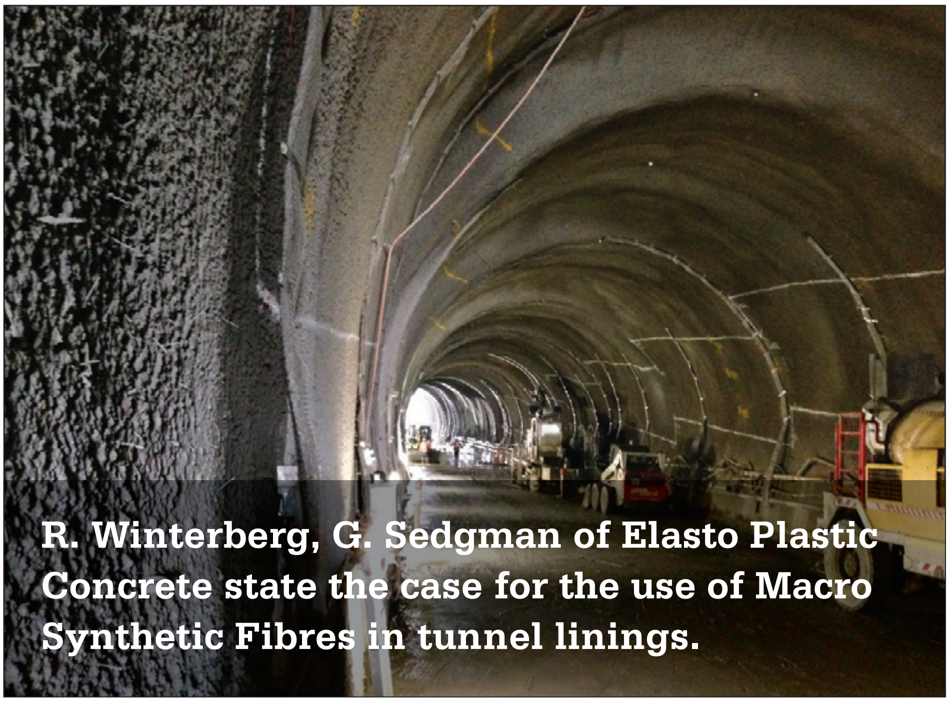
In-service performance of Macro Synthetic FRC in tunnel linings



R. Winterberg, G. Sedgman of Elasto Plastic Concrete state the case for the use of Macro Synthetic Fibres in tunnel linings.

Left: The North Strathfield Rail Underpass tunnel in Sydney, Australia, incorporated a single pass macro-synthetic fibre reinforced permanent sprayed concrete lining[3].

MACRO-SYNTHETIC FIBRE REINFORCED CONCRETE or shotcrete (MSFRC or MSFRS) is a technology that is becoming an accepted form of reinforcement in the construction community and is seen by many design engineers as offering a viable alternative to steel fibre and steel bar reinforcement in applications such as tunnel linings. The technology is now common place in applications such as shotcrete for primary and secondary ground support in both mining and civil tunnel applications. For example it has become the standard form of reinforcement in the Australian mining industry, where 2014 marked the end of steel fibre reinforcement use in shotcrete[1]. Additionally, an increasing number of tunnels are adopting permanent sprayed concrete linings using macro synthetic fibres, examples of which include the A3 Hindhead tunnel near Guildford in the UK and the North Strathfield Rail Underpass in Sydney, Australia[2,3].

Applications such as permanent tunnel linings have required further research and investigation to confirm that macro synthetic fibre reinforcement meets the strict performance criteria. This is a consequence of the highly performance-based nature of the industry in which engineers constantly monitor lining behaviour and adapt design and construction methods to achieve improvements in outcomes. This research combined with a number of major tunnel lining projects recently completed using macro synthetic fibre reinforcement sees the future of this type of reinforcement looking extremely bright.

For civil tunnel lining applications there are a number of factors design engineers must consider when determining which reinforcement product can meet the design performance criteria. These include structural capacity, durability, corrosion, crack width, creep and embrittlement to name a few. It is always important for a designer and the client to understand the benefits of adding any type of reinforcement to the concrete - in order to assess value for money. What are the benefits in terms of durability or extended asset life because of the use of macro synthetic fibre?

This article examines a number of these key considerations with the aim of summarising the latest research and industry thinking as well as presenting instances where MSFRC will deliver a distinct advantage to the finished product.

Durability

The durability of a tunnel concrete lining encompasses a number of factors including the permeability of the concrete, concrete strength, reinforcement and control of cracks. The durability of the concrete matrix in FRC is affected by the same parameters governing plain concrete when subject to the exposure conditions typical of an underground environment. When macro-synthetic fibres are used in concrete (in the absence of steel bars), there is no need to be concerned about chloride ion penetration, carbonation, and to a lesser degree, water impermeability, since there is no steel within the concrete which could be subject to corrosion. This frees the designer from the difficulties of trying to satisfy multiple performance requirements related to corrosion resistance thereby allowing greater flexibility in design. The designer can therefore focus on strength gain, shrinkage, sulphate resistance, and post-crack performance without the complications of trying to satisfy other parameters such as crack width control, which largely governs traditional design approaches for the sake of protecting the incorporated steel against corrosion.

Corrosion

If steel bars or fibres are included within a tunnel lining, the mix design becomes more challenging and compromises must be made to satisfy concerns over durability. Chloride ion penetration and carbonation depth need to be considered thereby restricting the design of the mix. Maximum allowable crack widths are much smaller when using steel bars or steel fibres since cracks, should they occur, act as points of rapid salt ingress to the

Left: Spraying of MSFRS at the Helsinki West Metro Extension project

Below: Macro-synthetic fibre reinforced cast in situ in the final lining of the Oliola water tunnel, Spain[9].

reinforcement. Maximum acceptable crack widths are about 0.15mm for steel bar reinforcement, and recent in-field tests by Kaufmann[4] and Bernard[5], supported by earlier research by Nordstrom[6,7], all indicate a maximum acceptable crack width of only 0.10mm for steel FRC. This places very stringent requirements on crack control when steel reinforcement is used, especially for steel fibres since crack width control is much more difficult and unpredictable for steel fibres than for steel bar reinforcement.

In contrast, crack widths are not a concern when macro-synthetic FRC is used since there is then no corrodible material present within the lining. Crack width limits are therefore governed by other considerations, such as water-tightness. However, if significant in-plane compressive loads are present in the lining (which is almost always the case) flexural cracks will not penetrate through more than a small fraction of the total lining thickness so water ingress to the tunnel is unlikely to occur through unplanned cracks.

Examples of where corrosion has been seen as a potential problem are the subsea tunnels in Norway and Finland. Research on durability in these aggressive environments, due to the saline water peculating through the rock to the tunnel lining, has brought about a complete ban on steel fibre in these constructions and the use of macro synthetic fibres for all shotcrete reinforcement[8].

The Ryfast Subsea tunnel, currently under construction (the longest subsea tunnel in the world) near Stavanger, is a current example of this as is the Helsinki West Metro Extension.

Another example of the successful application of macro-synthetic fibres in this regard is the 4.47km Oliola water tunnel in North Eastern Spain, which has now been in service for 5 years and was constructed using a BarChip fibre reinforced secondary concrete lining to eliminate the risk of corrosion in this environment[9].

Most concrete or shotcrete mix designs focus on durability and corrosion protection to provide high resistance against chemical attack over their service life, which in tunnelling is typically 120 years. To achieve this, the mix designs often contain large proportions of pozzolanic binders, which in turn can show significant post-hardening of the concrete with age. This leads to embrittlement of the fibre concrete matrix, which is responsible for post-crack performance loss when using steel fibres.

Embrittlement of FRC

Embrittlement of concrete or shotcrete with age due to post-hardening and its detrimental effect on the post-crack performance of steel FRC, has been known for nearly 20 years. Numerous investigations have indicated that aging can lead to a significant loss of post-crack performance for steel FRC[10,11,12].

The change in behaviour with age is due to a change from a high-energy pull-out mode of post-crack fibre behaviour to a brittle low-energy rupture mode. This leads to rupturing of steel fibres at crack widths in excess of the elongation capacity of the fibre. Thus, the performance degradation primarily affects resistance to late-age load conditions such as nearby underground construction, seismic loading, or changes in groundwater pressure.

Extensive research into post-crack behaviour of steel fibres, strand, and bar in concrete suggests that rupture is caused by excessively high friction between the steel and cementitious paste that is more closely related to the hardness of the binder paste. Paste hardness increases with the strength of the concrete, but is also related to the elastic modulus and composition of the paste. For this reason, satisfactory performance at early ages (around 28 days) is not a guarantee of acceptable performance at late ages for steel FRC. The performance of steel FRC at crack widths in excess of 1.0mm can fall by as much as 50% compared to the optimum exhibited at early ages, thus a performance reduction factor should be applied to the long-term flexural resistance of steel FRC[5,12]

Macro-synthetic FRC is largely unaffected by this phenomenon since changes in paste hardness make little difference to the behaviour of the fibre within the composite beyond the first few days of hardening. The performance of macro-synthetic FRC evident at 28 days can therefore be relied upon to be retained with age. Thus, designers can be more confident about the long-term retention of post-crack performance.

Crack width control

An investigation into the potential use of BarChip macro-synthetic fibres was undertaken to determine whether these fibres were effective in reducing mean crack widths generated in conventionally reinforced concrete members as a result of flexural loading[13]. Use of macro-synthetic fibres to reduce maximum crack widths in reinforced concrete flexural members subject to aggressive environmental exposure is more rational than the use of steel fibres because the latter are more sensitive to the corrosive effects of environmental exposure at cracks. The fibre was an experimental variant of a standard BarChip fibre that has been developed for crack width control purposes.

In this first part of the research, the focus was on the effect of the presence of special macro-synthetic fibres on the cracking development and the developing crack spacings. Through a set of experimental trials involving 32 beams reinforced with normal levels of steel bar reinforcement, and between 0 and 6kg/m^3 of BarChip macro-synthetic crack width control fibres, it has been demonstrated that these fibres are indeed capable of reducing mean crack spacings by up to 30% compared to plain reinforced concrete members.

This result is useful in the field because, unlike steel fibres, macro-synthetic fibres are entirely immune to the effects of corrosion and thus their potential location close to the surface of a member (in a crack or otherwise) will not compromise durability. Inclusion of up to 6kg/m^3 of BarChip crack width control fibres may therefore prove a useful tool for reducing maximum crack widths in RC members in aggressive environments where maximum acceptable crack widths of about 0.10-0.15mm must be achieved.

The reduced crack widths will offer higher durability and therefore longer asset life and less maintenance over the design life. Malaga Airport High Speed Rail was a project which benefited from this type of reinforcement. Macro synthetic fibre was used in combination with the traditional reinforcement cage. The addition of macro-synthetic fibre was able to assist in keeping crack widths, which may have been produced from either the TBM rams or in service loads, much smaller than if there was no fibre. This design reduced repair and maintenance costs and increased asset life in the long term.

Above: Malaga Airport High Speed Rail segmental lining used a combination of steel cage and macro-synthetic fibre reinforcement

Creep considerations

Creep has always been a question for designers as they see the material properties between steel and macro synthetic fibre as very different. However, in segmental linings hoop compression forces typically govern the occurring stresses and tensile stresses are minimal after installation and grouting to the substrate. Potential cracks, which have developed during hauling, handling and installation of the segments, or during TBM propulsion, are expected to close over time due to the natural creep of concrete under high compressive forces. The creep of the type of reinforcement plays a negligible role herein.

The particular requirement for long-term testing of macro-synthetic FRC is only necessary when long-term tensile stress is expected to be imposed on a cracked section in service. This almost never occurs in reality as the section is typically under compression due to high axial forces from surrounding groundwater and earth pressure. In service, the tensile behaviour is not as significant as during production and transient stages. If transitory tensile stresses are expected, then there is no need for long-term test data because macro-synthetic FRC performs very similarly to steel FRC in the short term.

However, concerns have been raised about the long-term performance of macro-synthetic fibres in respect of creep and the associated consequences for crack width development with time under sustained flexural loads. To address these concerns, a method to determine the effects of creep and shrinkage on the time-dependent behaviour of cracked, macro-synthetic fibre reinforced concrete cross-sections containing conventional bar reinforcement subjected to a sustained bending moment and axial force has been developed[14]. The results of this analysis show that the inclusion of macro-synthetic fibres in the concrete has only a minor effect on the flexural strength of the cross-section, but the fibres reduce time-dependent in-service deformations and significantly reduce maximum crack widths when used in combination with conventional reinforcing bars. This research work will be presented at the World Tunnelling Congress (WTC 2015) in Dubrovnik, Croatia this year in May.

The physical properties of different macro-synthetic fibres vary greatly and for the majority of the research and the completed projects presented in this article only highly engineered macro synthetic fibres with a tensile strength of > 600MPa and a Modulus of Elasticity of >10GPa has been used. These fibre characteristics are required to achieve and maintain the presented performance outcomes.

Conclusions

Highly engineered macro-synthetic fibres prove to be effective in reducing crack widths in RC members and therefore significantly add to a tunnel lining's durability.

The inherent isolated creep properties of macro-synthetic fibre reinforcement play a subordinate role in the long-term performance of tunnel linings where compression forces typically govern.

High-performance macro-synthetic fibre reinforcement is ideal for aggressive exposure conditions and guarantees durable performance over the design life cycle without suffering matrix embrittlement and performance loss with age.

…making it an ideal construction material for tunnel linings.

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