Performance of Macro Synthetic Fiber Reinforced Tunnel Linings

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ABSTRACT

Macro synthetic fiber reinforced concrete or shotcrete is seen by many design engineers as offering a viable alternative to steel reinforcement in tunnel linings. The technology is now commonplace for primary and permanent ground support in both mining and civil tunnel applications. It has for instance become the standard form of reinforcement in the Australian mining industry, and has been used for a majority of permanent tunnel linings in recent tunnel construction in Norway. Similarly, macro synthetic fibers are becoming a standard solution for the initial lining in the USA.

The use of macro synthetic fiber offers innovative solutions, yielding robust and sustainable tunnel lining designs. Citing recent research and actual projects, this paper presents state-of-the-art design considerations for fiber reinforced tunnel linings relating to structural and long-term performance. Topics include seismic resistance, crack width control, corrosion and durability, as well as sustainment of performance with age.

INTRODUCTION

Macro synthetic fiber reinforced concrete (MSFRC) and shotcrete (MSFRS) has reached maturity as an engineered material and is widely used in all forms of tunnel linings, for temporary as well as permanent ground support in both, mining and civil tunnel applications. In the Australian underground mining industry, it became the standard form of reinforcement, where 2014 literally marked the end of steel fiber use in shotcrete [1], and has been used for over 80 percent of permanent tunnel linings in recent tunnel construction in Norway. Similarly, macro synthetic fibers are becoming a standard solution for tunnel initial linings in the USA. Recent examples in civil tunneling are the Devil’s Slide Tunnel and Caldecott Fourth Bore Tunnel in California or the Anacostia River Tunnel Intershaft Connector Tunnel in Washington D.C. In addition, an increasing number of tunnels are adopting shotcrete permanent linings using macro synthetic fibers. Examples include the A3 Hindhead tunnel near Guildford in the UK and the North Strathfield Rail Underpass in Sydney, Australia [2, 3].

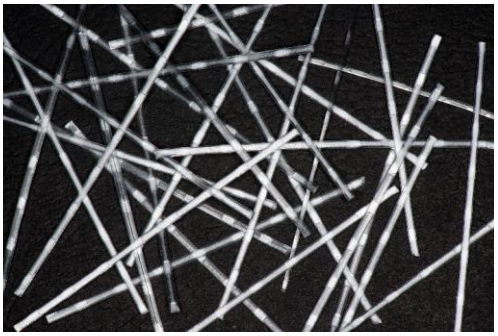

Figure 1. EPC DucTil 57 macro synthetic fiber

Macro synthetic fibers have a similar size than steel fibers and are not to be mistaken with monofilament micro synthetic fibers, which are nonstructural and serve a completely different purpose; in tunneling typically to increase the fire resistance of concrete linings [4]. Macro synthetic fibers have typical lengths between 0.8 to 2.6 inches (20 and 65 millimeters [mm]) and have typical equivalent diameters of 0.016 to 0.039 inches (0.4 to 1.0 mm) (Figure 1). Due to their flexibility, they are much easier to handle, pump and shoot than steel fibers because macro synthetic fibers are less prone to plug and wear slick lines. The tensile strength and the Young's modulus are typically around 300 to 700 Mega Pascal (MPa) and 5 to 14 Giga Pascal (GPa), respectively. The typical base material of macro synthetic fibers is polypropylene.

The physical properties of different macro synthetic fibers available on the market vary greatly. For tunnel applications, only highly engineered macro synthetic fibers with a tensile strength greater than 600 MPa and a Young's modulus greater than 10 GPa are recommended. These fiber characteristics are required to achieve and maintain the envisioned structural performance and are typical to date.

Usual dosages for shotcrete primary ground support and initial tunnel linings are in the range of 5 to 10 pounds per cubic yard (lb/yd^3) (3 to 6 kilograms per cubic meter [kg/m^3]). Typical dosages for shotcrete or cast-in-place tunnel final linings range between 8.5 and 15 lb/yd^3 (5 to 9 kg/m^3).

The influence on the structural properties of macro synthetic fibers, as well as steel fibers, in typical dosages in concrete in the elastic state is marginal. However, the structural post cracking bearing capacity is significantly improved, compared to unreinforced concrete. The fibers are bridging the opened crack by providing resistance under tension. The structural load bearing mechanism is comparable to rebar reinforcement under tension, crossing a crack, but on a smaller scale. Due to the load bearing capacity after cracking, the failure mechanism is modified from a brittle failure of unreinforced concrete into an elasto-plastic failure mode. Therefore, energy absorption or toughness performance criteria are generally used to specify and rate fiber reinforced concrete (FRC) performance rather than compressive strength, only.

Since a similar failure mode is also provided by classical rebar or wire mesh reinforcement, why is FRC so successful and advantageous for tunnel and mining applications?

(1) The installation of rebar reinforcement for a rounded structure is time consuming and expensive. FRC can be brought easily in any shape and is, therefore, quicker and more economic by using either the shotcrete or the cast-in-place process, resulting in increased efficiency and production rates.

(2) Transportation and storage of rebar, which can be logistically challenging in underground application, is being avoided, because the fibers are mixed and transported with the concrete.

(3) FRC can be applied by using the shotcrete process. This is a key factor when using shotcrete initial linings, especially if the access to the unsupported face is prohibited as a safety precaution or the geological conditions require an immediate support after excavation.

(4) In hard rock tunneling and mining or when used as a sealing layer in soft ground tunneling, shotcrete is typically installed in relatively thin layers, following a natural, irregular excavation surface. Less shotcrete is needed when using fiber reinforcement compared to rebar or mesh reinforcement, because rebar or mesh reinforcement is relatively stiff and cannot follow the irregular shape as good and bridging over valleys between high points. To fully embed the rebar and mesh reinforcement, more material is needed to fill these valleys.

(5) Fibers are homogeneously distributed in the concrete matrix and provide isotropic structural behavior, while reinforcement provides anisotropic behavior. This becomes important if the loading conditions are not determined or predictable and locally random, i.e., due to joints, block failures, or locally adjusted rock bolt patterns.

INITIAL SUPPORT IN HARD ROCK TUNNELING OR MINING

The most significant support element in hard rock tunneling as well as mining applications is the arching effect in the surrounding rock mass itself. Rock bolts are installed either as spot bolting to keep distinct large rock blocks in place or as systematic bolting to transfer loads into more distant orbits around the tunnel opening.

Shotcrete is used in hard rock tunneling primarily for two purposes: (1) to bridge the gap between rock bolts by building local arches from bolt to bolt. These arches are collecting the load locally and transferring it to the rock bolts and (2) to seal of the exposed rock surface after excavation to protect it from the elements to avoid deterioration of the structural properties due raveling of disturbed or weathered rock. The blockier and more disturbed the rock mass is, the more important becomes the role of shotcrete in hard rock tunneling and mining. Ultimately, the conditions become “soft-ground-like” and a completely different structural model is being applied, which is further discussed below.

Figure 2 shows the described failure modes schematically. Since initial shotcrete linings in hard rock tunneling and mining are typically relatively thin and the lining follows the irregular rock surface, the shotcrete lining on an excavation cross-section scale does not provide a structural bearing arch. Rather than failing due to a combined thrust/bending load, the failure mode is comparable with a punching or shear failure induced by a more or less concentrated load. There are basically two scenarios to structurally model the conditions. As shown in the upper picture in Figure 2, the concentrated load is created by a distinct rock block punching through the lining. However, another way to look at the situation can be derived from the lower picture. The rock bolts are resisting the load exerted on the lining. In this case, the rock bolt punches through the lining at failure.

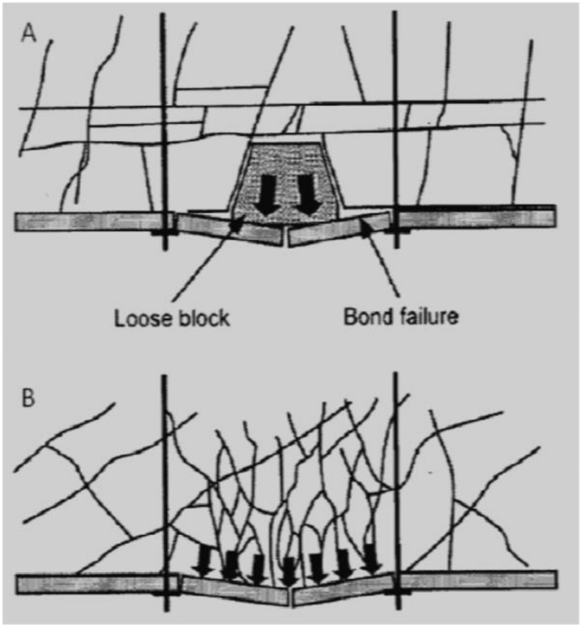

Figure 2. Flexural failure modes due to (A) loose block and (B) weak rock zone from Martin et al [5]

In both cases, the static system is similar – a plane, fixed at its circumference, which is statically undetermined. Based on the failure mode, structural tests to evaluate the toughness performance are typically conducted on different types of panels rather than on classical beams.

The flexural toughness and post-crack performance of fiber reinforced shotcrete (FRS) can be determined using a variety of internationally recognized methods, including beam tests, e.g. ASTM C1609 [6] or EN 14651 [7]. More relevant for the structural behavior of a shotcrete tunnel lining is the EFNARC square panel test [8], which has been adopted into the European suite of harmonized standards on testing of sprayed concrete, EN 14488-5 [9].

In 1998, Dr. E. S. Bernard developed a new method to test flexural toughness at the University of Western Australia, Sydney, with the aim to reduce variability and to increase the repeatability of the results [10]. The test is known as the Round Determinate Panel (RDP) test and nowadays internationally widely used in tunneling and mining. The RDP test is standardized by ASTM C 1550 [11]. For an RDP test set, at least three molded round FRS or cast concrete panels are to be produced and at least two panels must break in three pieces, as shown in Figure 3, and be within certain size specifications. ASTM 1550 specifies a depth and diameter of the panels of 75 and 800 mm, respectively. Testing involves the application of a load to the center of the panel by a hemispherical-ended steel piston. A servo-controlled testing rig is used to maintain a constant deflection rate of 4.0 ± 1.0 mm per minute. The panel rests on three pivots evenly spaced around its circumference and deflection is carried out until a central displacement of at least 40 mm is achieved. The energy absorbed is recorded at 10, 20, 30, and 40 mm deflection.

Figure 3. Panel displaying the characteristic crack pattern [12]

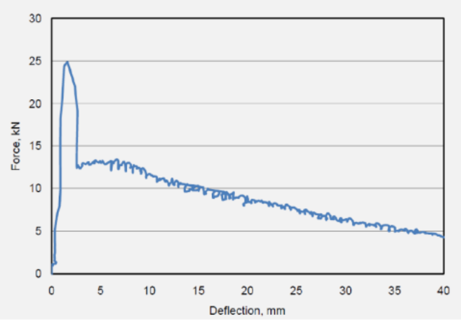

Figure 4. Typical load vs. deflection curve for macro synthetic fiber reinforced shotcrete [12]

The flexural strength or toughness of the panel is determined by calculating the area beneath the load vs. deflection curve, which is measured in Joules and is referred to as the absorbed energy. Figure 4 shows a typical load vs. deflection curve for shotcrete [12]. As shown in the figure, the deflection is carried out to 40 mm at a constant strain rate. The initial cracking appears already at a very small deflection and the load bearing level of the panel reduces to approximately half of the elastic maximum as the load is now primarily carried by the fiber-shotcrete interaction. After the initial cracking and load reduction, the load bearing level slowly decays as the crack widens and fibers are pulled out of the matrix.

In civil tunneling in the US, typical specified flexural toughness requirements are in a range of 320 to 350 Joules at seven days of age [13]. A typical dosage rule of thumb for macro synthetic fiber reinforcement shotcrete to achieve the seven-day strength is around 70 Joules per kilogram (J/kg) macro synthetic fibers, resulting in 350 Joules energy absorption with a dosage of 5 kg/m^3. Under practical conditions and in order to securely meet the specified requirements, an assumption of 55 to 60 J/kg seems to be on the safer side [12]. However, the RDP does not provide structural properties for a closed design solution. The RDP test is rather an empirical benchmark test, where specific benchmark values are used as basis for a classification and quality control on site.

Since the mid-1990s, multiple national bodies have developed guidelines for the use of FRC and FRS, e.g., in the USA and Canada, by the American Concrete Institute and the American Shotcrete Association, or in Australia by the Concrete Institute of Australia and the Australian Shotcrete Society [14]. These documents provide guidance that is generally independent of the fiber material, whether it is steel or synthetic. However, design principles differ regionally or are owner specific, and depend on the support system required.

F. Papworth suggests in his paper “Design Guidelines for the Use of Fiber Reinforced Shotcrete in Ground Support” a correlation between Toughness Performance Levels (TPL) by D. R. Morgan with the Q-system classes and FRS performance [15]. Table 1 is a modified table displaying the Standard Deflection Criteria of Papworth’s correlation in which the TPLs are defined by Morgan et al. as follows [16]:

1. TPL IV – Appropriate for situations involving severe ground movement, with an expectation for cracking of the FRS lining, squeezing ground in tunnels and mines, where additional support in the form of rock bolts and/or cable bolts may be required.
2. TPL III – Suitable for relatively stable rock in hard rock mines or tunnels where low rock stress and movement are expected and the potential for cracking of the FRS lining is expected to be minor.
3. TPL II – Should be used where the potential for stress and movement induced cracking is considered low (or the consequences of such cracking are not severe) and where the fiber is providing mainly thermal and shrinkage crack control and perhaps some enhanced impact resistance.

Table 1. Correlation of Morgan’s TPLs to Q-System rock classes, and EFNARC and RDP values [15]

Ground Condition		Standard Deflection Criteria	
TPL	**Rock Class**	**EFNARC (J)**	**RDP$_{40mm}$ (J)**
IV	F	>1400	>560
	E	>1000	>400
III	D	>700	>280
II	C	>500	>200

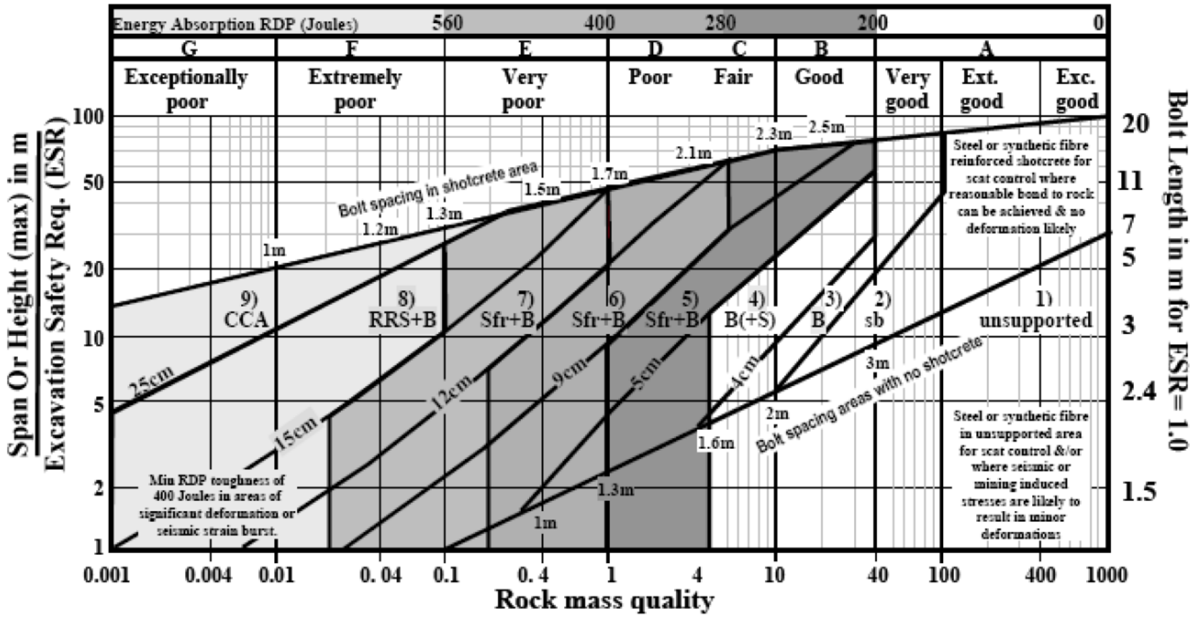

Figure 5. RDP values correlated with the Barton chart [15]

Morgan’s TPLs are based on beam tests; however, results from panel tests are the preferred way for the assessment of shotcrete for tunnel linings so the EFNARC panel-based toughness performance recommendations were developed based on Morgan’s TPL and published performance data. Using these EFNARC performance recommendations and an RDP correlation developed by Dr. Bernard [17], Papworth created the practical correlations shown in Table 1. It is important to note that these values represent test results for panels at 28 days of age.

The Q-system is internationally the most applied classification system for hard rock. It was developed by Barton et al. in 1974 [18] and updated in 1993 [19] and 2002 [20]. The Norwegian Concrete Association, representing a highly developed country regarding shotcrete, bases its general design approach on this widely recognized empirical rock stability classification [21]. Papworth correlated the energy absorption criteria used in the Barton chart to the RDP test using the aforementioned correlations (see Figure 5) [15].

INITIAL SUPPORT IN SOFT GROUND OR SOFT GROUND LIKE CONDITIONS IN TUNNELING OR MINING

The governing structural model of tunneling or mining in soft ground or soft ground like hard rock conditions is very different from the model in hard rock mining, because rock bolts are not efficient in soft ground or soft ground like conditions. The major element of the support in soft ground is still the arching effect in the surrounding ground mass itself. However, to keep the arch in place and restrain movements, a manmade structure consisting of a structurally bearing shotcrete arch has to be built inside the tunnel. The arch has to provide a structural minimum thickness and follow a designed geometry.

Shotcrete is used in soft ground tunneling primarily for two purposes: (1) to provide a structural arch inside the tunnel to support the natural arch of the substrate and (2) to seal the exposed ground surface immediately after excavation to protect the ground from the elements to avoid deterioration of the structural properties due to raveling.

An important factor in soft ground tunneling is the time between the excavation and the point when the ground surface is completely sealed off and supported by shotcrete, because during this timeframe the ground is exposed and relaxes, which potentially promotes convergence and settlements. Therefore, the timeframe has to be minimized to avoid unacceptable large deformations and instabilities in the surrounding ground body, which can lead to unacceptable surface settlements in tunnel projects with low overburden.

Compared to hard rock tunneling, the initial linings in soft ground are typically thicker, act, and are designed to be structurally stiffer and provide a supporting arch. In geological homogeneous conditions and if the cross-section geometry is not changing the situation can be simplified in a two-dimensional model in the plane of the tunnel cross-section.

After evaluating the interaction between the ground and the initial lining, the forces acting on the lining can be evaluated and are typically displayed as a combination of thrust and bending moment. An important indicator is the eccentricity of the normal force, which is evaluated by dividing the moment by the thrust. The structural model, even if simplified in two dimensions, is still statically indeterminate because the lining is bedded around the entire circumference.

A classical design approach for FRC tunnel linings in civil tunneling applications is the use of Moment-Normal Force (M-N) interaction diagrams (aka. Moment-Thrust Capacity Limit Curves) [22 – 25] (see Figure 6). The factored design forces acting on the section must remain within the M-N envelope.

This approach adopts and modifies traditional design methods from unreinforced and reinforced concrete structures. The FRC material properties are herein derived from beam tests, which are eventually used as a basis to supplement the stress-strain relationship of the concrete on the tension side using defined procedures [22 – 25] (see Figure 7). The idealized stress-strain diagram enables setting up the capacity limit curves, which are obtained by equilibrium iterations on a given cross-section.

This approach generally provides structural gains for FRC and FRS versus unreinforced concrete, but typically, the post-crack load bearing capacity is less than the maximum reached in the elastic stage. The advantage of FRC versus unreinforced concrete is that it offers considerable load bearing capacity in the post-cracking phase, due to the elasto-plastic ductile failure behavior of fiber reinforced concrete [22 – 25], which is similar to conventionally reinforced concrete. In tunnel linings, which are statically highly indeterminate, this ductile behavior allows for load re-distribution, thereby increasing the structural capacity of the structure as a whole.

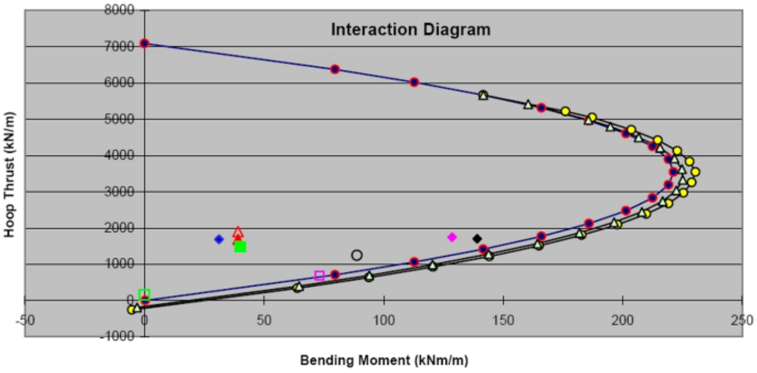

Figure 6. M-N interaction diagram of FRC (example)

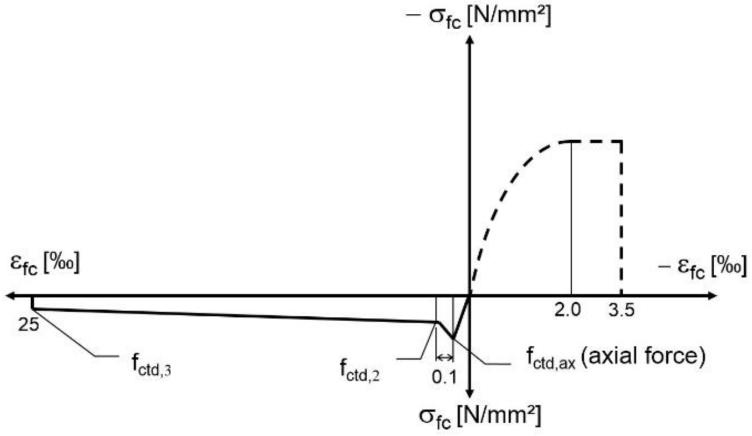

Figure 7. Idealised stress-strain curve of FRC (example)

An economic, state-of-the-art tunnel lining design considers the load-redistribution in the ground and the ground-support interaction. Load redistribution induces deformations and thus, a ground support is required that is flexible enough to withstand this deformation. Historic lining designs were structurally stiff and attracted a lot of loading, which in return required heavy reinforcement. Modern designs allow for controlled deformations resulting in much thinner and softer linings. However, the structural integrity of the deformed lining has to be considered. To take full advantage of the material properties of FRC, the design approach of tunnel linings has to move from an elastic to an elasto-plastic approach, similar to the consideration of plastic moments commonly used in steel-structure design. After reaching the elastic capacity of the lining, the lining cracks, but is still able to provide plastic bearing capacity. The load is hereby redistributed within the tunnel lining by increasing the bearing capacity of the structural system as a whole. The driving design factor is hereby moved from the maximum bearable load to a maximum allowable deformation or rotation capacity of a plastic joint (crack), which is provided by the fiber reinforcement.

FINAL LININGS IN TUNNELING

Final linings are typically installed in addition to the initial lining in civil tunneling applications. Characteristically, the initial lining is supposed to bear no or just limited load during the life of the tunnel. Therefore, the long term behavior is usually only of concern for the final lining, but not for the initial lining.

Tunnel final (or permanent) linings are either designed as drained tunnels or as fully tanked structures. While in the first case no or just marginal groundwater is acting on the lining, the full water pressure has to be borne by the final lining in the latter case. For durability reasons, especially if designed as a watertight concrete structure, crack width and crack depth are driving factors of the design.

For the structural design of final tunnel linings, similar methods as discussed for the initial lining in soft ground may be applied. However, for final lining applications there are a number of additional factors design engineers must consider. While cracking and deformations may be well acceptable for the initial lining or short-term ground support, they may be undesirable for final linings. Apart from the structural capacity, the long-term structural behavior becomes more important for final lining applications. The driving factors herein are durability and corrosion, crack width control, embrittlement, and retaining the load-bearing capacity with age as well as creep, which are further discussed below.

The design of cast in place (or cast in situ) permanent linings often yields a heavy steel rebar reinforcement due to the acting load combinations. The purpose of fibers here is to partly replace rebar and to improve the cracking behavior of the lining. Macro synthetic fibers act directly at the surface, where they bridge the developing crack and thus, support the protective cover for the steel rebars as a hybrid solution.

Full replacement of the steel rebar cages by fibres can be possible in TBM driven segmental linings. The segment designs –if not in soft ground– aim at largely compressed sections with little to moderate bending moments. Additional reinforcement may be only required for temporary load cases, typically for TBM propulsion, in the form of bursting ladders at joints. This technology has reached maturity today, and continues gaining popularity, because of its economic benefits. ITAtech activity group Support has recently finalized the “Design Guidance for Precast Fibre Reinforced Concrete Segments”. ITA has published the draft report on the World Tunnel Congress 2015 in Croatia [26]. The document provides examples of design and features project references using macro synthetic fiber only and hybrid solutions.

Macro synthetic fibers are providing great advantages under dynamic and seismic loading conditions by adding additional toughness, which is capable to absorb more energy, and by changing the failure mode from brittle to elasto-plastic. That in return provides more seismic load bearing capacity.

LONG TERM BEHAVIOR OF FRC TUNNEL LININGS

The durability of a tunnel final lining encompasses a number of factors including the permeability of the concrete, concrete strength, durability of the 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. However, macro synthetic fibers are not subject to corrosion. Typical issues like chloride ion penetration, carbonation, and to a lesser degree, water impermeability are, therefore, of no concern. This simplifies the design approach by reducing the number of critical durability problems, thereby allowing much greater flexibility in design.

Maximum allowable crack widths when using steel bars or steel fibers are small, because cracks act as points of rapid ingress of corrosive media to the reinforcement. Maximum acceptable crack widths are about 0.006 inches 0(0.15 mm) or just 0.004 inches (0.10 mm), as shown by recent in situ tests by Nordstrom [27, 28] and Bernard [29]. In contrast, crack width control is not critical for durability when using macro synthetic fibers since they are not susceptible to corrosion. Crack width limits might have to be considered though for water-tightness or structural capacity. Recent research has shown that the addition of macro synthetic fibers to steel rebar reinforced concrete reduces crack widths and crack spacings by 30% in bending [30]. Thus, MSF can add a significant gain of design life to steel reinforced concrete structures.

Most mix designs for shotcrete, and sometimes also for precast segments, focus on durability and corrosion protection to provide high resistance against chemical attack over their service life, which in tunneling is typically between 80 to 120 years. To achieve this goal, the mix design often contains large proportions of pozzolanic binders, which can develop significant post-hardening of the concrete over time. This leads to embrittlement of the fiber concrete matrix, which is responsible for post-crack performance loss when using steel fibers [29, 31, 32].

The change in behavior with age is due to a change from a ductile high-energy pull-out mode of post-crack fiber performance into a brittle low-energy rupture mode of the fiber itself, because of rupturing of steel fibers at crack widths, which exceed the elongation capacity of the fiber. The fibers break rather than being pulled out of the concrete matrix. This effect leads to performance degradation by primarily affecting the capability to react to a change of loading conditions while the structure is aging. Typical examples for changed loading conditions in tunneling are nearby underground or subsurface construction, seismic loading, or changes in hydrological conditions or tidal effects.
Macro synthetic FRC is largely unaffected by this phenomenon since post-hardening or changes in paste hardness make little difference to the behavior of the fiber within the composite beyond the first few days of hardening. The performance of macro synthetic FRC evident at 28 days is, therefore, unaffected over time.

In general, the magnitude of creep deformation in uncracked shotcrete does not depend on the type of reinforcement and is similar for a centrally layered light mesh or steel or macro synthetic fibers [33]. In cracked concrete, however, the load ratio (applied creep load over static capacity) governs creep deformation. There is only a minor difference in the performance of FRC in combination with reinforcement with a light mesh or macro synthetic fibers up to load ratios of 50 percent during a loading period of 100 days.

The 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. However, this loading regime seldom exists in tunnel linings, which are typically loaded under compression. Thus, the concerns which have been raised about the long-term performance of macro synthetic fibers in respect of creep and the associated consequences for crack width development with time under sustained flexural loads appear to be significantly overstated. The results of recent research [34] shows that the inclusion of macro synthetic fibers in the concrete has only a minor effect on the flexural strength of the cross-section, but the fibers reduce time-dependent in-service deformations and significantly reduce maximum crack widths when used in combination with conventional reinforcing bars.

CONCLUSIONS

Macro synthetic fibers are easy to pump and to apply using the shotcrete process, reduce the wear and tear on pumps and slick lines, and are easier and safer to handle than steel fibers or classic rebar reinforcement in tunneling.

The performance requirements and design approaches for tunnel initial linings in hard rock and soft ground are inherently different, due to the support requirements and failure mechanisms. In hard rock mining and tunneling, an empirical approach based upon the RDP test and the Barton Q-chart is common. In soft ground tunneling and final linings, typically a modified stress-strain-relationship for the FRC is used. However, this design approach does not fully utilize the elasto-plastic benefits of FRC. An alternative design concept was provided.

For final linings, the long-term behavior and durability are the governing factors of the design. Macro synthetic fibers are not susceptible to corrosion and do not have to meet stringent crack width limitations for durability. High-performance macro synthetic fiber 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.

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