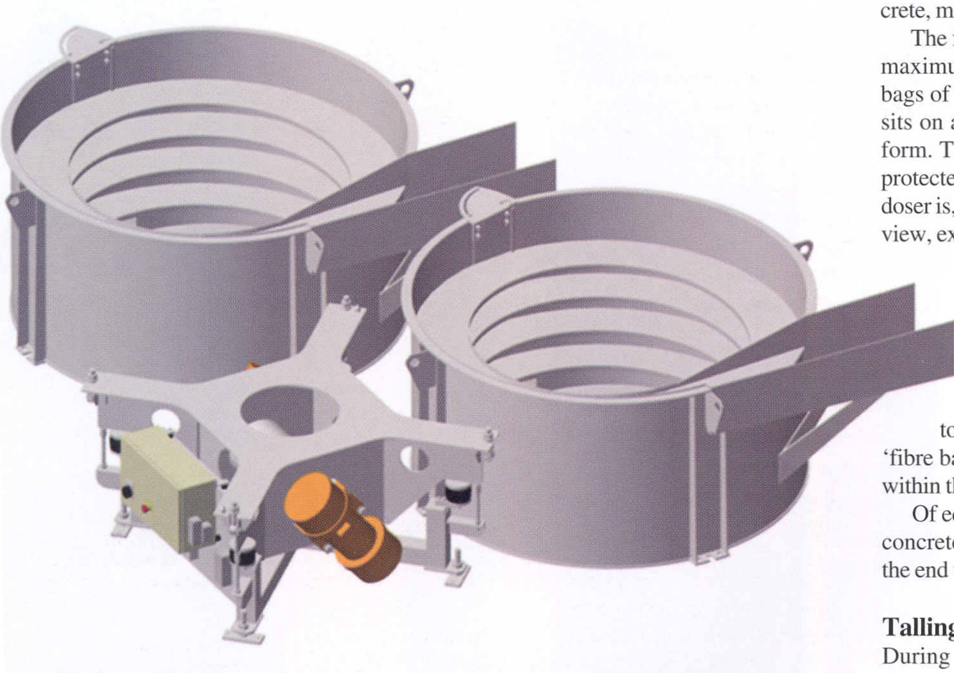

Figure 2 above: Fibre doser with dual fibre containers for quick changeover between fibre types.

Tallington investment

During 2008, Incite was contacted by its UK and Eire agent, Beton Machinery Sales regarding Tarmac Precast at Tallington. The company had taken the strategic deci-

	Fibre Type 1	Fibre Type 2	Fibre Type 3	Fibre Type 4
Material	Steel	Steel	Synthetic (Macro Fibre)	Polypropylene (Poly Fibre)
File format	Glued Strip	Loose	Pucks	Loose
Size (L/D)	80/60	75/50	48mm long	micro filament
L/D ratio	75	67	N/A	N/A
Diameter of fibre bundle	N/A	N/A	40-42mm	N/A
Dosage per m^3	31.5kg	31.5kg	7kg	1-2kg
Supply Weights of fibre	1100kg bags	500kg	360kg	unknown
Storage Requirements (kg)	1.5 Tonnes	1.5 Tonnes	400kg	150kg
Storage Conditions	Dry	not important	Dry	Dry
H&S handling requirements	Mechanical due to weight and risk of skin damage	Mechanical due to weight and risk of skin damage	Mechanical due to weight of bags	Will depend on bulk bag size
Cycle time per load ($6m^3$ per load)	5 minutes	5 minutes	5 minutes	5 minutes
Part Loads	Yes, min $1m^3$	Yes, min $1m^3$	Yes, min $1m^3$	Yes, min $1m^3$
Tolerance (%)	+/-1%	+/-1%	+/-1%	+/-2%

Table 1 – Different types of fibre used and their quantities.

Horizontal cast units	cage	steel fibre	cage+steel fibre	cage+poly fibre	cage+steel +poly fibre	macro fibre
75mm slump concrete	P					
75mm slump concrete		P				
75mm slump concrete			P			
75mm slump concrete				P		
75mm slump concrete					P	
75mm slump concrete						P
Vertical cast units Vibrated / self compacting						
150mm slump concrete/ 600mm slump flow	P					
150mm slump concrete/ 600mm slump flow		P				
150mm slump concrete/ 600mm slump flow			P			
150mm slump concrete/ 600mm slump flow				P		
150mm slump concrete/ 600mm slump flow					P	
150mm slump concrete/ 600mm slump flow						P

Most common type concrete including standard products

Contract specific

Bespoke will eventually replace some standard product designs

Table 2: Types of concrete used to produce tunnel and shaft segments.

sion to start using fibres to reinforce its precast products. Prior to this, it had performed preliminary studies on which type of fibre would suit its needs (see Tables 1 and 2). Tarmac wanted a flexible system that could dose several fibre types, both steel and synthetic, with short change-over time between fibre types.

The company has a plant with a $4.5m^3$ pan mixer, (see Figure 3). To avoid contamination of fibres in the normal concrete, Tarmac wanted the fibres to be added directly into the truck mixer, in connection with the discharge of the concrete from the mixer.

Incite recommended a fibre doser, type SF1200, with dual-fibre containers for quick change-over between different fibre types. The doser feeds fibres into a fibre elevator, transporting them 12m vertically. The fibres are then added to the truck mixer via a free-fall chute. Tarmac also invested in a building with an integrated hoist for lifting the bulk bags of fibre. The building also serves as a protection against the weather elements as well as a storage room for the fibre bulk bags (see Figures 4–6).

The fibre-dosing system has a control panel, which gives several options to interface the fibre doser with the main batching plant control system. Tarmac chose an analog interface option, 4–20mA and fibres can now be handled as an additive by the main batching plant computer system.

Figure 4 above left: Batching plant at Tarmac after installation of fibre-dosing system.

Figure 5 far left: Interior of building for lifting device and fibre doser.

Figure 6 above: Intersection between fibre doser and fibre elevator.