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Characteristics of steel and polymer based fibre concrete

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Characteristics of steel and polymer based fibre concrete

Benoit de Rivas

ABSTRACT

Fibre reinforcement has been used in concrete for millennia. Thousands of years ago the Romans used fibre reinforcement in their concrete - in the form of horse hair. These days we particularly use steel and synthetic fibres. Synthetic fibres are often marketed as being equal to steel fibres. But is this realy true? This paper discusses various material characteristics of steel and polymer fibres, with special regards to the long-term performance.

INTRODUCTION

Steel fibre reinforced concrete (SFRC) has been introduced in the market in the second half of the 1970's. Neither 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 floors on grade, floors on piles, tunnel linings, mining, prefabricated elements.

In the beginning, steel fibres were used to substitute a secondary reinforcement or for crack control in less critical construction parts. Nowadays, steel fibres are widely used as the main and unique reinforcement for industrial floor slabs, foundations, prefabricated concrete products and tunneling applications.

Steel fibres are now considered for structural purposes helping to guarantee the construction's stability and durability in:
- industrial floors on piles
- precast elements
- building foundations
- cellars

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.

One of the aspects that are boosting the use of FRC is the introduction of guidelines for the design of FRC. In 2013, the fib presented the Model Code 2010 in which a specific part related to FRC is inserted. This document has sparked great interest in the concrete construction community and several documents consider Model Code 2010 as a reference.

Indeed 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 10.000 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.

MATERIAL PROPERTIES OF STEEL AND POLYMER FIBRES

Fibre Reinforced Concrete (FRC) is a composite material characterized by a cement matrix and discrete fibres (discontinuous). The matrix is either made of concrete or mortar. Fibres can be made of steel, polymers, carbon, glass or natural materials.

The properties of the composite depend on the characteristics of the constituting materials as well as on their dosage. Other factors such as the geometry, the volume fraction and the mechanical properties of the fibres, the bond between fibre and concrete matrix, as well as the mechanical properties of the matrix, significantly affect the FRC properties.

The behaviour of fibre reinforced concrete is more than a simple superposition of the characteristics of the concrete matrix and the fibres; to analyse the behaviour of this composite material, also the interaction between both has to be taken into account, i.e. the transfer of loads from the concrete matrix to the fibre system

Therefore, for efficient load transfer, the following three conditions must be satisfied:

1. Sufficient exchange surface (number, length, diameter of fibres).
2. The nature of the fibre-matrix interface allows for proper load transfer.
3. The intrinsic mechanical properties (Young's modulus, anchorage and tensile strength) of the fibre allows the forces to be absorbed without breaking or excessively elongating the fibre.

In fact, in a hyperstatic or statically indeterminate structure, the better the cracking is "controlled" as soon as it arises (small openings), the better will be the multi-cracking process and thus the more the structure will tend to show ductile behavior.

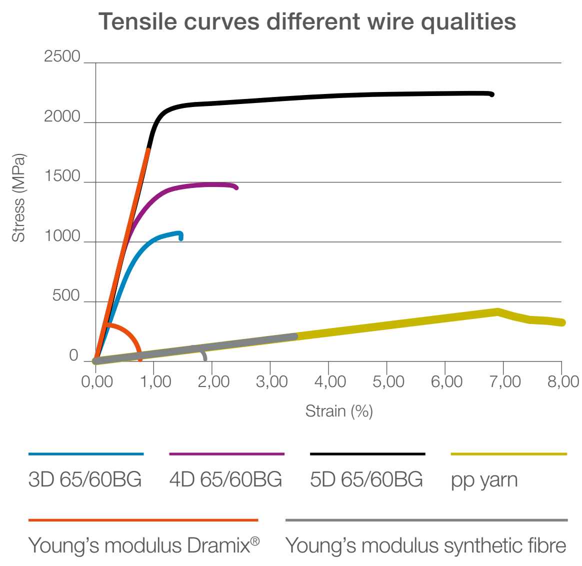
Steel fibers are significantly stiffer than concrete, whereas synthetic fibres are less stiff.

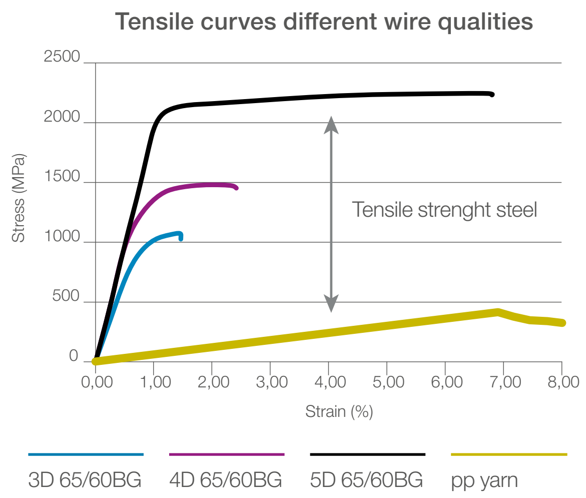
The Modulus of Young of the fibres

The reinforcing ability of a fibre depends on the anchorage of the fibre into the concrete, the tensile strength and the modulus of Young.

The Young's modulus of concrete is typically 30.000 MPa, of steel fibre typically 210.000 MPa, and of polyethelyne fibre typically 3.000 to 10.000 MPa. For well-anchored fibres, and equal solicitation of the fibre, the elongation of the polymer fibre, and subsequently 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.

	Concrete	Dramix® steel fibres	Synthetic fibres
Young's modulus	30,000 MPa	210,000 MPa	3,000 - 10,000 MPa
Tensile strength	1 - 2,5 MPa	1000 - 2,300 MPa	200 - 600 MPa
Loss of mechanical performance		370° C	50° C
Melting point		1500° C	165° C
Creep		370° C	>20° C





If we look at the Young's modulus of different types of fibre we get a very important insight - steel fibres are significantly stiffer than concrete (higher Young's modulus), whereas synthetic fibres are less stiff than concrete (lower Young's modulus).

Tensile strength of the fibres

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

Specific density of the fibres

The specific density of steel fibres is typically 7.850 kg/m^3, versus 910 kg/m^3 for polymer fibres, and 2.500 kg/m^3 for concrete. Polymer fibres are light, which is favorable for health and safety, but they are lighter than water and much lighter than concrete: the polymer fibres actually float on water, with potential risks for fibres at the surface in, for instance, flooring application. Floating fibres could also create high safety issue blocking the pump in presence of water in tunneling and mining. Floating fibres could pose problems for any dewatering proces: blocking the pump is a critical issue that you have to solve in all area of your gallery for obvious safety reason.

Low density combined with high rebound using with spray concrete process could create critical environmental issue.

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Example Ryfast tunnel Norway: Floating Macro synthetique

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 pressurized vapor 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 do not rust, even if the fibres are sticking out at the surface. Bright steel fibre scan shows 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.

Steel fibres transform a brittle concrete into a ductile material, which is able to withstand fairly large deformations without losing its bearing capacity.

Mixability of the fibres

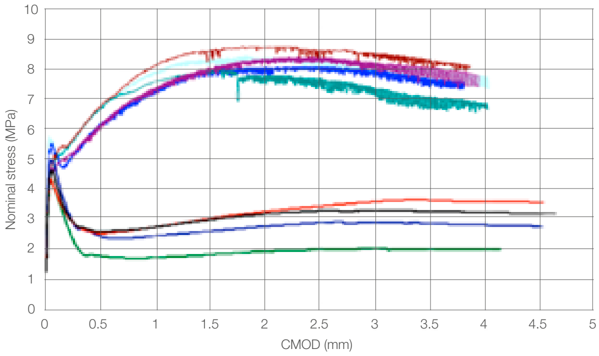
Some macro synthetic fibres tend to fibrillate during mixing. This fibrillation process goes on in the truck-mixer, until all fibres are completely destroyed. Quality degradation during mixing does not occur for steel fibres.

PROPERTIES OF STEEL AND MACRO SYNTHETIC FIBRE CONCRETE

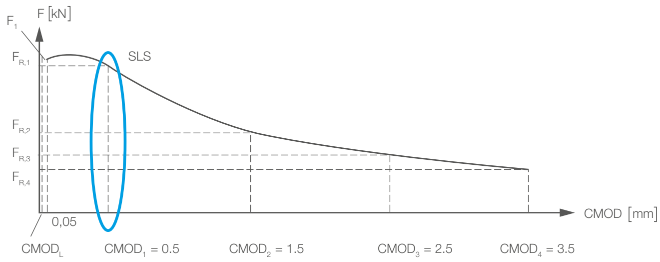
Fibre concrete is well known for its ductility. The effect of fibres is a combination of reinforcement and networking. Steel fibres in particular mainly change the behaviour of the concrete: steel fibres transform a brittle concrete into a ductile material, which is able to withstand fairly large deformations without losing its bearing capacity. Ductility means load redistribution and a higher bearing capacity of the structure, while the mechanical properties of the basic concrete material stay 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 chart, 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 2.5 mm, whereas macro synthetic fibres work optimally after 3 mm of crack width.



EN 14651 40kg Dramix 4D 80/60BG vs 8kg macro high performance (ref Roma University Report published in tunnel talk).



Due to the low Young's Modulus of synthetic fibres, crack widths are very significant (>0.5mm) before fibres start to work.

Learning point

1. 35kg/m^3 Dramix 5D65/60BG guaranty considering the right mix design
   - hardening post crack behavior
   - performance class C40/50 4c mini
2. 8kg/m^3 synthetic fibre reinforced concrete
   - softening post crack behavior
   - performance class $f^{R1k}/f^{Lk} > 0.4$ hardly met

We should keep in mind that according to Model code 2010 fibre reinforcement can substitute (also partially) conventional reinforcement at ultimate limit state if the following relationships are fulfilled:

- $f^{R1k}/f^{Lk} > 0.4$; $f^{R3k}/f^{R1k} > 0.5$

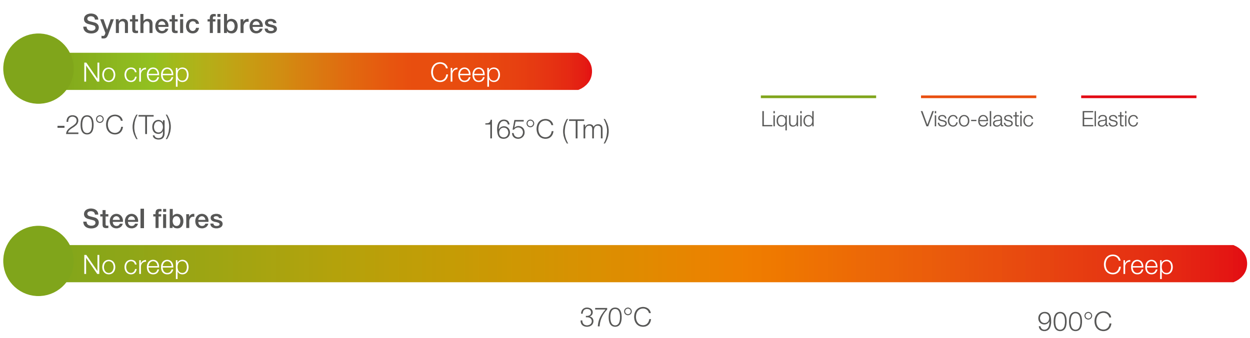
This criterion could hardly be met with macro fibre with current dosage proposed in the market.

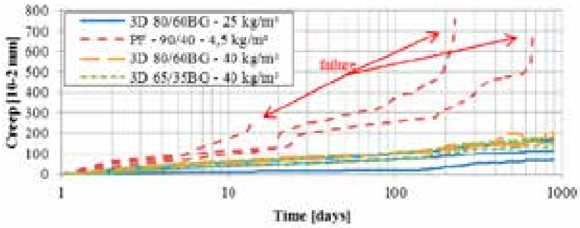
DURABILITY

Creep of steel fibre and macro synthetic fibre concrete

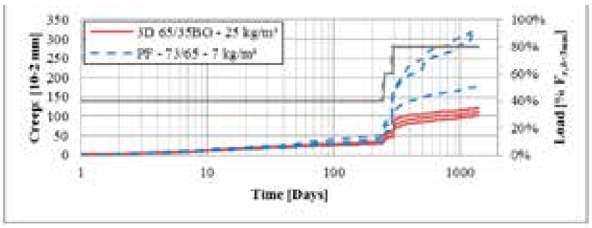
Creep is the tendency of a solid material to move slowly or deform permanently under the influence of sustained stresses. It can occur because of long-term exposure to high levels of stress that are still below the yield strength of the material.

Creep is more severe in materials that are subjected to heat for long periods, and exponentially increases as they near their melting point.
Experience from 14 years of creep testing of steel and polymer fibre reinforced concrete (ref FRC-CREEP 2016 | RILEM TC 261-CCF) conclude that the majority of tested Polymer FRC specimens fail under sustained loading while all steel FRC specimens remain intact.

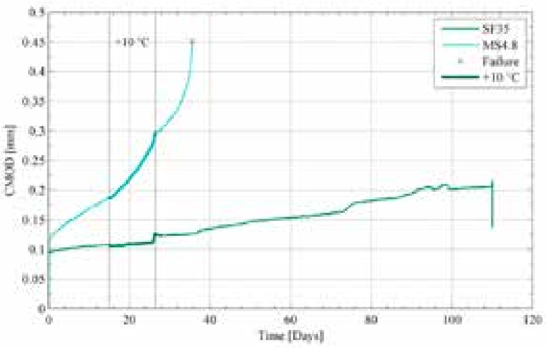




Program B1: EN14488-5 on 600mm x 600mm x 100 mm at 60% FR,δ=3mm



Program B2: EN14488-5 on 600mm x 600mm x 100mm at 40%-60%-80% FR,δ=2mm



CMOD increase exponentially by a delta temperature of 10°C

Aggressive environment

The main factor that determines the durability of a concrete structure is achieving a low permeability which reduces the ingress of potentially deleterious substances. Low permeability is achieved by using the right concrete mix design.

Control of micro-cracking is also an important parameter. Fibres are being used successfully in hybrid foundations and cellar projects to reduce cracking widths to 0.2 mm or even smaller.

Fibres have the advantage over conventional reinforcement to be randomly distributed through the entire concrete construction. The homogeneous reinforcement allows a redistribution of the tensile stresses resulting in a greater quantity of uniformly distributed micro-cracks of limited width and depth. To obtain durable concrete, and to ensure the material properties to satisfy the requirements of the design, the application process should conform following criteria to provide a high performance concrete with minimal variance in quality:

- thoroughly mixed homogeneous concrete, including fibres;
- reduce the risk of human influences affecting negatively the quality of the concrete; automatic dosing should be used where possible, allowing a good quality concrete to be applied by a certified batching plant.

*"The durability of SFRC and in particular corrosion of steel fibres has been the pivot of numerous research projects for the past decades. The existing literature on durability of SFRC is vast and covers a broad field, including different deterioration mechanisms and exposure conditions.... **For steel fiber reinforced concrete, the minimum concrete cover (c^{min}) is only for optionally inserted reinforcing steel but not for the steel fibers. Fibers can corrode near the surface and cause rust discoloration if necessary. The influence for the durability is not given.**"*

(DAfStb November 2012)

We should keep in mind

- When the crack does not exceed 0.3mm of opening in fiber-reinforced concrete, it presents a very tortuous and, at times, discontinuous path, which makes the circulation of aggressive agents more difficult.
- When the crack opening does not exceed 0.3mm, self-healing mechanisms can occur and the corrosion products (in the case of metal fibers) can be deposited in the interior of the cracks. These two physical mechanisms consequently obstruct the cracks and therefore prevent circulation of aggressive ions.

Example of return of experience in Norvegian road tunnel

Since November 2015 macro polymer fibre is prohibited in Norvegian road tunnel and steel fibre is currently the only alternative. This was new in NPRA latest edition. Background information have been explained in the publication "The ban of polymer fibre in FRSC in Norvegian Roads" by Synove A Myren during the spray concrete symposium 2018.

In the meantime a huge R&D program and very complete state of the art document was published by professor Hagelia. The main conclusion obtained during the tenure of the R&D program Durable Structures (2012-2015), provided new evidence regarding design of durable sprayed concrete subjected to aggressive environmental loads.

It was admitted that durability data still represents only 25 % of the designed lifetime and there are still remaining uncertainties regarding the ultimate service life of many of the studied concretes with w/c-ratios around 0.45 or higher. However, the use of steadily better concrete mixes in new projects, presently specified with w/c-ratios = 0.40, in combination with minimum 100 mm thickness in subsea tunnel sections seems to represent a very durable design, also for steel fiber reinforced concrete.

Bio deterioration of marine fibre reinforced concrete

Recently, synthetic fibres have been used as an alternative to nominal reinforcing bars in a concrete marine structure at the Fylde coast of England. This structure provides an excellent platform for studying the effects of a marine environment on the long-term mechanical performance of synthetic fibres and the durability of the surrounding concrete.

It's well-known that green algae and other species can cause significant deterioration of concrete through bio solubilization.

Peter Hugues's study (November 2012 Concrete international) indicates that biological activity can lead to weakening of the bond between macro synthetic fibres and the concrete matrix.

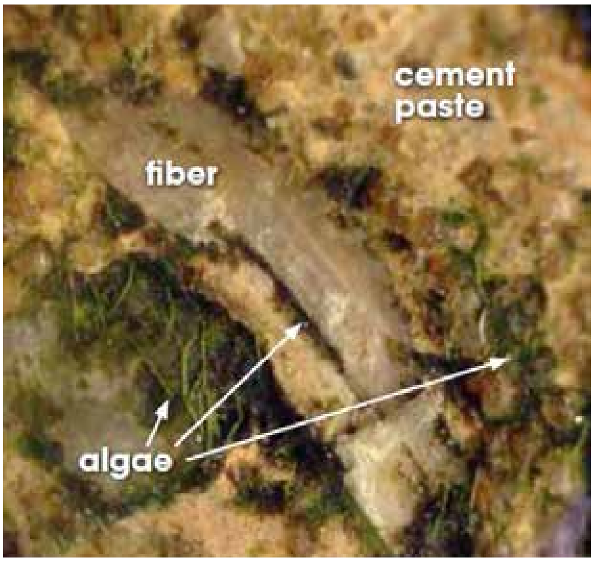


Figure Algae growth on underside of fiber within cement paste matrix and fibre-cement paste interface

The mechanism described is detrimental to the long-term performance of the polymer fibres and has a significant effect on the durability of the concrete surface. This algae research has generated new insights into algal colonization and opens up the prospect of more detailed studies on the mechanical bio deterioration of macro synthetic fibre reinforced marine concrete.

DESIGN RULES FOR STEEL AND MACRO SYNTHETIC FIBRES

- Since October 2003, Rilem TC 162-TDF design guidelines [1] are available for steel fibre concrete. No such guideline is available yet for macro synthetic fibre concrete.
- Fibre materials with a Young's modulus which is significantly affected by
    - time and/or
    - thermo-hygrometrical phenomena are not covered by this Model Code
- ISO 13 270 Point 3.1 Note 1 to entry: Steel fibres are suitable reinforcement material for concrete because they possess a thermal expansion coefficient equal to that of concrete, their Young's modulus is at least 5 times higher than that of concrete and the creep of regular carbon steel fibres can only occur above 370 °C.

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 a magnet can remove the fibres, as is the case for steel fibres.

Summarize of reinforcing properties of steel & synthetic fibres

	Steel fibres	Macro synthetic fibres	Micro synthetic fibres
Plastic shrinkage behavior	✗	✗	✓
Drying shrinkage reinforcement	✓	✓	✗
Plastic shrinkage reinforcement	✗	✗	✓
Load bearing reinforcement SLS	✓	✗	✗
Load bearing reinforcement ULS	✓	✓	✗
Long term reinforcement	✓	✗	✗

CONCLUSION

Specific technical strengths and weakness of the different fibres, are often less well-known, and lead to confusion.

Fibres for concrete, they appear in all colors, shapes, sizes and materials. Today the majority of the fibre used in concrete can basically be classified into 3 families for underground application:

1. Steel fibres: structural application, cracking control, durability, SLS and ULS design
2. Micro synthetic fibres: fire protection and to prevent plastic shrinkage cracking.
3. Macro synthetic fibres: non-structural applications when SLS is not important and when fire resistance is not important. Mainly used for temporary structures with high deformation

There is no good and bad product but the right product should be used for the right application.

The main purpose of this paper was to offer an insight into the technical performance of the different materials.

This paper should help to answer which fibre to use/specify for which application and why, based on a good understanding of the material properties.

Steel fibre concrete has proven over the years to be a reliable construction material. After 40 years of experience, the first Rilem design guidelines for steel fibre concrete were edited in October 2003 and Model Code in 2010. Fibre concretes, such as macro synthetic fibre concrete, are more and more understood and could be used in some specific appropriate technical context.

Creep data, shear resistance, crack control, durability, design methods, sustainability … are lacking at the moment for macro synthetic fibre concrete, but experience will learn.

Benoit De Rivaz
Benoit De Rivas holds a degree in Civil Engineer from the University of Paris VI. His undergraduate thesis master's degree focused on reinforced and prestressed concrete. Benoit started as job site engineer for tunnelling in different international projects for over 10 years for main French contractors. Later he joined Bekaert in 'Research and Development with Dramix in tunnelling applications' for over 10 years. Today, Benoit is the Global Technical Business Development Manager for Bekaert Maccaferri Underground Solutions. Benoit is member in different international committees: AITES (WG12 on spray concrete), ITA-CET foundation, AFTES (working group on precast segment), Efnarc (executive committee), Asquapro (spray concrete committee) and ITA TECH (member of the steering Board).

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Responsible editor:
Gilles Debusschere - 07 2019