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Fibre Reinforcement – Steel vs. Macro (Structural) Synthetic

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This is not to say that macro synthetic fibres do not have their applications - a number of fibre suppliers actually sell both steel and synthetic. This paper has been written to provide what will hopefully be perceived as an unbiased assessment of the true comparative performance of steel and macro synthetic fibres.

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FIBRE REINFORCEMENT STEEL VERSUS MACRO(STRUCTURAL) SYNTHETIC

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Introduction

Around the millennium, suppliers of micro synthetic fibres started to offer macro synthetic fibres, with the typical marketing approach being that they can provide the same performance as steel fibres at a lower cost per cubic metre and with enhanced durability (no rusting). Interestingly, the performance established for steel fibres using the EFNARC(1996) panel test to a mid point deflection of 25mm and the correlating 40mm mid point deflection of the newly introduced ASTM C-1550(2005) test was taken by the early suppliers of macro synthetic fibres to be the bench mark by which macro synthetic fibres should be compared to steel, despite the fact that the shapes of the curves for each type of fibre are markedly different with no work having been undertaken to establish the relevance of a performance test determined for steel fibres when using macro synthetics.

This is not to say that macro synthetic fibres do not have their applications, a number of fibre suppliers actually sell both steel and synthetic. This paper has been written to provide what will hopefully be perceived as an unbiased assessment of the true comparative performance of steel and macro synthetic fibres.

Background on steel fibres

Steel fibre reinforced concrete (SFRC) was introduced into the European market in the second half of the 1970's. No standards, nor recommendations were available at that time which was a major obstacle for the acceptance of this new technology. In the beginning, steel fibres were mostly used as a substitute for secondary reinforcement or for crack control in less critical parts of the construction. However, over time, SFRC came to be applied in many different construction applications, such as in tunnel linings, ground support in mines, floors on grade, floors on piles and prefabricated elements, to the point where, nowadays, steel fibres are widely used as the main and unique reinforcement for industrial floor slabs, shotcrete and prefabricated concrete products. Steel fibres are also now being considered for many structural purposes contributing to the construction's strength, stability and durability in:-

- foundation piles
- pile supported slabs
- precast tunnel segments
- concrete cellars and slab foundations
- pre-stressed construction elements as shear reinforcement

This evolution into structural applications was mainly the result of the progress made in SFRC technology, as well as the research done at different universities and technical institutes in order to understand and quantify the material properties. In the early nineties, recommendations for design rules for steel fibre reinforced concrete started to be developed. Since October 2003, RILEM TC 162-TDF(2003) recommendations for design rules have been available for steel fibre reinforced concrete.

Background on macro (structural) synthetic fibres

Micro synthetic fibres are typically 6 to 12 mm long and have a diameter of 16 to 35 micron, and are widely used to reduce plastic shrinkage cracks, as well as to reduce concrete spalling during a fire. As Young's modulus for a polyolefin is typically around 3,000 to 5,000 MPa, it is generally understood that the reinforcing effect of these fibres is gone after a couple of hours of hardening of the concrete, as hardened concrete typically shows a Young's modulus of around 30,000 MPa.

Macro synthetic fibres typically have dimensions equal to steel fibres, with length varying from 15 to 60 mm, and diameters from 0,4 to 1,5 mm. Macro synthetic fibres are to be considered as a relatively new construction material, but are often marketed as being equal to steel fibres on the basis of their performance in toughness tests. But is this a reasonable proposition?

Fibre Reinforcement.

Fibres have typically been added into the internal matrix of other materials to form a composite material of enhanced robustness that will perform better in terms of its load carrying characteristics. Typical well established examples are horse hair or straw added to mud bricks, asbestos or cellulose fibres added to cement sheets (FRC), glass fibres or mats inside a polymer matrix (fibreglass) and glass fibres added to cement or cement sand mortars(GFRC). In all these cases the primary aim is to either increase the load carrying capacity of the parent material or make it less prone to damage during installation.

When it comes to cementitious materials, the aim has typically been to enhance the inherently low tensile strength of the parent matrix when subjected to either direct tensile or flexural strain actions. This is typically achieved by targeting one of the three load/deflection or tensile stress/strain response graphs shown in Figure 1.

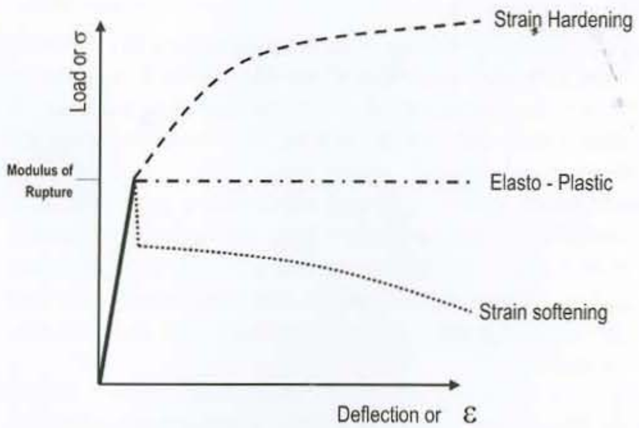


Figure 1: Load/Deflection responses for a cementitious composite

Perfect elasto-plastic behaviour as depicted in Figure 1 is a concept rather than an achievable performance when dealing with real materials. It is, however, certainly feasible to achieve either strain softening or strain hardening behaviour dependent on the type and dosage of fibres. In a statically determinate element such as a simply supported beam or a round panel supported on three points, as in the ASTM C1550 test mentioned earlier, it is obviously necessary to provide strain hardening behaviour rather than strain softening behaviour if the element is not to suffer catastrophic failure once the parent material cracking load or modulus of rupture is reached.

The way this is avoided when testing strain softening materials is to rapidly reduce the applied load, a scenario not often encountered in the real world. Similarly, if true elasto-plastic behaviour could be achieved the cracking load could continue to be supported but only at the expense of ever greater rotations and deflections in the supporting element, not usually a viable option from the point of view of serviceability.

The problem is, that in order to achieve strain hardening behaviour it is normally necessary to use quite high dosages of fibres and although this might be cost effective and practically achievable in very thin, low volume, light elements such as used in Glass Fibre Reinforced Cement and Fibre Reinforced Cement applications, it is neither economically viable nor practically achievable in the field when using large volumes of bulk materials like concrete or shotcrete.

If then, the achievement of strain hardening in full scale concrete and shotcrete elements is economically uninteresting and practically problematic how can the use of fibre reinforced concrete be justified in real life applications? The answer is quite simple, use SFRC in statically indeterminate applications, where the ability of the structural element to redistribute loads after cracking can result in strain hardening behaviour as shown in Figure 2, despite using exactly the same SFRC.

The types of structural elements where static indeterminacy can be relied on to provide load redistribution and strain hardening behaviour are typically slabs on ground, pipes, shotcrete for ground support and in fact many other common applications used in everyday construction - it is not an uncommon phenomenon.

The ability of SFRC to provide strain hardening behaviour depends, not only on providing continuity in the loaded element but on the performance of the fibre reinforcement, where the performance of the fibre reinforcement is in turn a function of the dosage and physical properties of the fibres used.

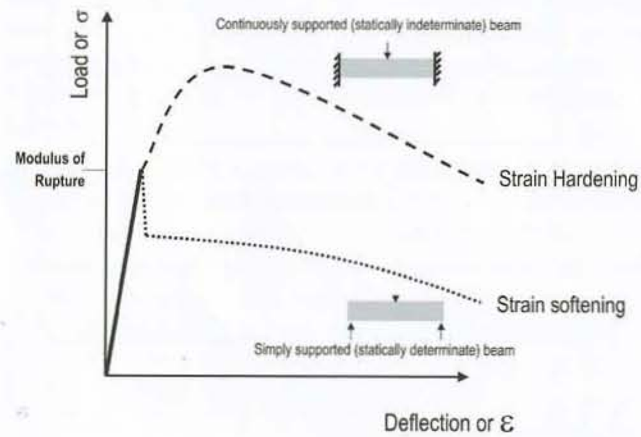


Figure 2: Effect of fixity on strain hardening behaviour of the same shotcrete

STEEL VERSUS MACRO SYNTHETIC FIBRES

There are two main differences between steel and macro synthetic fibres in terms of the load carrying capacity provided in fibre reinforced concrete(FRC) as follows:-

1. Young's modulus

Steel fibres combine a high tensile strength (typically 800-2000MPa) with a Young's modulus of around 210,000MPa, whereas polyolefin fibres have more moderate tensile strengths(300-600MPa) coupled with a quite low modulus of typically 3,000 to 5,000MPa. Compare these modulus values to that of concrete, which is typically around 30,000MPa.

What this means in practical terms for SFRC is that steel fibres tend to pick up load at very small crack widths and hence deflections/rotations for the parent concrete, thereby providing the ability for load redistribution to occur and the potential for a strain hardening load carrying capacity to be exhibited at quite low dosage rates. Synthetic fibres on the other hand start working at significantly larger crack widths, so that where the optimal performance for steel fibres is typically in the crack width range of 0.3-1.0mm the optimal performance for synthetic fibres does not normally occur until crack widths of at least 3mm are achieved. This difference in load carrying behaviour for beam tests can be seen in Figure 3 for synthetic fibres at a dosage of 1% by volume(9.1kg/m^3) and steel fibres at 0.5% by volume(40kg/m^3). These volume percent dosage rates were chosen in order to provide reasonably equivalent fibre counts per cubic metre.

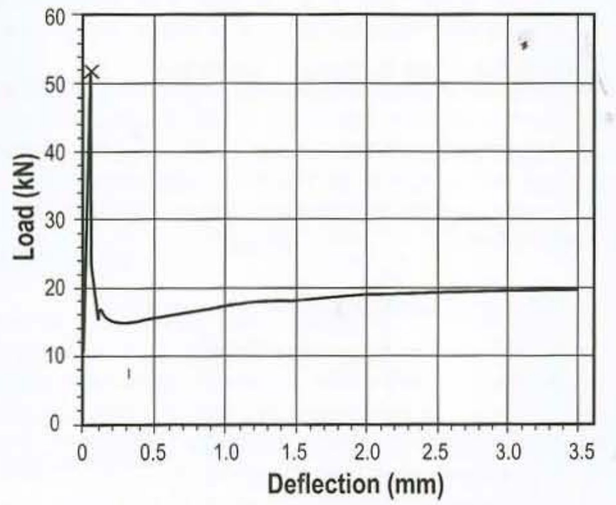


Figure 3a: Typical Load v Deflection curve for 1% by volume macro synthetic

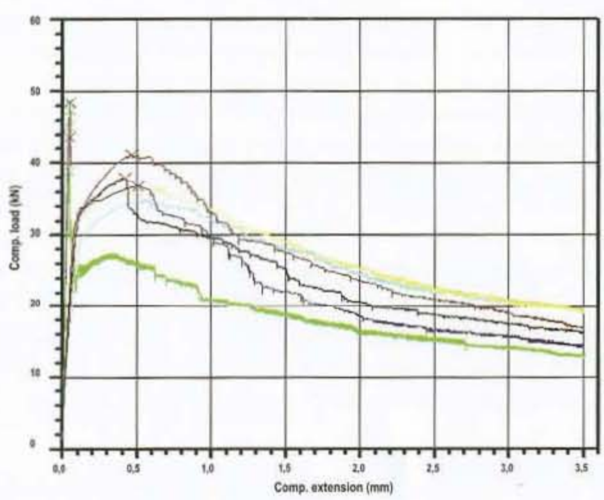


Figure 3b: Typical Load v Deflection curve for 0.5 vol % of hooked end steel fibres

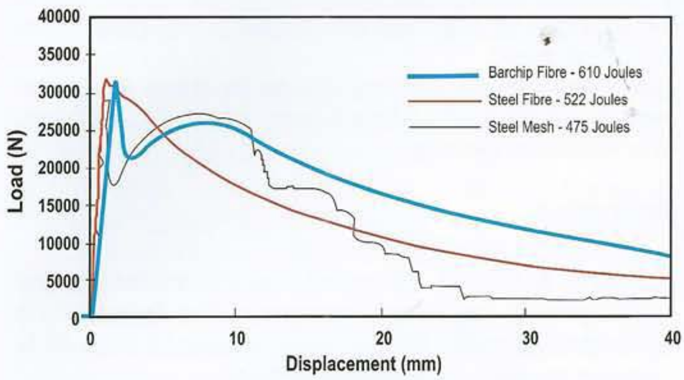
The load that can be supported when a FRC is used in a statically indeterminate element is determined by many factors, including the following:-

1. The distance between supports - the bending stress in an element spanning between supports increases as the square of span, so that for all else remaining equal doubling the span will quadruple the bending stress in the shotcrete.
2. The occurrence of cracking and the subsequent strength of the cracked concrete – in strain softening concrete the strength after cracking is lower than before cracking with this strength being a function of the fibre dosage and the tensile load in the individual fibres spanning the crack. In turn the tensile load in each individual fibre spanning a crack is determined by its Young's modulus times its strain(a function of the crack width at each fibre).
3. The rate and extent of crack development – at the earliest stage of cracking of strain softening concrete in a statically indeterminate system the concrete will work to redistribute the stresses in it from cracked to uncracked sections. If the consequential build up of stress at an uncracked section becomes great enough then cracking will occur there also. This process proceeds with continued deflections and rotations in the concrete until the final crack pattern is fully established, at which time the ultimate load capacity of the concrete is achieved and after which the load carrying capacity of the concrete will reduce(refer Figure 2).

Items 2 & 3 together explain the phenomenon of strain hardening in concrete that spans continuously past supports even though it would exhibit strain softening behaviour in a statically determinate beam or ASTM C1550 round determinate panel test i.e. as the first cracks develop the load carrying capacity is determined as a function of both the cracked and uncracked strength, only to revert to strain softening behaviour once the full crack pattern is established and the load carrying capacity is determined as a function of the cracked strength only. This progression in the load carrying capacity will be much as represented in Figure 2 and is typical of the load/deflection graphs produced when performing the EFNARC square panel test referred to earlier.

Concrete is a brittle material. Consequently, it only takes relatively small deflections and rotations to cause cracking. For this reason, to get the optimum strain hardening performance, the maximum cracked capacity needs to be mobilised at relatively small crack widths, exactly what occurs with steel fibres due to their high Young's modulus. With synthetics however, due to their low Young's modulus, the full crack pattern is typically established before the full strength of the cracked section can be mobilised and the strength provided by the cracked section during the strain hardening phase is well below optimum. Refer to the load capacity provided in Figures 3 & 4 at a deflection of less than 1mm. NB a 100mm thick continuous concrete slab supported at 2 metre centres will crack over the supports at a mid support deflection of less than 0.3mm, so it doesn't give a lot of leeway for the maximum cracked strength to be mobilised before another crack forms.

Interestingly, at this point in time in the mining industry, the effectiveness of a fibre reinforced shotcrete in terms of ground support is seen in terms of the toughness or energy absorption being provided in an ASTM C1550 round determinate panel test to a mid point deflection of 40mm, with the graph in Figure 4 (downloaded from the internet with the crack width information added) being a typical example of this approach. The argument is made, based on the graph information, that "synthetic fibre reinforced shotcrete is capable of sustaining superior energy absorption values when compared to steel fibre or steel mesh reinforced shotcrete and is undoubtedly the most suitable reinforcement selection where high ground deformations are expected".



Mesh - F41; Steel fibres - Hooked end @ 40 kg/m^3; Structural synthetic - 48mm macro synthetic @ 10 kg/m^3

Figure 4: Comparison of performance for RDP tests

There is no argument that macro synthetic fibres can provide a sufficient level of reinforcement, provided the dosage is adequate, to ensure strain hardening behaviour can be achieved, at least in the short term. The problem is, that the basis for comparison between steel and macro synthetic fibres being used to justify quite low dosages of macro synthetic fibres is currently the toughness (or area under a load/deflection graph) determined to very high deflections and crack widths. The relevance of this approach seems very dubious if the importance of load carrying capacity or strain hardening behaviour is accepted and serviceability requirements, in regards to deflections, rotations and crack widths are not being overlooked. It is also in disagreement with the approach taken by RILEM(2003) and many other international performance standards, where the typical approach is to use the results from beam tests up to a maximum crack width not exceeding 4mm to determine the capacity of fibre reinforced concrete or shotcrete.
The relative importance of load carrying capacity at small crack widths, and hence small deflections and rotations, is of recent times, assuming much greater importance to the designers of civil engineering tunnels in Australia. Even though the specified test of choice is typically the ASTM C1550 round determinate panel test, the specifications now require the performance to comply with mid point deflections between 0.72mm and 7.5mm, instead of, or in conjunction with, the overall toughness to a mid point deflection of 40mm. The mid point deflections nominated are in fact chosen on the basis of correlating back to equivalent crack widths used in third point loaded flexural beam tests.

2. Creep

It is one thing to achieve a certain level of load capacity or strain hardening but it can be quite another to maintain it, especially if the element carrying load is quite prone to creep. For this reason it is important to understand the creep properties of both steel and macro synthetic fibres. A perceived lack of definitive test information along with the lack of a standard test procedure led Lambrechts(2005) to publish the results of some in house creep tests performed at NV Bekaert in Belgium and the results are shown in Figure 6.
Macro synthetic fibres type1 and type 2 were added at a dosage of 4,55 kg/m3 (0,5 vol%). Dramix RC-65/35-BN steel fibres were dosed at 20 kg/m3(0.25 vol%). As there is no standard test method it is worthwhile summarising the main features of the test procedure adopted as follows:-

1. The long term load chosen to establish the creep behaviour of the beams was taken as 50% of the residual load capacity measured at a deflection of 5mm in a standard displacement controlled beam test - It is known that increasing the long term load as a percentage of a sections measured load capacity will tend to increase the amount of creep measured.
2. The residual strength at a deflection of 5mm was established for each beam using a standard test method, at which point the beam test was stopped. 50% of this load was then applied to that beam in the same four-point bending configuration used in the beam test - In this way the tensile stress in each fibre crossing the crack under the long term load was targeted to be 50% of what it was for a 5mm deflection in the beam test. Hence every fibre beam tested was targeted to have exactly the same relative starting point in terms of the stress in the fibres – 50% of their actual capacity.
3. The resulting creep deflection was measured at regular intervals for a period of over 1 year. The results achieved were recorded in 1/100mm increments as per the Y-axis of Figure 6.
4. No effects of temperature or humidity variations were taken into account.

As can be seen from Figure 6, the polypropylene fibres tended to creep 7 to 20 times more than the steel fibres after 1 year. Moreover, the creep of the macro synthetic fibres was continuing after one year i.e. the creep curve for the macro synthetic fibres and hence the crack widths, rotations and deflections had not stabilised. Therefore considerably higher creep was still expected for the macro synthetic fibres over time, perhaps eventual rupture.

What this means in terms of FRC using macro synthetics as the sole reinforcement, is that if there is a sustained load on a structural element, there will be a marked tendency for the deflections, crack widths and rotations in that element to significantly increase over time.

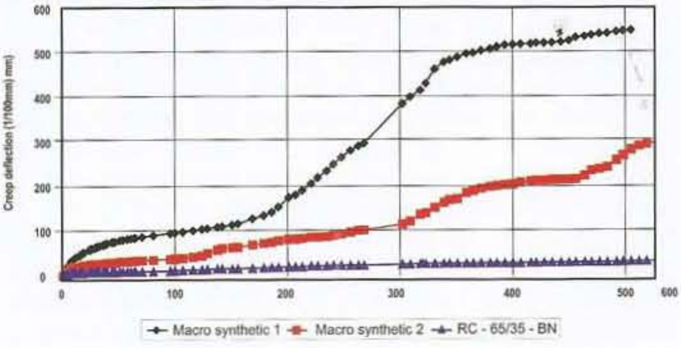


Figure 5 Creep deflection (in 1/100mm) versus time (days)

Conclusions

The actual performance level required of FRC in most, if not all, structural applications, is to provide an increasing level of load carrying capacity after cracking initiates i.e. strain hardening behaviour. If this cannot be achieved, either by virtue of the level of reinforcement or the use of statically indeterminate elements, then the FRC should be designed as plain concrete.

In terms of quantifying the structural capacity of FRC it is necessary to utilise guidelines such as RILEM TC 162-TDF(2003), which are based on the results of beam tests where the crack widths do not exceed 3.5mm.

The comparative performance of steel fibre and macro synthetic fibres when used to produce FRC should never be done on the basis of the toughness (area under the load/deflection graph) produced for crack widths exceeding 3-4mm unless the shape of the graphs are also considered.

The propensity for synthetic fibres to creep should be considered when the applied loads are to be sustained over extended periods.

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