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THE TECHNICAL PERFORMANCE OF STEEL AND POLYMER BASED FIBRE CONCRETE

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ABSTRACT: This paper discusses various material characteristics of steel and polymer fibres, with the translation into applications such as sprayed concrete linings and flooring.

Keywords: Macro synthetic fibre, steel fibre, sprayed concrete, flooring

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INTRODUCTION

Steel fibre reinforced concrete (SFRC) has been introduced in 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 meantime, SFRC has been applied ever since in many different construction applications, such as in tunnel linings, mining, floors on grade, floors on piles, prefabricated elements, … In the beginning, steel fibres were used to substitute a secondary reinforcement or for crack control in less critical constructions parts. Nowadays, steel fibres are widely used as the main and unique reinforcement for industrial floor slabs and prefabricated concrete products. Steel fibres are also considered for structural purposes helping to guarantee the construction's ability and durability in:

- foundation piles reinforcement
- reinforcement of a slab on piles
- full replacement of the standard reinforcing cage for tunnel segments
- reinforcement of concrete cellars and slab foundations
- steel fibres as shear reinforcement in pre-stressed construction elements

This evolution into structural applications was mainly the result of the progress in the 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 Recommendations for design rules are available for steel fibre reinforced concrete.

Around the millennium, suppliers of micro synthetic fibres started to offer macro 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 the modulus of Young of a polyolefine 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 modulus of Young of around 30.000 MPa. Macro synthetic fibres typically have dimensions equal to steel fibres, with length varying from 15 to 60 mm, and diameter 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. But is this really true?

MATERIAL PROPERTIES OF STEEL AND POLYMER FIBRES

Modulus of Young of the fibres

The reinforcing ability of a fibre depends on the anchorage of the fibre into the concrete, the tensile strength and modulus of Young.
The Young's modulus of concrete is typically 30.000 MPa, of steel fibre typically 210.000 MPa, and of polyolefine fibre typically 3.000 to 5.000 MPa.
For well anchored fibres, and equal solicitation of the fibre, the elongation of the polymer fibre, and the corresponding crack width in concrete, might be considerably higher compared to steel fibres. This might have an impact on the durability of the concrete, especially in combination with traditional reinforcement.

Tensile strength of the fibres

The tensile strength of steel wire is typically 1.000-2.000 MPa, versus 300-600 MPa for macro synthetic fibre.

Specific density of the fibres

The specific density of steel fibres is typically 7.850 kg/m³, versus 910 kg/m³ for polymer fibres, and 1.000 kg/m³ for water. Polymer fibres are light, which is favourable for health and safety, but they are lighter than water: the polymer fibres actually float on water, with potential risks for fibres at the surface in flooring applications.

Fire resistance of the fibres

Polypropylene fibres typically melt at temperatures around 160°C. Therefore micro polypropylene fibres are proven to be suitable to improve the fire resistance. The exact reason is not yet fully understood, but it is generally accepted that the fine micro fibres start to melt in extreme fire conditions, thereby leaving small channels through which the pressurised vapour can escape. Consequently less damage, less spalling of the concrete is to be expected.
Macro synthetic fibres do melt at equal temperature, but are not fine enough to provide the concrete under fire with the necessary network of channels. Moreover since the fibres melt, they are less suitable in those building constructions, where the reinforcing effect of the fibres is important.

Resistance against oxidation

Polymer fibres don't rust, even if the fibres are sticking out at the surface. Bright steel fibres can show some staining if the fibres are at the surface, but never cause spalling of the concrete. If for aesthetical reasons, staining is not allowed, as in some prefabricated structures, galvanised steel fibres can be applied.

Mixability of the fibres

Some macro synthetic fibres tend to fibrillate during mixing. This fibrillation process goes on in the truckmixer, until all fibres are completely destroyed. Quality degradation during mixing does not occur for steel fibres.

PROPERTIES OF STEEL AND MACRO SYNTHETIC FIBRE CONCRETE

Fibre concrete is well known for it's ductility. The effect of fibres is a combination of reinforcement and networking. Steel fibres in particular mainly change the behaviour of the concrete: steel fibres transform a brittle concrete into a ductile material which is able to withstand fairly large deformations without loosing it's bearing capacity. Ductility means load redistribution and a higher bearing capacity of the structure with the mechanical properties of the basic concrete material unchanged.

Reinforcing effect measured in beam tests

In general, most macro synthetic fibres perform rather moderately in a bending test. The pure reinforcing effect is rather poor due to the low modulus of Young, and the rather low tensile strength. As can be noticed from the curve on Figure 1 and 2, most macro synthetic fibres start working at much larger crack widths than steel fibres; steel fibres with anchorage, depending on fibre type, typically work optimally at crack widths 0.5 mm to 1 mm, whereas macro synthetic fibres work optimally after 3 mm of crack width.

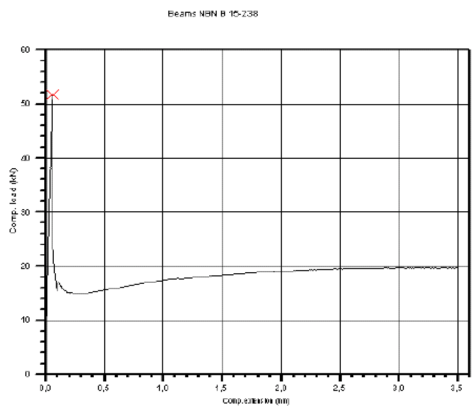

Figure 1: typical load deflection curve for 1% vol of macro synthetic fibres

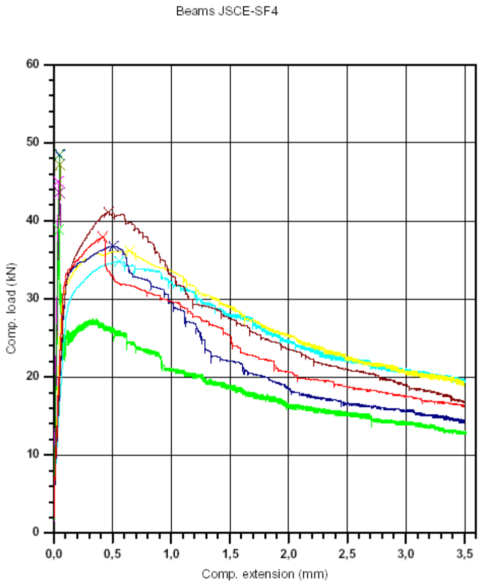

Figure 2: Typical load deflection curve for 0,5% of steel fibres with hooked ends

Creep of steel fibre and macro synthetic fibre concrete

There is little information available as to the creep of concrete reinforced with macro synthetic fibres. The few papers [3, 4] that are available must be treated with care because the conclusions are sometimes based on a limited amount of test specimens, the creep tests are executed on different size test specimens, and different test procedures, as no standard test procedure is available, and some creep tests are executed only during three months. The conclusion from those papers is that the creep coefficient is, depending on the type of the macro polymer fibres, of the order of 1 to 20 times the creep coefficient of steel fibre concrete.
In order to investigate the difference in creep behaviour between steel fibre and macro synthetic fibre reinforced concrete, N.V. Bekaert has set up a test program to compare the creep of both materials. Beams have been produced at the Bekaert laboratory with following mix design:

427 kg/m³ Cement CEM I 42.5R
854 kg/m³ Sand 0/5
854 kg/m³ Broken limestone 4/7
w/c = 0,50

Macro synthetic fibres type1 and type 2 have been added at a dosage of 4,55 kg/m³ (0,5 vol%). Dramix® RC-65/35-BN steel fibres have been dosed at 20 kg/m³.

The beams have been pre-cracked: the beams have been loaded in a displacement controlled way, as prescribed by most standards on steel fibre concrete. At a deflection of 5 mm, the load has been removed. The residual load at that moment can be read from the load deflection curve. (Figure 3)

The beams are now ready to be subjected to the creep test. Therefore 50% of the residual load is applied on the pre-cracked specimens. The load is applied in a four-point bending configuration. The deflection is measured, and shown on the Y-axis in 1/100 mm on Figure 4.

As can be noticed from Figure 4, the polypropylene fibres tend to creep 7 to 20 times more than the steel fibres after 1 year. Moreover the creep of the macro synthetic fibre is not finished yet: the creep curve for the macro synthetic fibre is not yet stabilised. Therefore at present, the creep tests are still going on, as considerable higher creep can still be expected for the macro synthetic fibres.
These deformations of course induce more wider cracks.

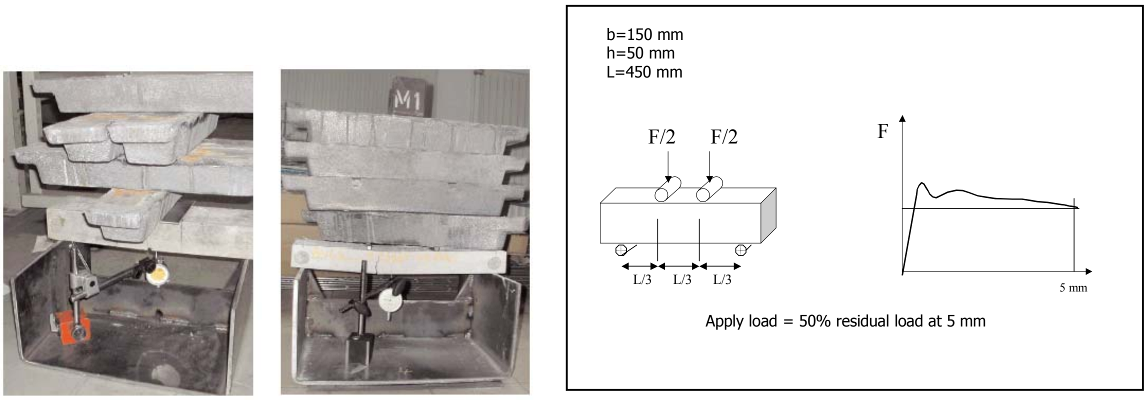

Figure 3: Set-up of creep test

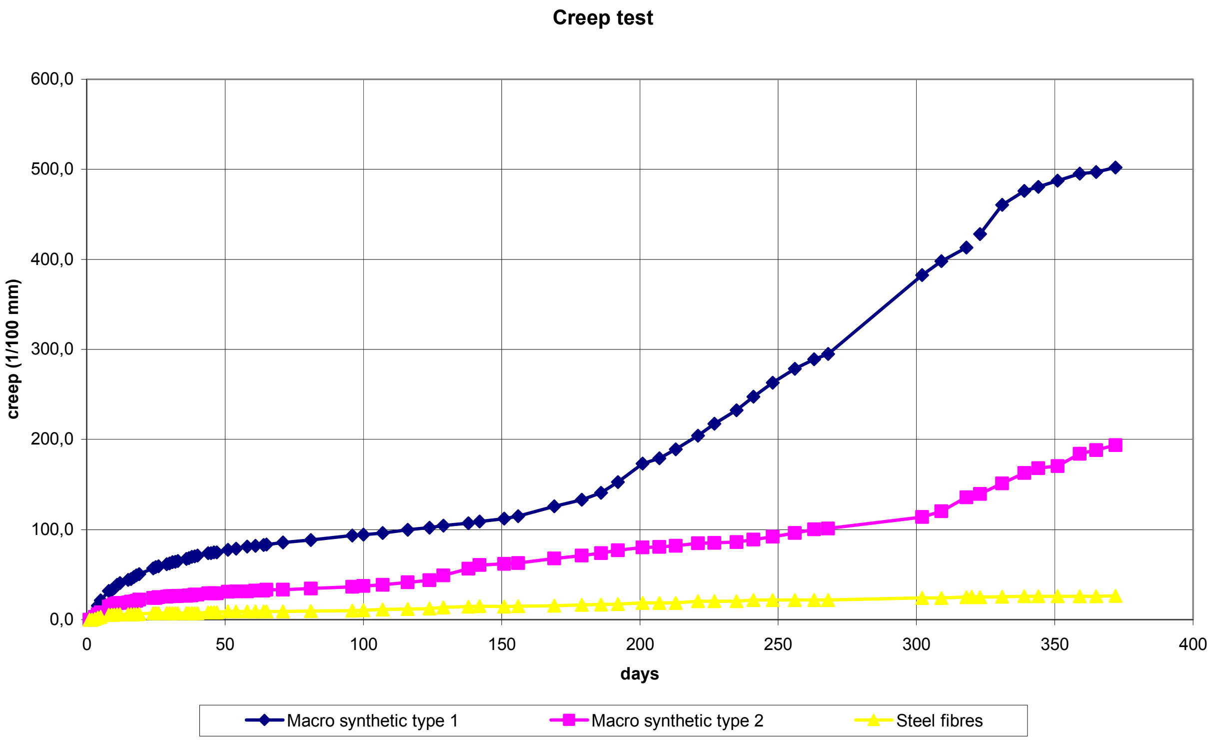

Figure 4: Creep (deflection in 1/100 mm) versus time (days)

Design rules for steel and macro synthetic fibres

Since October, 2003, Rilem TC 162-TDF design guidelines are available for steel fibre concrete. No such guideline is available yet for macro synthetic fibre concrete.

Quality control of steel versus macro synthetic fibre concrete

As part of the quality production control, wash-out tests are quite common in order to check the dosage of fibres in fresh concrete. This is always time consuming, but a lot easier when the fibres can be removed by a magnet, as is the case for steel fibres.

FIBRE CONCRETE PROPERTIES TRANSLATED INTO FLOORING APPLICATIONS

It is generally accepted that a toughness ratio (Re3) of minimum 30% is required of the fibre concrete in order to be able to increase the load bearing capacity of the fibre concrete floor in bending. This can generally not be reached by dosages lower than 4 kg/m³ for most macro synthetic fibre types. Mixing a quantity as much as 4 kg/m³ (0.4 vol%) requires special attention. Moreover, there is the intrinsic tendency of the fibre to float on top of the concrete, which does not make it easier to power float the surface.
It can be expected that an accidental shrinkage or bending crack might result in a relatively wide crack due to the low modulus of Young of the polymer fibre, and that the crack might even open further due to the expected creep.

FIBRE CONCRETE PROPERTIES TRANSLATED INTO SOIL SUPPORTING APPLICATIONS SUCH AS SPRAYED CONCRETE LININGS IN MINES

Immediately after the excavation of a tunnel, the rock material is regarded as elastic. A short time after excavation, the stress situation will change, and if the rock is weak enough, a crushed zone will develop around the tunnel opening (plastic zone).
If some support is established, the P_i of Figure 5 represents the support pressure against the rock surface. When designing the rock support necessary to limit and stop deformation, the ground reaction curve and the support curves are used. Considering stable rock, as shown by the dashed line 1 in Figure 5, the load decreases when deformation is allowed to take place. No support would be required here. Considering less stable or fractured rock, as shown by the full line 2 in Figure 5, the load increases again, due to the weight of the broken plastic zone in the roof. In this case support is needed, and should be established before the plastic zone looses cohesion.

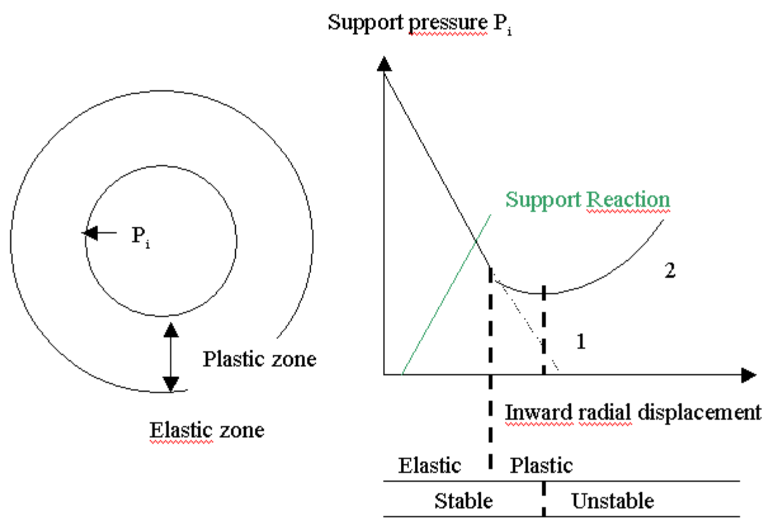

Figure 5: Support pressure after a tunnel is excavated

The ability to sustain loads whilst undergoing significant deflections needs to be an intrinsic property of the chosen support system. The presence of steel fibres in a concrete matrix, with the potential to bridge and apply tension across any cracks that form, has the ability to change an inherently brittle material into a ductile one.
How do macro synthetic fibres compare towards steel fibres in linings?
With respect to the hardened shotcrete, steel fibre reinforced shotcrete typically is better at providing higher post-crack residual load carrying capacity than high volume synthetic fibre reinforced shotcretes at low deformations when crack widths are narrow.
Hence steel fibre reinforced sprayed concrete with a sufficient dosage of performant fibres is generally preferred in permanent mine works where durable structure and near watertight conditions with narrow crack widths are needed, e.g. underground hoist rooms, crusher stations, electrical and pump rooms, …
On the other hand, high volume macro synthetic fibre reinforced shotcretes may display good ductile behaviour at what is considered larger deformations. As such its use could be considered in applications where larger ground deformations and hence wider cracks developing in the shotcrete are to be expected and are allowed, such as temporary mining openings.
But, the support system has to withstand continuously the ground pressure, particularly in mining operations where the loading conditions may even change frequently when mining is going on. Creep becomes an issue. There is very little information as to the creep of concrete reinforced with macro synthetic fibres neither on the ageing effect of these synthetic fibres in the alkaline concrete matrix. As can be seen from Figure 6, steel fibre reinforced shotcrete (SFRS) has a minor creep behaviour keeping the extra deformation under loading to a minimum while sprayed concrete reinforced with synthetic fibres shows a large increase of the deformation, which finally may result in the collapse of the structure.

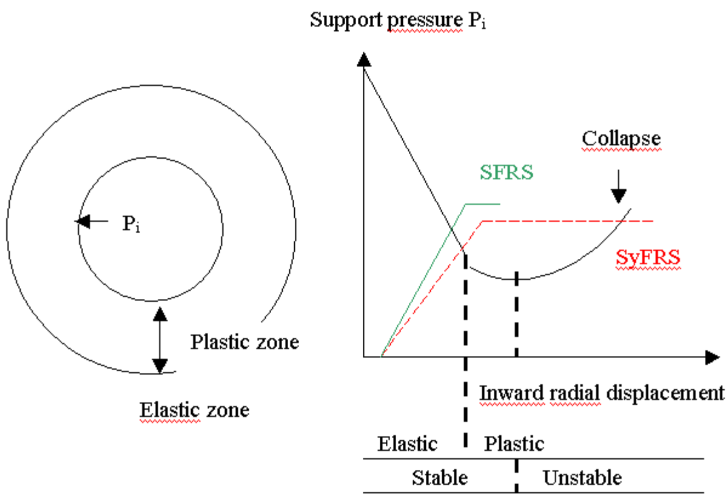

Figure 6: Creep effect on the support of a lining

CONCLUSION

Steel fibre concrete/shotcrete has proven over the years to be a reliable construction material. After 30 years of experience, the first Rilem design guidelines for steel fibre concrete were edited in October, 2003.

New fibre concretes, such as macro synthetic fibre concrete, are not yet fully understood, but gain attention. Creep data, shear resistance, crack control, durability, design methods… are lacking at the moment for macro synthetic fibre concrete, but the experience will learn.

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