CURRENT STATE OF THE ART USAGE OF STRUCTURAL SYNTHETIC FIBRES AS A REPLACEMENT FOR STEEL MESH AND STEEL FIBRES IN SPRAYED PRIMARY LININGS, FINAL LININGS, CAST IN SITU LININGS AND IN PRECAST SEGMENTAL LININGS

Garry Martin[1], Karoly Peter Juhasz[2]

[1] *Tunnelling and Precast Manager, Elastoplastic Concrete (Europe), Dublin, Ireland*

[2] *Static Design Engineer, JKP Static, Budapest, Hungary*

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INTRODUCTION:

The purpose of this paper is to bring to the attention of the audience the numerous cases around the world that have substituted steel mesh and steel fibres for structural synthetic fibres as their reinforcement option in different types of tunnels.

The paper will explore the state of the art usage of structural synthetic fibres including, the characteristics of such fibres (the physical characteristics, the bond of the fibres to the cement matrix and the tensile properties, as well as how synthetic fibres function within the cracked matrix) and how they compare to traditional reinforcement options.

The way in which the performance of such fibres is determined, showing the different testing methods used, such as beam tests, EFNARC panels tests and RDP panels tests and what sort of performance can be expected, (joules of energy absorption or residual flexural energy resulting in an re3 number) will also be discussed.

Based upon the results from testing, we will then demonstrate how different types of calculation methodology can be used, ranging from equivalent flexural strength, to the latest finite element analysis models using programmes such as ANSYS and ATENA for sprayed linings and above all precast segmental linings.

A practical users guide will be explained, showing why many tunnels have chosen to use synthetic fibres (particular mention will be given to concerns covering such matters as corrosion of steel fibres and the approach adopted by the Norwegian Road Authorities, who have recommended steel fibres not be used in sub-sea tunnels, as well as a practical guide on how the fibres are added to the concrete), also there will be an explanation of creep as relating to steel and structural synthetic fibres.

Finally there will be a case study review of several tunnels that have adopted structural synthetic fibres, including high speed rail, road, metro and water tunnels from around the world.

MAIN SUBJECT MATTER

Historical context

Fibres have been used in conjunction with building materials of various kinds since man first began to build structures. The addition of grasses to mud has been used in African huts for millennia, straw has been added to mud or clay to make wattle and daub houses in Europe since the Middle ages and horse hair has been added to plaster renders around the world for longer than anyone can remember.

However, in today's highly regulated and highly engineered world, fibres in concrete are seen by some engineers as something of a new phenomenon and somehow, no quite proven or fully understood. It would seem that we have become blinded to the potential and historical value of fibre reinforcement in the light of the extensive usage of steel bars and mesh over the course of the last couple of hundred years and forgotten our fibre based reinforcement roots.

At EPC we have decided to revisit this historical trend and our structural synthetic fibres have been around since the mid 1990's, where they first gained acceptance in floor slabs and Japan's high speed rail network, both in slab track usage and as a replacement to steel mesh in embankment stabilization, as we continue to update fibre reinforcement for a new age of cement based materials.

Today, fibres from the Barchip range of synthetic fibres are used in 90% of the mines in Australia as a means of ground support in sprayed concrete linings, Norway has built over 200km of tunnels, using Barchip fibres as their sole means of ground support, including sub-sea tunnels that stretch for over 7km and at depths of over 250 metres below sea level. Spain has used Barchip fibres to build its high speed rail tunnels through extremely difficult ground conditions, as primary and secondary linings and even trusted Barchip to construct the series of water tunnels that irrigate vast stretches of arid land throughout Catalunya. So what are synthetic fibres and how do they work?

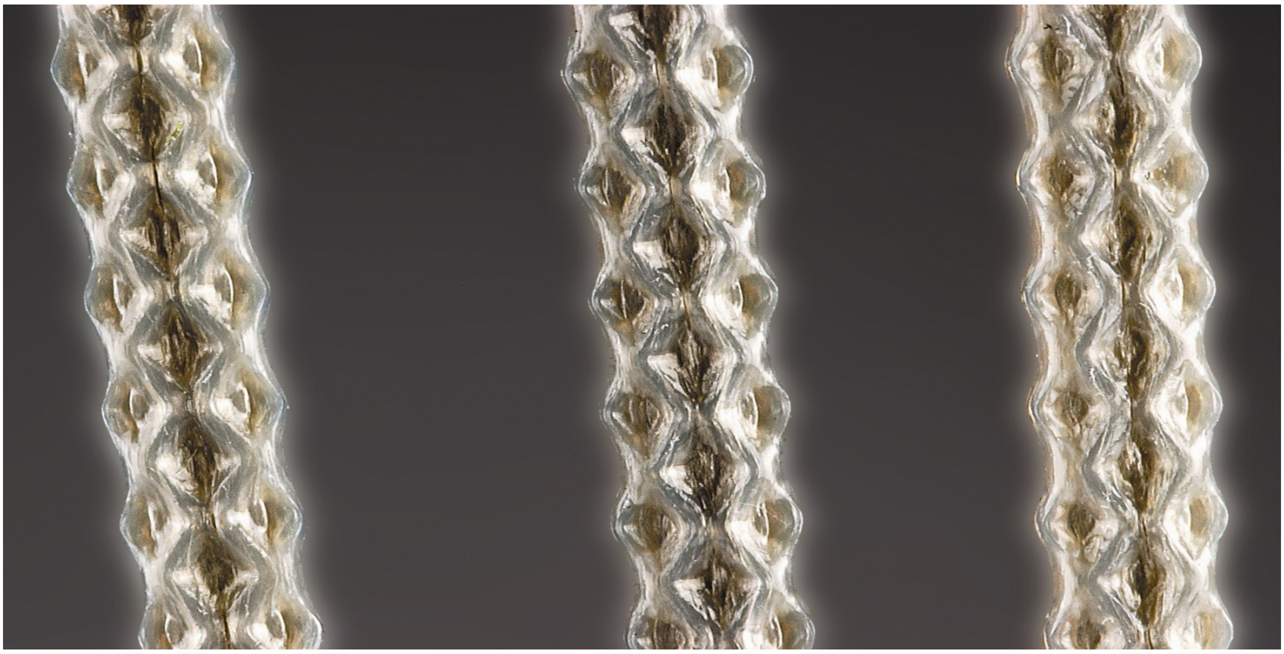
What is a structural fibre and how does it work?

Barchip structural synthetic fibres are manufactured from a high tenacity polymer that after a carefully studied manufacturing process results in individual fibres having a tensile strength of 640 mpa. (Most steel rebar is acknowledged to have a tensile strength of around 500 mpa)

Whilst a great deal of the fibre's function is determined by the quality of the raw materials, it is perhaps the care given to the manufacture that provides Barchip fibres with their unique benefits, especially when we take into consideration how a synthetic fibre works in concrete.

Synthetic fibres, work in a way that is somewhat different to steel fibres, which are usually dependent for their function upon hooks at the end of a simple profile of drawn wire and depend upon a slow pull out of the hooks through the concrete matrix as the crack opens for their performance.

Synthetic fibres, on the other hand, function as a measure of the bond they achieve with the concrete matrix along their entire length and to this end, Barchip fibres are manufactured with a series of profiles that are embossed into their surface. As part of our ongoing commitment to improvement, we test a wide range of different profiles every year and we have determined a number of unique cuts that are most apt for different concrete strengths and each fibre which makes up the Barchip range has a specifically chosen design of embossing that ensures maximum performance with a certain class of concrete.



Manufacturers of other synthetic fibres have chosen different methodologies that range from fibrillation, to undulating waves along the length of their fibres; however, it would seem from testing that a combination of low tenacity materials and poor design choices, result in lower levels of performance or a high degree of variability in the degree of fibrillation that takes place from mix to mix.

Fibre function in concrete – ductility not increasing strength

When discussing fibres, a logical jumping off point would be to examine what we think fibres and steel rebar or mesh for that matter are doing in concrete in the first place. It is often said that the addition of rebar or mesh or indeed fibres to concrete makes the concrete stronger. That is not true. The addition of steel in any of its formats (rebar, mesh or fibres) or synthetic fibres, does not increase the strength of concrete, as witnessed by testing plain concrete and "reinforced" concretes to first crack, whereby the first crack is typically fairly similar for plain concrete, rebar and fibres.

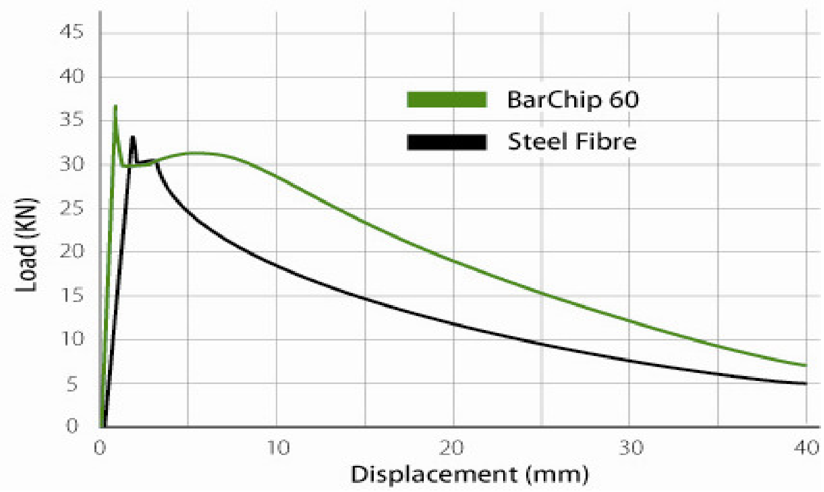
What fibres or rebar are actually doing therefore is increasing the toughness of the concrete, once it has cracked, giving it a residual level of load carrying capacity after the peak load has been surpassed.

Testing and design

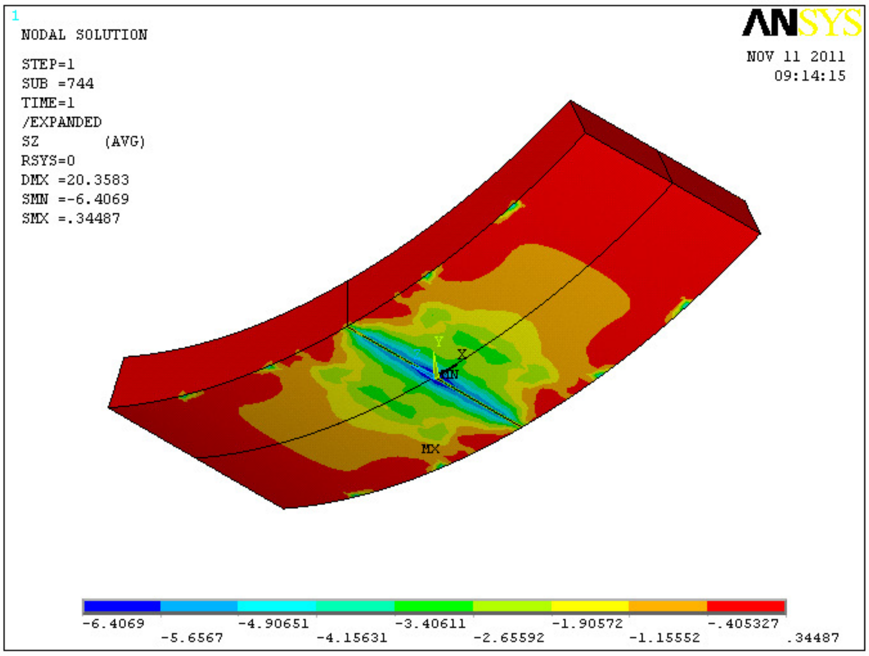
Having determined that the role of steel or synthetic fibres in concrete is to provide ductility or toughness, how do we measure the degree of performance? There are basically two different means of doing this. In accordance with current testing regimes accepted around the world: a beam test or a plate test is performed.

Above: Round panel test.   Below: ATSM 1609 beam test

In both cases, the beam or plate is supported and a central loading applied until first crack and then the concrete is loaded further until a set point of deflection is reached. The beam test gives us a measurement that is called the re3 value and plate tests provide a number of joules of energy absorption.



Based upon the figures achieved from these test methods, which match the performance of a specific quantity of fibre to a particular class of concrete, useful performance based inputs can be added into the latest finite element analysis software such as Ansys or Atena and combined with the geometry of a segmental lining or a tunnel profile and service limit loads and ultimate limit loads that would be expected for particular rock classes or for de-moulding and stacking or placement loadings.



Equivalence and more

This combination of transparent testing by independent bodies to determine the calculation inputs, coupled with internationally recognized calculation methods and software, allows fibre manufacturers to clearly demonstrate not only the equivalence of fibre performance with that of steel mesh or rebar, but also how fibres can offer increased performance, particularly in controlling micro cracks, so that crack propagation is more tightly controlled and thus makes larger cracking more difficult to develop.

Fibres are dispersed throughout the concrete and not at a set depth, as is the case for mesh or rebar and as such, will intercept cracks at a much earlier stage in their development and thus add greater resilience to any structure that is manufactured using them. Testing has shown fibre reinforced concrete to be more resistant to accidental damage, as well as providing significant benefits where anti-spalling is required, particularly in blast walls, or whereby a controlled collapse scenario is required, particularly in structures where earthquake damage is to be expected.

Practical usage and advantages

Having shown how a fibre's performance can be determined and how calculations can be carried out to the satisfaction of design engineers, it is also important that contractors and end users of the fibres also see the benefits of switching away from their dependence on steel.

Obviously one of the main advantages of fibres over steel rebar or cage is size. Fibres typically come packaged in degradable paper sacks that can be added direct to aggregate belts or into the back of truck mixers or via automated dosing systems that are wired into the batching systems of readymix concrete plants and treated as just one more element of a particular concrete recipe.

There is no transportation, no cutting, welding, typing or specialist labour skills required when using fibres. Only relatively small dosages of fibres are needed on most jobs, meaning that handling and storage requirements are thus vastly reduced too, as are the back office processes of ordering, arranging transport and stocking unwieldy amounts of steel.

Going green with synthetic fibres

In the case of synthetic fibres, the benefits are even greater, given that using a typical performance based ratio between structural synthetic fibres and steel fibres of 1:5, that means that in order to get the same required performance out of a given amount of fibre, if we used 1 full truck of synthetic fibres, 5 trucks of steel fibres would be needed. Obviously this implies not only significant cost savings in terms of handling, processing, storing and transportation, but also reduces the carbon footprint of synthetic fibres to a level of 70% less than that of steel on a performance basis. So not only are the fibres easier to handle, do not require any extra labour, free up storage space and administration time and costs, they also improve the green profile of any given job.

Tipping the balance - corrosion

So whilst it is clear that synthetic fibres can be shown to meet all of today's criteria for design using internationally accepted design standards and they are far easier to use than mesh on the jobsite and greatly improve the green credentials of any project, these factors alone have not been enough to change the opinion of many engineers. However, there is one major factor of concern that surrounds the use of steel, be it rebar or cage or steel fibres and that is corrosion.

In underground structures that are expected to have a durability of 120 years, it simply isn't feasible to guarantee any structure that will rust if it comes into contact with water. This fact has led the

Norwegian Road Authority to prohibit the use of steel fibres in all of its sub-sea tunnels, as the risk of corrosion is too great, as published in the document: Underground Openings – Operations, Maintenance and Repair (Publication No.17) Norwegian Tunnelling Society – 2008.

Corrosion and performance loss

Independent testing undertaken in Australia, showed that in cracked panels, steel fibre concretes lost over 45% of their 28 day energy absorption when re-tested after one year; whilst the same panels with synthetic fibres lost only 0.2% of their performance over the same period. It has been this factor that has proven to be the tilt point for many designers to now look at synthetic fibres in a more positive light. Why take the risk of performance failure due to corrosion when that risk factor can simply be eliminated by using a material that will not corrode. Moreover, advanced alkalinity testing has shown that synthetic fibres will more than resist being encased in concrete for more than 100 years, as has been shown in studies using advanced ageing simulations, such as those carried out by Hannant and by our own manufacturers in Japan at Hagihara Industries.

A counter reaction - creep

In light of all of the positives that have seen a shift starting to develop within the tunnelling industry away from steel and an ever increasing number of tunnels being built with synthetic fibres, the steel industry has been noted to react by raising doubts about the suitability of synthetic materials based upon the creep deformation of cracked concrete using such fibres.

Unfortunately, a number of half truths and dubious experimental test data have been circulating in the specialist press for some time, where certain low quality synthetic fibres have been tested in concretes that would never be used for tunnel construction, not even in temporary linings, let alone precast segmental linings and test beams measuring creep have apparently shown beams creeping so much that they have failed completely.

Not all synthetic fibres are equal

It is true, that not all synthetic fibres are equal and that there are certain materials on the market that should not be used in applications underground, which is why the industry has accepted the requirement of all fibres used in the construction industry bear the CE mark, that guarantees certain quality parameters of the product and minimum performance values in accordance with measurable variables as certified by official notifying bodies or whereby groups such as the British Tunnelling Society have mandated that any synthetic fibre to be used underground should have a minimum tensile strength of at least 500 mpa.

Creep control by design

However, it is perhaps the design parameters themselves and the innate conservatism of designers that give the biggest degree of actual understanding of the creep factor, placing it more in the realm of a measurable and understood phenomena and not in the role of fairytale monster, as indicated by S. Bernard in words he contributed in the Tunnelling Journal of April 2010 which dealt with the latest advances in sprayed concrete in tunnelling, in which he wrote,"In normal civil engineering applications, under design codes, loads are limited to less than half the ultimate capacity of the lining and serviceability requirements limit tensile strains to keep crack widths less than 0.3mm. Creep is less likely to be a concern since the stresses are lower (Bernard 2008). Thus it could be concluded that yes, creep is a factor that needs to be addressed, but it is neither a doomsday scenario, where suddenly structures made from synthetic fibres will catastrophically and unexpectedly fall apart, nor is it something that is beyond our capacity to control. Adequate design of underground structures, can include appropriate safety factors for creep based upon the eventuality of such occurring or determining that it is of less importance and thus reducing the corresponding factors.

Conclusion

Obviously, the myriad benefits that structural synthetic fibres bring to the underground construction sector have been noted by designers and contractors alike and today there are huge numbers of structures that have been built using structural synthetic fibres, ranging from relatively simples ones such as pathways and cycle ways, to airport drainage channels, industrial floors, precast water tanks, through to road tunnels, rail tunnels, water tunnels and metro tunnels.

At EPC we are combining the latest in materials research and manufacturing techniques that bring together high performing polymers, with the latest in machine technology to provide ever higher performing fibres. We are constantly engaging with independent testing centres to verify our findings, which we then use as inputs into the latest engineering software, in order to generate finite element analysis calculations that show exactly what forces will be acting upon a structure right across the spectrum of expected scenarios so that we can assure both ourselves, designers and clients that when choosing to use a structural synthetic fibre, they will be using a technology that is not only proven by time, with usage dating back millennia, but one that has been optimized for today's materials and will stand up to the design requirements of the structure and continue to provide high levels of service long after steel alternatives might well have faded to less than half their expected performance levels.

The future is going to be built around structural synthetic fibre and it is assured to last.