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ABSTRACT

Fibre Reinforced Shotcrete (FRS) reinforced with macro-synthetic fibres has now been used to stabilize ground in underground mines and tunnels, and for slope stabilization, for over 10 years. Experience has demonstrated that macro-synthetic fibres are capable of exhibiting very high levels of performance and are a highly effective form of reinforcement for both temporary and permanent ground support. Engineering data also exists showing that macro-synthetic fibres excel with regard to corrosion resistance and embrittlement in shotcrete, and are very effective in ground subject to high deformation. Despite this, the design of FRS linings using this type of reinforcement lags behind that of linings incorporating alternative forms of reinforcement. There is a lack of appreciation within the engineering construction community that methods of design exist for this material and that these have been proven satisfactory. This paper will attempt to summarize generic approaches to the design of temporary and permanent ground support based on macro-synthetic FRS.

INTRODUCTION

The design of Fibre Reinforced Shotcrete (FRS) linings for ground stabilization has been subject to development for many years. No completely satisfactory engineering model exists for ground interaction with shotcrete linings, especially for hard rock applications. FRS linings have nevertheless been found effective for ground control in thousands of mining, tunneling, and slope stabilization projects around the world. The widespread acceptance of FRS linings in the absence of deterministic engineering models of behaviour is largely due to the existence of observational methods of lining 'design'. Using this approach to design, lining thickness, strength, and toughness are varied on the basis of experience gained through previous projects regarding minimum satisfactory thickness and material performance requirements. Some of this experience is expressed in the form of the Q-chart (1) for permanent ground support using FRS and bolts, while temporary support requirements in hard rock are more satisfactorily addressed using simplified information of the type expressed in Table 1 (2). Alternately, simple deterministic models of load and resistance can be used (3). Lining design for other applications, including in soft ground and vertical shafts that require thick-shell linings subject to minimal or temporary flexural-tensile stresses, can be accommodated using the measured post-crack flexural capacity of macro-synthetic FRS together with conventional structural theory (4, 5).

Despite the existence of many hundreds of kilometres of tunnel successfully stabilized using macro-synthetic FRS, engineers responsible for civil tunnels remain hesitant to specify this material for permanent ground support. Much of this hesitancy is probably due to a lack of familiarity with the material. When considering use of macro-synthetic FRS one therefore needs to be clear about the many benefits this material presents both contractors and owners of FRS infrastructure compared to steel FRS and steel bar reinforcement since macro-synthetic FRS exhibits a number of differences in performance that must be recognized in order to use it appropriately.

The advantages of macro-synthetic FRS are evident in both the wet and hardened states. In the wet state macro-synthetic FRS is slightly easier to pump than steel FRS of similar performance, and presents the shotcrete contractor with the advantage that pumps and hoses are subject to less wear than occur when using steel FRS. Macro-synthetic fibres are also safer to handle as they pose very little risk of human injury during handling and the as-sprayed surface presents a diminished risk of laceration. In addition, the low mass of fibres used per cubic metre for most levels of post-crack performance offers the contractor an advantage in terms of reduced environmental and transport costs that can make a substantial difference to the overall attractiveness of shotcrete in remote areas. Carbon emissions per cubic metre of FRS are also substantially lower for a given level of post-crack performance when using macro-synthetic fibres compared to steel fibres or steel bars.

In the hardened state, macro-synthetic FRS offers three distinct advantages over steel FRS and conventional bar reinforcement. The most important of these is the potentially lower overall cost per cubic metre for most specified levels of post-crack performance. If high levels of residual strength are required across very narrow cracks (less than 0.25 mm) then steel fibres are likely to be more economically competitive. However, if high performance is required across cracks wider than 0.25 mm then macro-synthetic fibres are likely to result in a cheaper FRS mix. This makes macro-synthetic FRS highly suited for temporary ground control in, for example, mines or primary linings in civil tunnels. Moreover, macro-synthetic fibres can bridge much wider cracks than steel fibres and are thus more suited to the control of ground subject to high deformation (7). The low cost and adaptability of macro-synthetic FRS is the principal reason this material has been adopted so vigorously within the underground mining industry. In the context of post-crack performance, however, it must be noted that neither steel nor macro-synthetic FRS can equal the structural capacity of heavy steel bars. In highly stressed ground it may therefore be necessary to use macro-synthetic FRS in combination with steel sets, lattices, or heavy bars.

TABLE 1 – Toughness requirements for temporary FRS based on expected ground conditions (2).

Type of Support	**Minimum Toughness***
Low deformation	280 Joules
Moderate ground support	360 Joules
High-level ground support	450 Joules

* Energy absorption at 40 mm in ASTM C-1550 round panel test (6)

DESIGN FOR SERVICEABILITY

For serviceability requirements typical of underground applications an important advantage that macro-synthetic FRS presents over alternatives is superior corrosion resistance. Most shotcrete used for ground control will suffer some form of cracking due to ground movement either soon after construction or at later ages. Cracks usually result in exposure of the reinforcement to ground water or atmospheric gases and pollutants that, in the case of steel reinforcement, can quickly lead to corrosion (8, 9). Macro-synthetic fibres are completely immune to the corrosive combination of weak acids, salt, and oxygen, and to contaminants within ground water and the concrete itself (10, 11). It is for this reason that macro-synthetic fibres have been made mandatory for all sub-sea tunnels in Norway (12, 13), and are probably the most durable form of reinforcement available for coastal infrastructure subject to salt spray.

Macro-synthetic FRS is particularly suited to applications such as external slope stabilization in which crevice corrosion of reinforcement is likely. Inclined soil slopes tend to migrate downward over time resulting in a bulge near the toe even when stabilized with shotcrete and soil anchors (Figure 1). This will induce cracks in the lining that open upward to the atmosphere and facilitate rapid ingress of rainwater combined with carbonic acid from organic decomposition and CO_2 dissolution. Both steel fibres and bars suffer rapid corrosion under these conditions, thus macro-synthetic fibres are the 'natural' choice of reinforcement for this application based purely on corrosion concerns (10). Similar concerns over corrosion make macro-synthetic fibres a rational choice for most applications near salt water (14).

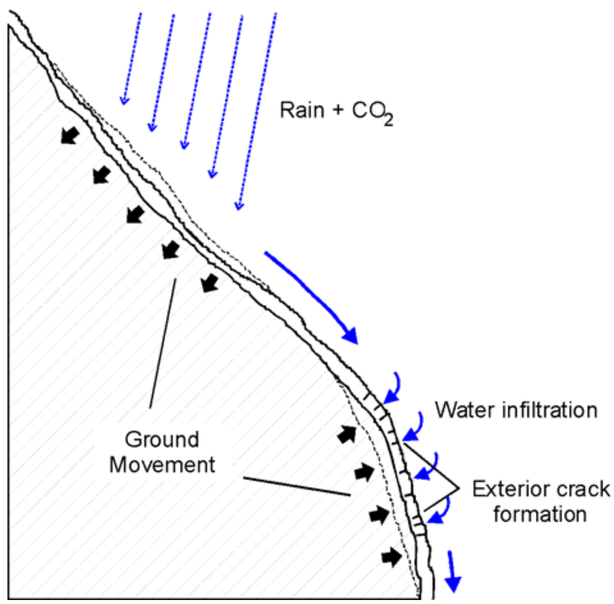

Figure 1. Crevice corrosion of steel fibres and bars on a slumping slope.

Another advantage of macro-synthetic FRS is superior retention of toughness with age (15). High toughness, whether expressed as post-crack energy absorption or residual strength, is primarily due to the friction that develops between the concrete matrix and fibres as they pull-out across widening cracks when a lining is subject to deformation. A well-designed FRS mix can absorb much more post-crack energy than shotcrete reinforced with conventional bars because steel bars can only sustain a small level of strain across cracks before they rupture and thereafter absorb no further energy. *Embrittlement* is the term used to describe the loss of post-crack load and energy absorption capacity that may occur when the strength and hardness of a concrete matrix become so great that the fibres change their mode of post-crack behaviour from the high-energy friction-based pull-out mode to the low energy rupture mode across widening cracks (Figure 2).

Recent evidence has emerged that steel FRS suffers embrittlement due to hardening of the concrete matrix and in the long term can loose up to 50 percent of the post-crack energy absorption capacity apparent at 28 days (16). In contrast, most macro-synthetic FRS is reinforced with fibres that are softer than the concrete matrix and therefore suffer the same mode of pull-out failure regardless of how strong or old the concrete becomes. The performance measured at 28 days is therefore more likely to be retained so that it can be relied upon to control ground movement at late ages. This is particularly important in the context of late-age alterations to FRS structures as well as seismic risk. Many designers believe that late-age deformation of linings is limited but ignore the very real risk of extreme and unforeseen events that may occur at any point during the life of a lining (17). Such events demand sustained toughness in a FRS lining. Macro-synthetic fibres therefore offer numerous advantages over steel fibres and bars in any application in which residual strength is required across cracks anticipated to be wider than 0.5 mm.

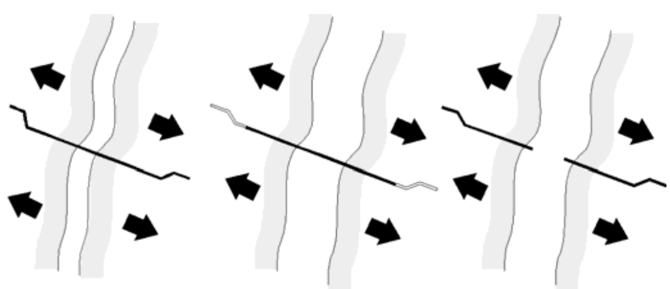

Figure 2. Post-crack failure mechanisms for FRS reinforced with steel fibres.

There also exist several disclaimers on the serviceability-related performance of macro-synthetic FRS that must be considered in lining design for serviceability. These disclaimers principally concern the performance of macro-synthetic FRS with regard to fire resistance and post-crack creep. The fire resistance of a FRS lining depends on the intensity of the fire and the strength and density of the shotcrete matrix (18). In high intensity fires macro-fibres of any composition will have little influence on post-fire flexural performance because the concrete matrix is so seriously damaged by high temperatures that residual toughness is negligible (19). After less intense fires in which the concrete matrix retains greater residual strength at the heated surface, steel fibres will retain greater post-fire capacity and are therefore superior to macro-synthetics. However, in the context of the spalling resistance of a shotcrete lining during a fire neither steel nor macro-synthetic fibre is as useful as micro-synthetic fibres because only the latter type of fibre can effect a substantial improvement in spalling resistance (20).

The magnitude of post-crack creep deformation suffered by macro-synthetic fibres is generally greater than that sustained by steel fibres bridging cracks, but the significance of this depends on the magnitude of creep deformation exhibited by the uncracked shotcrete matrix. Steel fibres appear to suffer very little time-dependent extension across cracks when subject to flexural action (21) whereas macro-synthetic fibres vary in their response depending on the design of the fibre and the magnitude of load. Below approximately 40% of static load capacity in the cracked state, many macro-synthetic fibres exhibit negligible creep extension and are therefore difficult to distinguish from steel fibres. However, above 50-60% of static capacity some types of macro-synthetic will show substantial extension (22). Moreover, the length of time over which the load is applied will also influence the outcome since most of the extension appears to occur over the first two weeks of post-crack loading (23). The creep properties of macro-synthetic FRS therefore depend strongly on the type of fibre used, magnitude of load applied, and duration of loading. It should be noted that the composition of fibres used in a FRS mix does not influence the magnitude of time-dependent deformation experienced in the *absence* of cracks.

The type of reinforcement used in shotcrete has no influence on abrasion and cavitation resistance, and minimal influence on impact resistance. If these properties are of concern for a particular project, for example in a hydro tunnel, then selection of an appropriate coarse aggregate type (for example, dolerite) and attention to the design of the cementitious fraction within the shotcrete will likely yield more favourable results (24). The permeability of shotcrete is not affected by the presence of fibres, but the magnitude of restrained shrinkage strain suffered as a result of drying at the surface appears to be reduced for both steel and macro-synthetic FRS compared to plain shotcrete of similar composition (25, 26). Experience in many hundreds of kilometres of mine tunnels constructed in Australia with macro-synthetic FRS and subject to highly aggressive drying conditions has demonstrated that shrinkage cracking of FRS linings between 50 and 100 mm thick over a hard-rock substrate is minimal even when no attempt is made to control shrinkage.

When local deflections within a FRS lining are of concern it must be recognized that both steel and macro-synthetic FRS exhibit substantially lower rigidity in bending after cracking than before cracking (27). Creep will also influence deflections and thus the creep characteristics (21) of a cracked FRS lining should be considered in analysis to determine the true time-dependent flexural rigidity of a lining. If substantial deflections are expected to occur then mining experience suggests that bond between lining and ground will be reduced to zero only a short period of time after spraying (days to weeks). A FRS lining should be designed to remain uncracked if high rigidity and tight controls on maximum deflections are required. Moreover, altering the thickness of a FRS lining is a much more effective means of influencing rigidity than changing the form of reinforcement.

DESIGN FOR ULTIMATE STRENGTH

Design of a FRS lining for ultimate strength requires that the load actions and load resistance of the lining be known or at least estimated. In hard ground the loads acting on a FRS lining are quite difficult to determine. Guidelines based on experience gathered over many years both in civil and mining applications are therefore of great assistance in determining lining toughness and thickness requirements. For civil applications, the Q-chart approach (1) is useful and has been found suitable for linings required for permanent ground support. The failure modes and design responses outlined by Barrett & McCreath (3) are also valuable. However, these guides have been found to be too conservative for mining applications where thinner linings with generally higher toughness requirements have been found more suitable and economical for short to medium term control of ground movement (see Table 1). While both these approaches rely on observation and require local thickening of the lining when stability is not maintained, the difference between these guidelines is related to the length of time that the ground is required to be stabilized. Longer time frames require more conservatism.

The performance requirements for temporary FRS linings used in underground civil projects are similar to those placed on most linings sprayed in underground mines. Macro-synthetic FRS has been found to be highly effective and competitive against all alternative systems of ground control in underground metalliferous mines and are therefore likely to be highly suited to most temporary support requirements in civil tunnels. For permanent support, the suitability of macro-synthetic FRS compared to alternatives is in part determined by the severity of the corrosion risk. In a moist environment with salt exposure cracks greater than 0.3 mm *will* result in rapid loss of steel reinforcement continuity across the crack. Tunnels in Norway stabilized with steel FRS linings have shown serious degradation due to corrosion after only 15-20 years service (13). Given that most groundwater contains at least some deleterious salt ions the longevity of steel reinforcement spanning across a crack in a tunnel lining is questionable and the expectation of a 100+ year design life is laughable.

For thick shell FRS linings in soft ground the options for design are numerous. Unfortunately, no single method of design has been found to be effective for all ground conditions (28) and thus the method must be selected on the basis of ground conditions at hand. For temporary support requirements steel FRS has been found effective under many conditions. Experience with macro-synthetic FRS is not as extensive as with steel FRS, but the recent El Ragajal tunnel project on the Madrid to Valencia-Murica AVE high speed rail line in Spain saw the successful use of a macro-synthetic FRS lining for temporary support of a wide span rail tunnel through soft clay. Soft-ground conditions are also encountered in mines on a regular basis and macro-synthetic FRS linings have been used very successfully in these conditions but published experience of these projects is not extensive (29).

The question of how to design permanent FRS linings for strength depends on the severity of flexural tensile stresses across cracks and the duration over which these stresses act. If flexural-tensile stresses are non-existent then the lining can be designed as a plain concrete arch or ring, in which case the reinforcement is merely provided as a backup in the event of something unforeseen such as a construction accident. If flexural-tensile stresses are moderate in magnitude (less than 2 MPa) and duration, evidence suggests that macro-synthetic FRS can perform satisfactory.

For structural calculation purposes it must be considered that FRS reinforced with macro-synthetic fibres tends to exhibit a uniform post-crack stress-strain relation in contrast to steel FRS which exhibits steadily diminishing residual strength with increasing crack width (Figure 3). The centroid of the tensile stress block for a macro-synthetic FRS is therefore closer to the extreme tensile fibre of a cracked cross-section subject to bending and the lever arm between net tensile and compressive forces is enhanced compared to steel FRS. The maximum magnitude of the post-crack flexural-tensile strength available in a macro-synthetic FRS section depends on the type and dosage rate of fibre used.

Methods of estimating ground loads and stresses in thick-shell tunnel linings are presented in numerous publications (30-33) and will not be repeated here. It should be noted that macro-fibres of any composition have a minimal effect on the early-age shear resistance of shotcrete (34) and are thus of little value in controlling fall-outs and rebound during and after spraying. Micro-synthetic fibres of less than 25 micrometres diameter are much more useful in this context due to their beneficial effect on internal cohesion. However, the mature age shear strength of FRS appears to be independent of the type of fibre used as reinforcement.

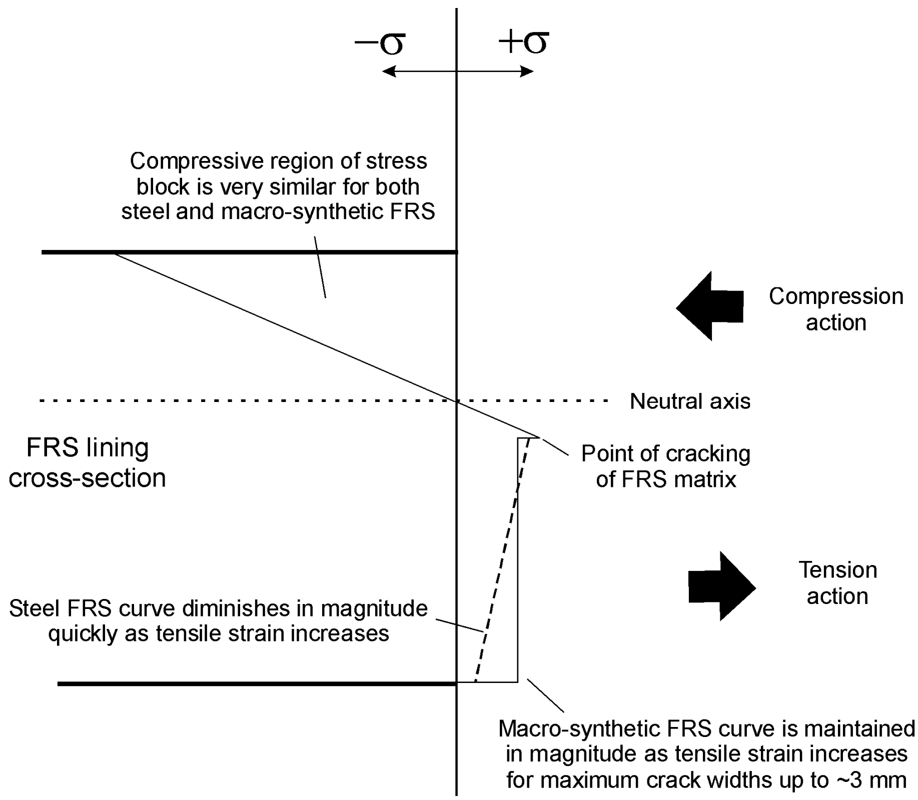

Figure 3. Stress distribution through a FRS lining subject to flexure and reinforced with steel or synthetic fibres.

SUMMARY

Shotcrete reinforced with macro-synthetic fibres represents a new and competitive material for use in ground stabilization in the tunnelling industry. In certain applications it offers substantial advantages over alternatives with regard to cost and performance. The durability of this material in corrosion environments is particularly attractive. These advantages have seen the widespread adoption of macro-synthetic FRS in the underground mining industry internationally as mining companies have sought to use the most effective and competitive materials available. The advantages revealed in mining applications are also eminently applicable to civil construction, and thus designers should examine the application of this material wherever corrosion and cost factors drive a requirement for innovative new solutions to problems of ground control.

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