Use of Steel Fiber Reinforced Sprayed Concrete in the Final Lining of Conventionally Excavated Tunnels

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ABSTRACT

Traditionally, conventionally excavated tunnels consist of a “double shell” type lining. The initial shell is a FRSC (fiber reinforced sprayed concrete) “temporary” lining that stabilizes the opening after excavation and contain short to medium-term loads. Following installation of a water proofing membrane a traditionally reinforced final cast in-place concrete lining is installed to contain long-term loads and provide durability. This presentation introduces an alternative SFRPSCL (Steel Fiber Reinforced Permanent Spray Concrete Lining) system that is a “single shell” of sprayed concrete. The advantages expected from the development of SFRPSCL as a permanent lining are many! Environmental Impact: Reduction of CO2 by reducing the steel weight vs. rebar; Reduction of CO2 by Thinner Lining = Less Concrete; More Durable = longer life. Cost Reduction / Performance: Reduction in weight of steel required plus no installation cost; No Formwork Required = less labor + quicker build time! Quality and safety can be achieved using the right product for the right use, specifying clear performance requirements and appropriate testing methods.

1 USE OF SPRAYED CONCRETE IN UNDERGROUND SUPPORT

Around the globe the use of sprayed concrete in ground support applications in tunnels and mines is considered the single largest use of shotcrete. In North America, swimming pool construction has been looked at as the single largest consumer of sprayed concrete followed by underground support applications as second.

1.1 Technological improvements of shotcrete for tunnels

Over the last 35 years sprayed concrete technology has evolved to where the method is considered as good or better than cast in place concrete. Figure 1 shows graphically the key milestones since its first use over 100 years ago.

New technology developed by all the different stakeholders in the tunnel construction industry, from raw material providers, equipment manufacturers, engineers to constructors have resulted in the following improvements to Sprayed Concrete Linings (SCL) in recent years:

- Development of mechanized wet mix shotcreting
- Usage of alkali-free additives
- Use of fibers for shotcrete mixing
- Development of high-performance steel fibers
1.2 Shotcrete in tunnel linings

Depending on underground conditions, rock quality, overburden, tunnel diameter and length, ground water level, a tunnelling method must be selected using manual or mechanized excavation. Manual excavation includes drill and blast or the use of a road header. Depending on the tunnel parameters the tunnel cross section will be excavated in one operation or in different steps. In the last case, more temporary linings will be required to stabilize the underground at any moment.

1.2.1 Double shell method

Historically, tunnels constructed using sprayed concrete have been based on a (1) temporary sprayed concrete lining to stabilize the opening after excavation and to contain short to medium-term loads. If required, to assure watertightness a (2) waterproof membrane is placed next between the temporary and permanent linings. After the temporary lining has fully stabilized, a (3) permanent cast in-place (CIP) concrete lining is installed to contain long-term loads and provide durability and watertightness. This is referred to as the double shell method. (Figure 2)

Until recently, the long-term design of tunnels has neglected the contribution of the initial support (considered as only providing temporary support). The sprayed concrete was either not reinforced or was reinforced by welded mesh, which was often poorly encapsulated by the sprayed concrete. This led to voids between the mesh and the rock and to a lack of corrosion protection for the mesh, which are two reasons why the initial sprayed concrete layer was considered as temporary. Additionally, there was no calculation method to quantify the contribution of the primary support. Its design was empirical (Barton Chart – Q System) and any structural value was neglected over the long run. The cast-in-place concrete lining was designed to support all the long-term loads. With advancements in shotcrete and related technologies, it is now possible to construct a double shell lining using shotcrete to replace the CIP final lining.
1.2.2 Single shell method

Currently modern sprayed concrete technology equips the tunnelling industry with a more economic tunnel lining system in the form of a single shell of permanent sprayed concrete. Single Shell SFRPSCL (Steel Fiber Reinforced Permanent Spray Concrete Lining) systems have been designed/constructed around the globe where high-performance steel fiber reinforced sprayed concrete replaces the conventional double shell method of construction. This technology provides a structural lining that is durable, watertight and can be surface finished to a degree that is like cast concrete. The use of SFRPSCL allows to eliminate the traditional reinforcement in the final lining, reduction in total quantity of steel required, reduction in lining thickness and quantity of concrete required, reduction in labor, significant cost savings can be realized as well as reduced carbon footprint of the lining.

The term “single shell sprayed concrete method” does not refer to the placing of a single sprayed concrete layer but to the interaction of several layers as a single shell. No shear reinforcement is foreseen at the joints. The bond performance of the individual layers therefore is very important.

In addition to improvements in sprayed concrete technology, other advancements have led to the increased acceptance to adopt this new method of tunnel lining construction. These improvements include:

- Automated, mechanized construction – (remote controlled spraying)
- Safety culture - limited man access (replace mesh with fibers)
- Sprayed applied waterproof membranes (SAWM)
- Steel Fiber Technology – high performance fibers developed
- Higher skilled operators – Nozzleman and equipment training programs (ACI and EFNARC programs)
- Improved testing methods to characterize SFRSC performance (new (pr)EN 14488-3 panel w/ notch)
- Improved quality control methods and procedures
- Improved design standards and performance requirements such as fib 2010 Model Code
- Producing a sustainable, durable, low carbon lining are now a top priority.

2 DESIGN PRINCIPLES

The design of a tunnel should consider the interaction between ground and lining. To do so, the lining must be placed as close to the ground as possible. To preserve its natural strength, the ground should be kept as undisturbed as possible. Modern tunnelling tends to use as much as possible the self-bearing capacity of the underground. A suitable support system must be designed to allow the underground to move in a controlled way until it reaches a new equilibrium by creating a self-supporting arch inside the rock. The sprayed concrete lining must perform in a ductile way providing the required bearing capacity to allow the rock to
become self-supporting. Along with meeting structural requirements the lining must consider water infiltration, providing long term durability and sustainability (carbon footprint) considerations.

2.1 Empirical design tools

Beginning in the late 1950’s the development of observational methods of design such as the NATM (New Austrian Tunnelling Method) also sometimes referred to SEM (Sequential Excavation Method) were developed primarily for use in weak or squeezing ground. In the 1970’s, the empirical NTM (Norwegian Tunnelling Method) was developed in Scandinavia based on ground support protocols in hard, jointed rock masses. NTM ground support determination is based on using the “Q” System and Barton Chart, for determining the requirements for bolts and fiber reinforced shotcrete to strengthen the underground to become self-supporting.

These empirical design tools enabled the engineer for replacement of steel sets and timber lagging type designs, or steel reinforced cast in place concrete design, with the use of rock bolts and fiber reinforced shotcrete designs.

Design emphasis for 1st layer:
1. Load bearing capacity (short term)
2. Durability
3. Watertightness

Design emphasis for 2nd layer
1. Watertightness
2. Durability
3. Load bearing capacity

2.2 Structural design tools

Over the last 20 years design principles and testing standards have been developed and are available that allow more sophisticated design of a shotcrete tunnel lining. FRPSCL (Fiber Reinforced Permanent Spray Concrete Lining) can now be used for all type of tunnels in a wide variety of ground conditions.

Two general systems can be considered to create a single shield tunnel.
- One approach is a one step application method for small diameter tunnels, or tunnels founded in stable, dry ground conditions.
- The second approach is a two-layer application process where the first layer achieves tunnel stability and the second layer (acting monolithically with the first), is installed by spraying, enhancing durability and water tightness.

Today there are three different loading concepts when designing shotcrete in a tunnel lining. (Figure 3)
1. Double Shell Linings (DSL): consists of a primary lining that takes the temporary load plus a secondary lining to take the permanent load.
2. Composite Shell Linings (CSL): consists of a primary lining, sprayed waterproof membrane, and a sprayed secondary lining, where the primary lining acts compositely and takes a proportion of the long-term ground load
3. Single Shell Linings (SSL): a single lining takes on the temporary and long-term loads. It can be done in several layers and is frequently used in projects with little hydrostatic charge

Regardless of approach, a permanent sprayed concrete lining should be considered in the same way as any other permanent concrete structure. Hence, codes like Eurocode 2 and ACI 318, should be applied for the design and acceptance of the requirements for normal loading conditions in the long term. For structural use, mechanical performance of FRC must be verified according to the Model Code 2010 requirements.

The actions on the lining are evaluated with a geotechnical analysis and the use of FRC does not change the global behavior of the lining. At a geotechnical level, there is no difference between ordinary reinforced concrete lining and SFRPSCL.
The verification at SLS (Service Limit State) can be made based on either that the lining at final stage is 100% in compression or at final stage lining is partially in tension. The verification at ULS (Ultimate Limit State) is made by comparing the bending actions and axial forces derived by the geotechnical analysis with M-N envelopes defined at final stage.

2.2.1 Shotcrete layer bonding considerations

To provide a monolithic structure, the bond between shotcrete layers must be frictionally tight and form fitting. Shear reinforcement between the two layers should be avoided as it will aid the development of water paths to the inner surface of the tunnel and a consequential reduction in durability. The shear and tensile bond between layers can be ensured by the surface roughness of the first layer to provide an effective, mechanical bonded, interlocking surface.

How to prepare this layer? Bond strength is also enhanced by a slow drying and early thermal shrinkage concrete mix design by lowering the heat of hydration and by efficient curing of the fresh shotcrete layer.

2.2.2 Durability and water tightness considerations

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 important.

Steel fibers 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 sustain the long-term durability of a tunnel lining requires that no persistent flowing water through a crack can be tolerated. This can be achieved in a couple of different ways:

- Limiting the design crack width of the PSFRSCL to 0.1 mm if the sprayed concrete is to provide inflow control.
- Provide an alternative solution for groundwater infiltration such as a SAWM or other drainage system. In this case PSFRSCL crack widths should be limited to 0.03mm. (Eurocode 2)
2.2.3 Fiber requirements

Fiber Reinforced Concrete (FRC) is a composite material characterized by a cement matrix and discrete fibers (discontinuous). The matrix is either made of concrete or mortar. Today most of the fiber used in shotcrete applications can be classified into 3 families for underground applications:

1. Steel fibers: structural applications, cracking control, durability, SLS and ULS design
2. Micro synthetic fibers: fire protection and to prevent plastic shrinkage cracking.
3. Macro synthetic fibers: non-structural applications when SLS is not important and when fire resistance is not important. Mainly used for temporary structures with high deformation

Micro synthetic fibers can be added to the shotcrete with steel fibers in PSFRSCL linings for passive fire protection purposes. However, currently macro synthetic fibers are not considered appropriate for use in this structural application. The fib Model Code prohibits structural use of fibers with a Young’s modulus which is significantly affected by time and/or thermo-hygrometrical phenomena. Synthetic fibers at ambient temp go elastic and melt at 165° C (320° F) are not covered by the Model Code and current design standards. Due to the low Youngs Modulus of the fiber compared to that of the concrete itself, crack widths are larger than allowable.

According to ISO 13270: ‘Steel fibers 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 fibers can only occur above 370°C (698°F).’ (ISO/TC 17/SC 17) The fibers should meet the following criteria as well as specified performance requirements:

- Fibers should comply with the European Standard EN 14889-1
- Fibers with CE marking, system 1 (Fibers for structural use)
- Fibers out of drawn wire, with a tensile strength of the steel wire ≥ 1800 MPA
- Dimensional tolerances according to EN 14889-1 and ISO 13270
- Fiber length: 35
- Aspect Ratio (L/D) 65
- If galvanized min. 30 g/m²

3 PERFORMANCE CRITERIA AND TESTING STANDARDS

European standard EN 14487-1 mentions the different ways of specifying the ductility of fiber reinforced sprayed concrete in terms of residual strength and energy absorption capacity. It also mentions that both ways are not comparable. The energy absorption value measured on a panel can be prescribed when - in case of rock bolting - emphasis is put on energy which must be absorbed during the deformation of the rock. This is especially useful for primary sprayed concrete linings. (EN 14488-5). In North America, the ASTM testing standard for this purpose is ASTM C1550 – round determinant panel test.

The residual strength of the fiber reinforced concrete is prescribed when the concrete characteristics are used in a structural design model. For FRSPCL applications the residual strength will be the key material property to determined. Typically, bending tests can be carried out to determine the load-deflection relationship of a beam under either a three point or four-point loading. From this, the flexural tensile strength can be determined. Three-point bending tests are usually performed in accordance with EN 14651 standard. The EN 14651 is a test developed specifically to characterize FRC and derive design parameters. EN 14651 is the reference standard for the European Union CE label for steel and polymer fibers and has been adopted by several fiber manufacturers and designers, primarily in Europe, Asia and Middle East. The great advantage of this test is that it relates the strength to specific CMODs (Crack Mouth Opening Displacement) and the strength indices can be used directly in design for the appropriate Limit State. This test procedure has been adopted by Model Code 2010 and its implementation is relatively straightforward and independent of the type of fiber. It has also been found that the current ASTM C1609 four-point bending test can underestimate the residual strength value beyond the L/300 deflection in high performance SFRC. This is due to structural effects in the beam when fibers provide deflection hardening characteristics.
From the design when following the fib 2010 Model Code, the residual strength values which derived from this testing of importance are: Value fR1 (CMOD = 0.5mm) which is used for the verification of SLS design requirement and Value fR3 (CMOD = 2.5mm), which is for verification of the ULS design requirement for the lining. (fib Special Activity Group 5, 2010)

Testing to determine the residual strengths for sprayed FRC can be difficult as the specimens for the EN 14651 standard must be cut from sprayed panels. With the increased use of SFRSCL a new standard was developed which allows the residual strength parameters to be determined by performing a three-point bending test on the standard EN type square panel. This new test combines the values provided by the EN 14651 beam test with the advantages of the EN 14488-5 panel test (the same moulds can be used and due to the larger cracked section, the scatter is lower).

The advantages of this new test method in SFRSCL are:

- The geometry and dimensions of the specimens, as well as the spray method adopted will ensure distribution of the fibers in the matrix, which is close as possible to that encountered in the real structure.
- The dimensions of the test specimen will be acceptable for handling (no excessive weights or dimensions).
- The test will be compatible, with use in many normally equipped laboratories (no unnecessary sophistication).
- The geometry is the same as in the plate test for Energy Absorption.
- The plate can be sprayed on the job site – Eliminates the need to saw a beam out of a panel
- The scatter will be lower than the current standardised beam test
- The notch will provide a slower cracking process, thereby reducing the risk of a sudden fall
- This test provides residual flexural strengths values as required in the design per fib Model Code

4 PSFRSCL A SUSTAINABLE AND SMART SOLUTION

Concrete is one of the most widely consumed materials on the planet and is said to contribute approximately 8% of global carbon emissions; the main source of these emissions is the manufacture of Ordinary Portland Cement (OPC). In a tunneling project, it is generally considered that 60% to 70% of embodied carbon is contained in the concrete linings of the shafts and tunnels. The use of steel fibers to replace all or part of conventional reinforcement in a PSFRSCL has been demonstrated to lower the embodied CO2 of the lining. LCA (Life Cycle Assessment) tools have been developed to help evaluate the sustainability of different design alternatives. EPD for steel fibers are available from major fiber producers that can be used in performing these evaluations.

4.1 Project Example - Montreal, Quebec, Canada, Réseau Express Métropolitain (REM) Project

The REM project is currently under construction by a joint venture of SNC Lavalin, AECON, Dragados, EBC, and Pomerleau and the final design is being performed by a joint venture of SNC Lavalin and AECOM. Once completed at the end of 2024 the REM will be the 4th largest automated transportation system in the world! The project includes 3 underground stations in downtown Montreal. One of the underground stations, Edouard Montpetit (EMP) Station, will be the deepest station in Canada when complete. The EMP Station is built within the existing double track Mont Royal Tunnel (MRT). The side platforms are built by enlarging the existing tunnel. Using the NATM method of excavation the EMP Station utilizes permanent rock bolts and shotcrete reinforced with steel fibers for both the initial and final linings of the station structures (tunnels, shafts, caverns etc.). (Figure 4) First a layer of 5 cm of steel fiber shotcrete is applied as initial support and safety, then bolts are installed, a SAWM is then applied, and then another 5 cm of steel fiber reinforced shotcrete is applied. The PSFRSCL liner is designed for a 125-year service life.

The project also includes the rehabilitation and enlargement of the MRT. This 100 year old double track tunnel is about 5 km long and will also employ a PSFRSCL in the rehab/enlargement with the new final tunnel lining replacing an old CIP concrete one.
5 REFERENCES


