CHARACTERISTICS OF STEEL AND POLYMER BASED FIBRE CONCRETE

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ABSTRACT: This paper discusses various material characteristics of steel and polymer fibres, with special regards to the long-term performance.
Fibres for concrete, they appear in all colours, shapes, sizes and materials. Today the majority of the fibre used in concrete can basically be classified into 3 families:

1. Steel fibres
2. Micro synthethiques fibres
3. Macro synthetic fibres

Specific technical strenghts and weakness of the different fibres, are often less wellknown, and lead to confusion. They is no good and bad product but the right product for the right used. So it is also important to specified and test the right performance according the project requirement. Which testing method for which information and why? Which type of fibre for which application.

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

1. INTRODUCTION

Steel fibre reinforced concrete (SFRC) has been introduced 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 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, prefabricated concrete products and tunnelling application. Steel fibres are now considered for structural purposes helping to guarantee the construction's ability and durability in tunnelling and mining:

- precast segment
- Cast in place final lining
- Permanent spray concrete lining
- Shaft

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 aspect that are boosting the use of FRC in segmental linings 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 tunnelling community and several documents consider Model Code 2010 as a reference.

For this reason, fib Task Group1.4 "Tunnels" decided to create Working Party 1.4.1 on "Tunnels in Fibre-Reinforced Concrete". The Working Party prepared the present bulletin with the aim to support designer, clients and construction companies in introducing FRC in segmental lining tunnels referring to the indication of Model Code 2010.

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 polyolefin 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.

Macro synthetic fibres are to be considered as specific construction material but are often marketed as being equal to steel fibres.

But is this really true?

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

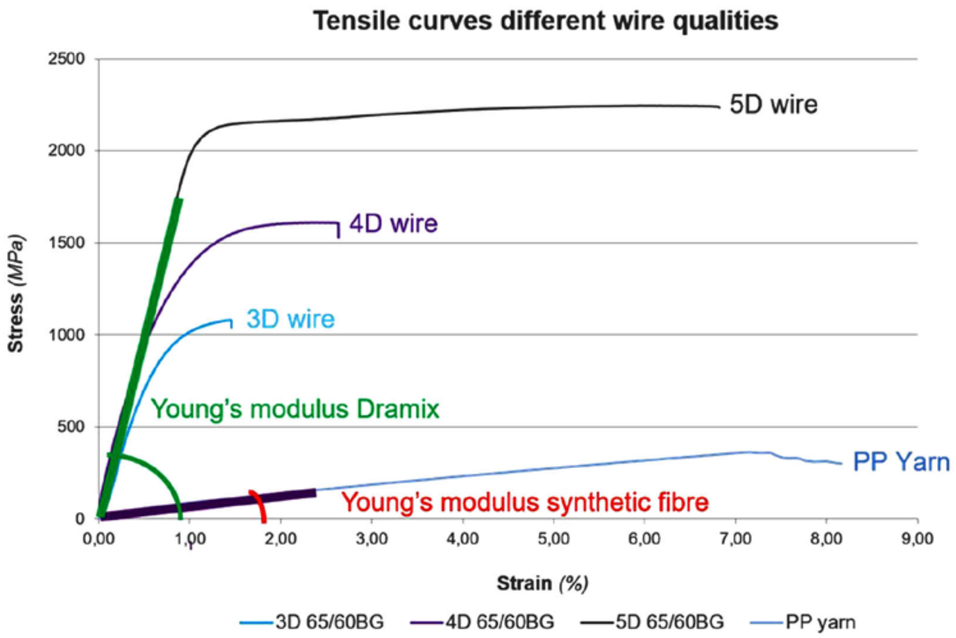
In fact, in a hyper static mechanical system, the better the cracking is "controlled" as soon as it arises (small openings), the better will be the multi-cracking process and thus the more the structure will tend to show ductile behaviour.

	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	1,000 – 2,300 MPa	200 – 600 MPa
Loss of mechanical performance		370°C	50°C
Melting point		1,500°C	165°C
Creep		370°C	>20°C

2.1 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 polyolefin fibre typically 3.000 to 5.000 MPa.

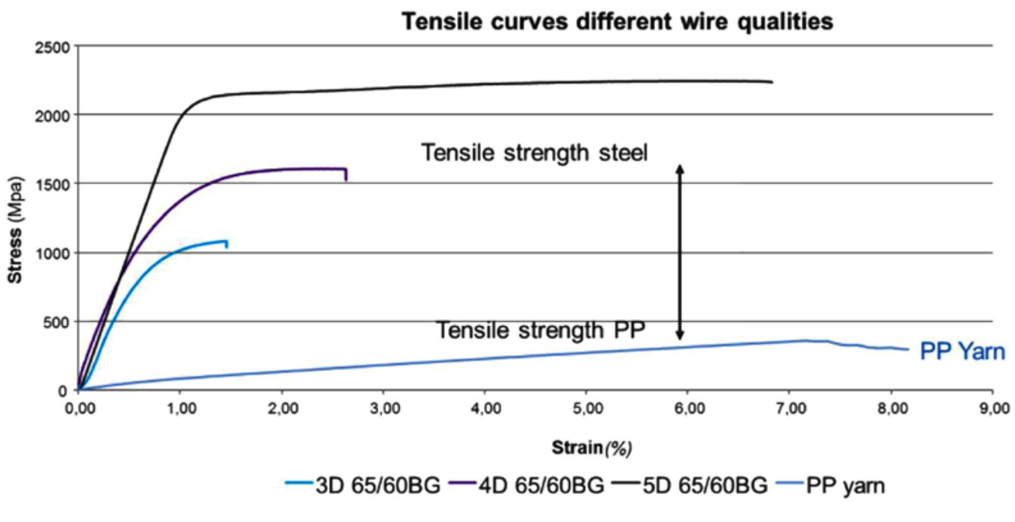


For well anchored fibres, and equal solicitation of the fibre, the elongation of the polymer fibre, and subsequently the corresponding crack width in concrete, might be considerably higher compared to steel fibres. This might have an impact on the durability of the concrete, especially in combination with traditional reinforcement.

If we look at the Young's Modulus of different types of fibre 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).

2.2 TENSILE STRENGH OF THE FIBRES

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



2.3 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 1.000 kg/m^3 for water. Polymer fibres are light, which is favourable for health and safety, but they are lighter than water: the polymer fibres float on water, with potential risks for fibres at the surface in, for instance, flooring application.

This floating fibre could also create high safety issue blocking the pump in presence of water in Tunnelling and mining. Floating fibre should could create pose some problems for any dewatering proce: 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.

Example Ryfast tunnel Norway: Floating Macro synthetic

2.4 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.

2.5 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.

2.6 MIXABILITY OF THE FIBRES

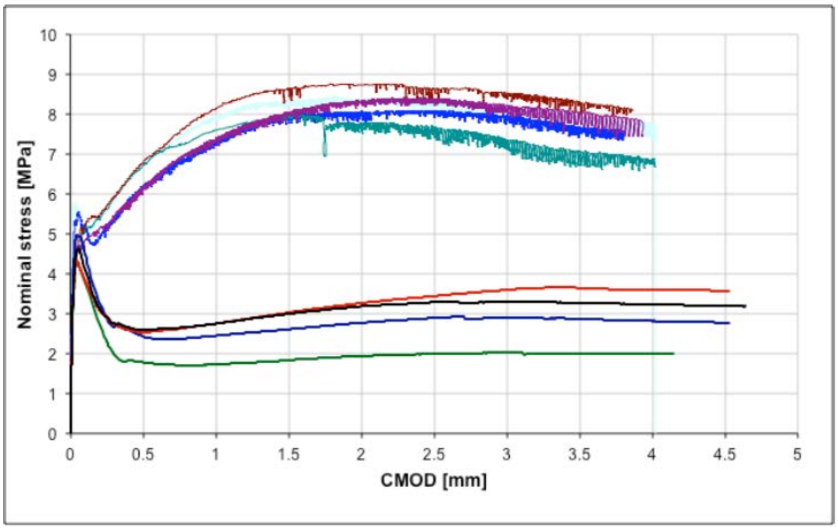
Some macro synthetic fibres tend to fibrillate during mixing. This fibrillation process goes on in the truck-mixer, until all fibres are completely destroyed. Quality degradation during mixing does not occur for steel fibres.

2.7 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 with the mechanical properties of the basic concrete material unchanged.

2.8 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, 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 vs 8Kg Macro high performance

(ref Roma University Report published in tunnel talk)

Learning point

1) 40kg/m³ Dramix 4D80/60BG guaranty considering the right mix design
   - ⇒ hardening post crack behaviour
   - ⇒ performance class C40/50 4c mini

2) 8kg/m³ Barchip
   - ⇨ softening post crack behaviour
   - ⇨ performance class fr1/fl > 0,4 hardly meet

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:

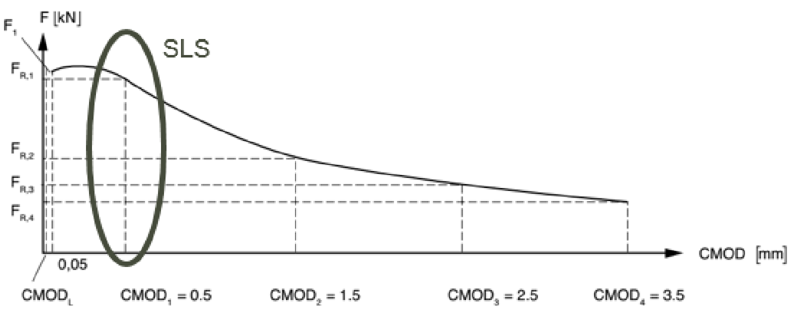
⇨ $f_{R1k}/f_{Lk} > 0.4$; $f_{R3k}/f_{R1k} > 0.5$

These criteria could hardly meet with Macro fibre with current dosage proposed in the market.

	Steel fibres	Macro Synthetic fibres	Micro Synthetic fibres
Load bearing reinforcement SLS	✓	✗	✗

For synthetic fibre to take up the same load as steel fibre

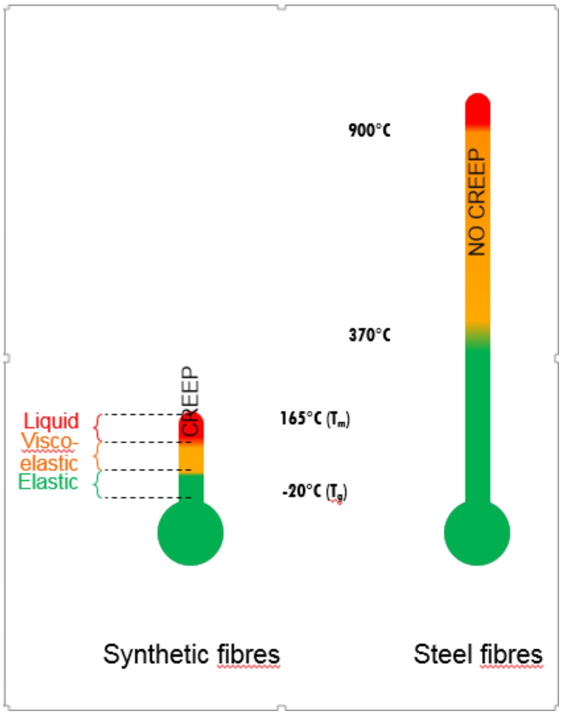
1. You could get a much bigger deformation.
2. You could therefore get a much bigger crack opening in your concrete element (such as your floor)



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

3. DURABILITY

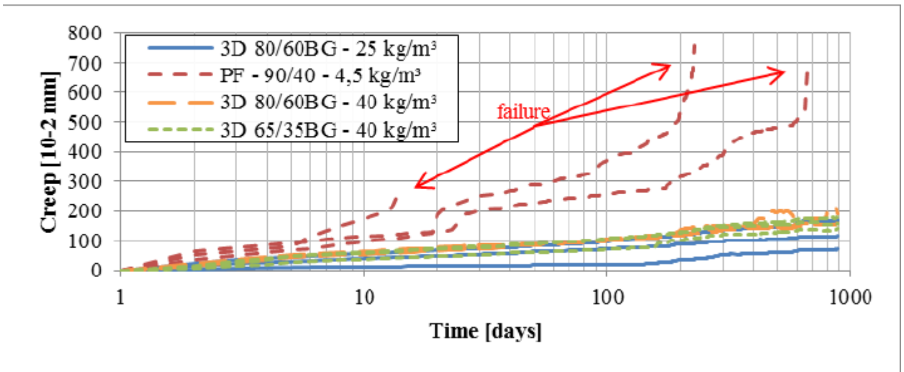
3.1 CREEP OF STEEL FIBRES AND MACRO SYNTHETIC CONCRETE



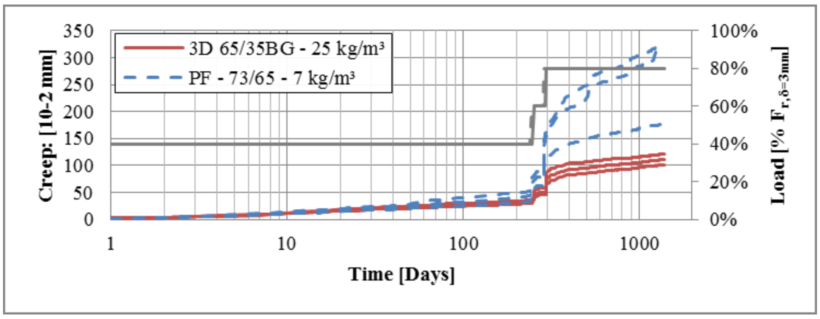
Creep is the tendency of a solid material to move slowly or deform permanently under the influence of mechanical stresses. It can occur as a result of long-term exposure to high levels of stress that are still below the yield strength of the material. Creep is more severe in materials that are subjected to heat for long periods, and generally increases as they near their melting point. Experience from 14 years of creep testing of steel and polymer fibre reinforced concrete conclude (ref FRC-CREEP 2016 | RILEM TC 261-CCF) conclude

- The majority of tested Polymer FRC specimens fail under sustained loading while all Stell FRC specimens remain intact.

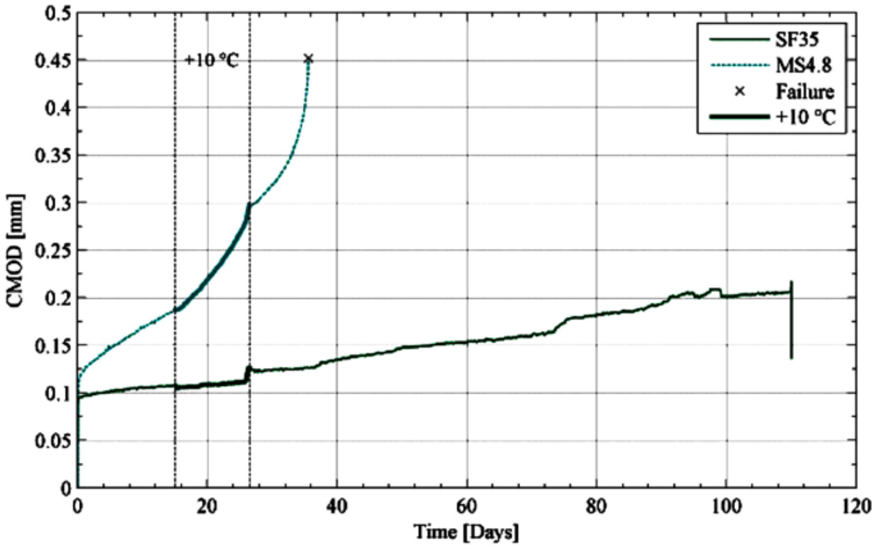
Program B1: EN14488-5 on 600mmx600mmx100mm at 60% FR, δ=3mm



program B2: EN14488-5 on 600mmx600mmx100mm at 40%-60%-80% FR, δ=2mm



- CMOD increase exponentially by a delta temperature of 10°C



3.2 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 sprayed concrete mix design with reduced shrinkage. Control of micro-cracking is also an important parameter. Fibres have been used successfully in permanent sprayed concrete tunnel projects to reduce cracking widths to 0.2 mm.

Fibres have the advantage over conventional anti-crack reinforcement to be randomly distributed through the entire tunnel lining structure. 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 sprayed concrete, and to ensure the material properties satisfy the requirements of the design, the application process should conform following criteria:

- to provide a high performance sprayed concrete with minimal variance in quality;
- thoroughly mixed homogeneous concrete, including fibres;
- reduce the risk of human influences affecting negatively the quality of the sprayed concrete; robotic spraying mobiles should be used where possible, allowing a good quality sprayed concrete to be applied by a certified operator in safer and more comfortable conditions with a minimum of rebound;
- in case of loose ground and running ground water, the system should be adjustable to provide sprayed concrete with immediate setting characteristics.

"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….

It can be concluded, that SFRC presents an overall improved durability to corrosion compared to conventional reinforcement." Fib bulletin 83

We should keep in mind

- When the crack does not exceed 300 μm of opening in fibre-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 300 μm, self-healing mechanisms can occur and the corrosion products (in the case of metal fibres) 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 subsea tunnel:

- Norwegian Public Road Association has recently updated version (November 2015) of the Process Code 1 - Standard description for road contracts, Manual R761, made changes to the requirements for fibre in shotcrete for rock support. The requirement in process 33.4 Securing with shotcrete now is that fibre should be acc. EN 14889-1 Fibre for concrete, Part 1 steel fibres. This means that only opens for the use of steel fibres in the shotcrete to the rock support. Macro synthetic are R & D program Durable structures have had an action within the durability of shotcrete, where extensive investigations in several tunnels have recently been completed. It is then made a compilation of these and previous studies. The result indicates that long-term durability of shotcrete with steel fibres can be addressed by stricter requirements for durability class in areas with saline (M40) in combination with increased shotcrete thickness for given rock mass classes. Implicit in this is also astricter requirements for the identification of corrosive environments during the geological mapping.

As November 2015 macro polypropylene fibre is prohibited in Norwegian road tunnels and steel fibre is currently the only alternative of sprayed concrete. The polymer fibre is environmental considerations (ref the ban of polymer in FRSC in Novatian Road Tunnels –spray concrete symposium 2018 publication-Synove A Myren).

- For the past decades, the construction industry has boomed in major part of the Middle East. One of the rising markets within the construction industry has been bored tunnels with segmental lining for various usage, e.g. metro, sewage and stormwaterto mention a few examples. The harsh environmental exposure conditions in the Middle East, such as very high content of chlorides and/or sulphates in the soil and groundwater challenge the durability design of the reinforced concrete structures in order to meet the, often seen, extended requirements to design life, 80 – 120 years. (ref Consultant's view of durable and sustainable concrete tunnel constructions in the Middle E Cowi C.Edvadrsen). Steel fibre has been considering as the best solution available to deal with most aggressive condition (soil ground water) in the world (example STEP project)
- 12% chlorides 4-5 times that of seawater
- 5000mg/l sulphates

And possible attack (MIC) inside the tunnel due to sulfuric acid.

3.3 BIODETERIORATION OF MARINE FIBER-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.

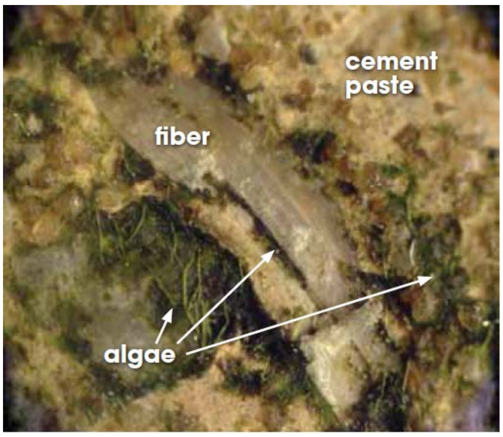


Figure Algae growth on underside of fibre within cement paste matrix and fibre-cement paste interface

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 research has generated new insights into algal colonization and opens the prospect of more detailed studies on the mechanical bio deterioration of macro synthetic fibre reinforced marine concrete.

4. 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-hydrometrical phenomena are not covered by this Model Code

ISO 13 270 Point 3.1Note 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.

	Steel fibres	Macro synthetic fibres	Micro synthetic fibres
Fire protection			X
Drying shrinkage reinforcement	X	X	
Load bearing reinforcement SLS	X		
Load bearing reinforcement ULS	X	X	
Long term reinforcement	X		

summary of the reinforcement properties

5. 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.

6. 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 colours, 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
3. Macro synthetic fibres: Non-structural applications when SLS is not important and when fire resistance is not important. mainly used for temporary structures high deformation

There is no good and bad product but the right product for the right used. The main purpose of this presentation 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 property

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 [1] 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 the experience will learn.

REFERENCES

[1] Rilem TC162-TDF: "Test and design methods for steel fibre reinforced concrete", TC Membership, Chairlady L. Vandewalle, Materials and Structures, Vol 36, October 2003, P560-567

[2] The evolution of the international projects in the development of steel fibre reinforced concrete, M. Vandewalle, presented at conference in Bergamot, Sept. 2004

[3] Post-crack behaviour of steel and synthetic FRC under flexural loading, J. MacKay, and J.-F. Trottier, Shotcrete: More Engineering Developments – Bernard, 2004 Taylor and Francis Group, London, ISBN 04 1535 898 1

[4] Creep of cracked fibre reinforced shotcrete panels, E.S. Bernard, Shotcrete: More Engineering Developments – Bernard (ed.), 2004, Taylor and Francis Group, London, ISBN 04 1535 898 1

[5] "Kriechversuche an Kunststoffmakrofaserbetonen, Untersuchungen zum Langzeitverhalten von Faserbetonen unter Biegezugbeanspruchung, ein Zwischenbericht", Tobias Bast, Andreas Eder, Wolfgang Kusterle, proceedings of the „Vilser Baustofftag 2007", Vils, Austria, 2007

[6] Test method for metallic fibre concrete – measuring the flexural tensile strength (limit of proportionality (LOP), residual)". EN1461:2005, April 3rd, 2005.

[7] Fib Bulletins 55-56: Model Code 2010 – First complete draft. (2010)

[8] ISO 13 270: Steel fibres for concrete — Definitions and specifications. (First edition 2013-01-15)

[9] Tunnel is an art: Marc Vandewalle NV Bekaert SA 2005

[10] FIB Bulletin 83 precast tunnel segments in fibre reinforced concrete State-of-the art report fib WP 1.4.1

[11] SCL Design Optimisation at Bank - A combined lining approach Proceedings of the World Tunnel Congress 2017 – Surface challenges – Underground solutions. Bergen, Norway.

[12] Brite Euram Project: sub task on durability

[13] Consultant's view of durable and sustainable concrete tunnel constructions in the Middle East) Carola Edvardsen COWI WTC 2018 Dubai

[14] The ban of polymer fibre in FRSC in Norwegian Road Tunnels –Spray concrete Symposium 2018 Trondeheim S ynove A Myren Per Hagelia and Oyvind Bjontegaard NPRA

[15] Biodeterioration of Marine Fiber-Reinforced Concrete Examination of a potential mechanism for accelerated degradation by Peter Hughes Concrete Journal Intrenational November 2012

[16] EXPERIENCES FROM 14 YEARS OF CREEP TESTING OF STEEL AND POLYMER FIBER REINFORCED CONCRETE FRC-CREEP 2016 | RILEM TC 261-CCF International RILEM Workshop on creep behaviour in cracked section of Fibre Reinforced Concrete Valencia, 9-10 March 2016

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