Updated Fiber-reinforced Shotcrete Testing Standard – Faster, Easier and Better!

By Bill Geers and Benoit de Rivaz

FIBER-REINFORCED SHOTCRETE IN UNDERGROUND LINING APPLICATIONS

Ground support applications in tunnels and mines are considered the single largest use of shotcrete in the world. Historically, both macro-synthetic and steel fiber-reinforced shotcrete have been utilized as the initial or "temporary" ground support system in a tunnel, or caverns. This initial ground support layer (with rock or cable bolts when necessary) was then overlaid by a waterproofing membrane (if needed), and then a structural cast-in-place reinforced concrete layer installed as the final lining. The initial layer of fiber-reinforced shotcrete was not considered to provide any long-term structural benefit because of the uncertainty of the long-term quality and durability of the product. This system of lining used on conventionally excavated tunnels and caverns is sometimes referred to as the Double-Shell Method.

Over the last 30-years, modern sprayed concrete technology and quality has evolved (Fig. 1) and now equips the tunneling industry with a more economical tunnel lining system as a Permanent Sprayed Concrete lining (PSCL) that replaces the cast-in-place final lining (also known as the Single Shell Method). The use of high-performance steel fibers in the shotcrete eliminates the traditional reinforcement in the final lining, providing a reduction in the total quantity of reinforcing steel required, a reduction in lining thickness and quantity of concrete required. With less labor required, construction time savings, and significant cost savings, this new method provides a more durable and sustainable structure while reducing the carbon footprint of the project. Note, the term "single shell" does not refer to the placing of a single sprayed concrete layer but to the interaction of several layers as a single shell (initial support), rock bolts (if needed), water proofing membrane (if needed), and shotcrete final layer.

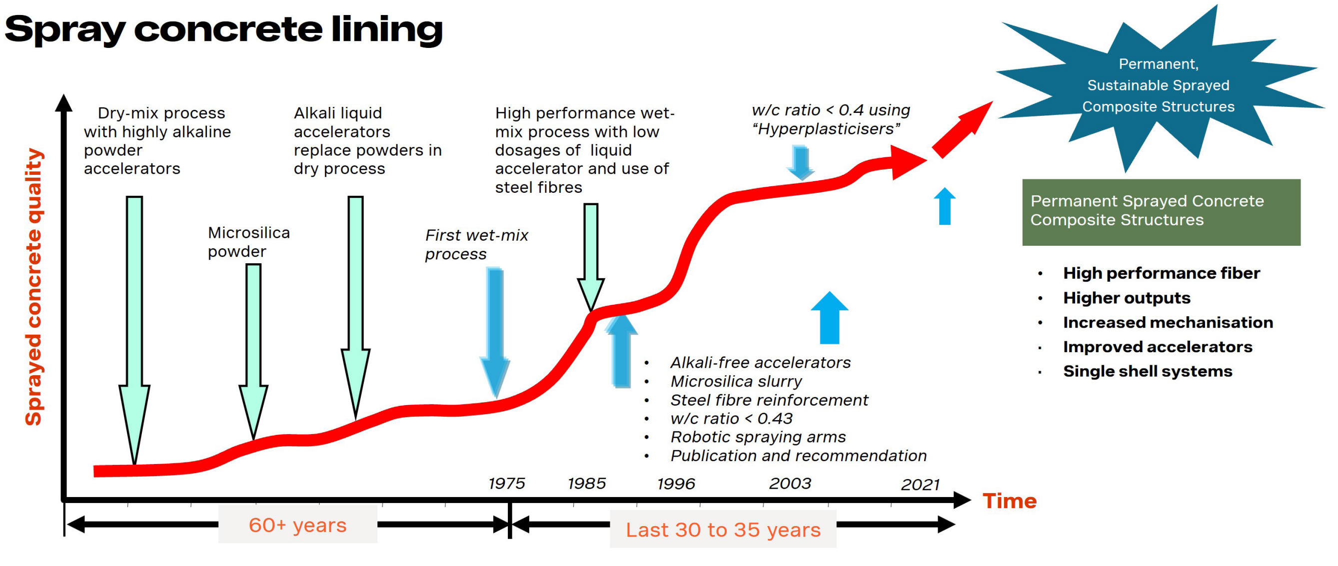

Fig. 1: Advancements in Shotcrete Technology and Quality

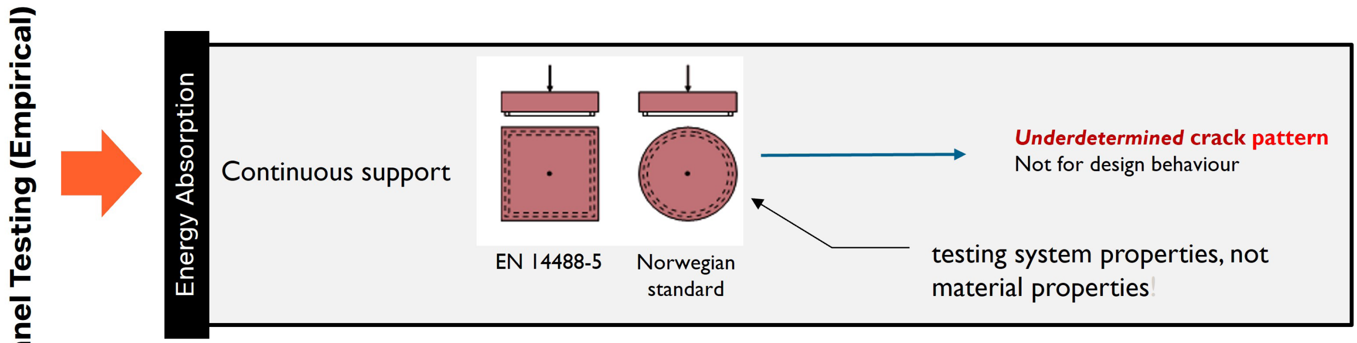

Fig. 2: Typical Panel Tests – For Empirical Design Values

CASE STUDY - BENEFITS OF DESIGNING STEEL FIBER REINFORCED PERMANENT SPRAYED CONCRETE LINING (SFRPSCL)

Designers have now employed and constructed tunnels and caverns using SFRPSCL worldwide. Research shows that more than 80% of the CO_2 emissions in the construction phase of a tunnel can be attributed to the cement and steel construction materials. It has been shown that reducing the quantity of cement and reinforcing steel used in a lining can significantly reduce CO_2 emissions.

An article in the June 2024 edition of Tunnel Business Magazine entitled "CARBON FOOTPRINT REDUCTION FOR MAJOR TRANSIT PROJECTS" by Verya Nasri, Medhi Bakhshi, and Pegah Jarast, of AECOM, New York, NY, details an evaluation of the tunnel lining system for the upcoming Montreal Blue Line Metro Extension project. This evaluation compared the historical double-shell lining method of conventionally excavated portions of the project to using the new SFRPSCL method.

The evaluation compared a conventional cast-in-place final lining constructed with conventional reinforcing and ordinary Portland cement concrete with a thin low-carbon permanent steel-fiber reinforced shotcrete lining. This evaluation detailed the embodied CO_2 emission calculations of the alternatives. By replacing the cast-in-place rebar reinforced final lining with a steel-fiber reinforced shotcrete lining and improving the mixture design (using portland limestone cement and 27% replacement of cement with supplementary cementitious materials) together with using real-time in-situ 3D laser scan technology in placing the shotcrete, CO_2 emissions were reduced by 80% (from 7.9 CO_2 kg per 1 m length of the tunnel to 1.7 CO_2 kg per 1 m length of the tunnel)! The study found that by converting the traditional double-shell lining to a SFRPSCL also provides for a significant reduction in construction costs and time.

With increasing government and owner mandates to decarbonize construction, and the fact that 80% of the embodied carbon from a typical tunnel project comes from the concrete lining, the shotcrete industry can expect SFRPSCL projects will increasingly become the standard method replacing conventionally reinforced cast-in-place linings.

FROM EMPIRICAL TO STRUCTURAL DESIGN

In the double-shell lining method, the design of the initial shotcrete support is considered non-structural and is typically accomplished using empirical tools such as the "Q" system and Barton Chart. The energy absorption value measured using a standard panel test is typically specified when, in the case of rock-bolting, emphasis is laid on energy which must be absorbed during the deformation on the rock. To determine the performance of the fiber-reinforced shotcrete in these applications, the standard testing methods use sprayed panels testing such as the ASTM C1550 round panel or the EN 14488 square panel to determine energy absorption values measured in Joules provided by the fiber-reinforced shotcrete. (Fig. 2)

For a structural lining design, the residual tensile strength provided by fiber-reinforced shotcrete using constitutive laws must be determined. In evaluating the behavior of fiber-reinforced shotcrete in tension, various test methods are possible. Typically, bending tests can be used to determine the load-deflection relationship of a beam under either a three-point (EN 14651 notched beam)

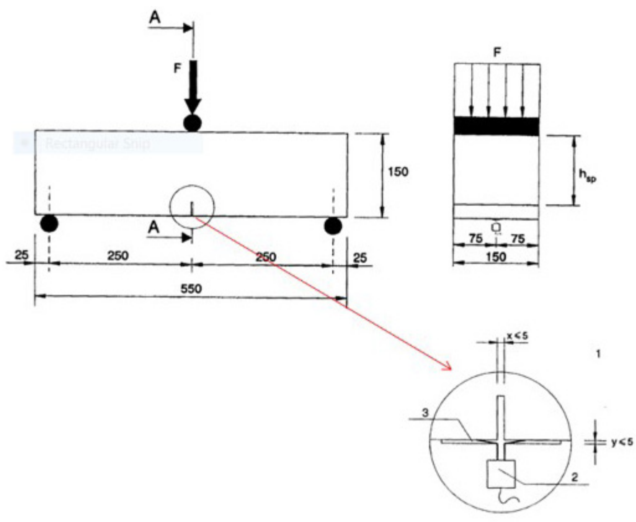

Fig. 3: EN 14651 Notched Beam Test for determining Structural Design Values

or four-point loading (ASTM C1609). From this, the flexural tensile strength can be determined.

The European EN 14651 three-point bending test with a notch standard is recommended by the international Tunnelling and Underground Space Association (ITA) Working Group 12 in their document entitled “Permanent Sprayed Concrete Linings”, because the notch beam provides for better controlled crack growth and generally less scatter in the results. (Fig. 3) This test method is also preferred in many countries because it directly provides the parameters needed for structural designs done by the fib 2010 Model Code.

The different ways of specifying the ductility of fiber reinforced sprayed concrete in terms of residual strength and energy absorption capacity are not directly comparable. The increased use of permanent shotcrete final linings in underground construction means that there will be more specifications requiring the determination of the residual strength provided by the fiber reinforced shotcrete. (Fig. 4)

NEW TESTING STANDARD DEVELOPED - BS-EN 14488-3:2023 - 3 POINT BENDING TEST (PBT) ON NOTCHED PANEL)

Testing to determine the residual strengths for sprayed fiber-reinforced concrete can be difficult because specimens for the beam tests must be cut from sprayed panels. With the increased use of SFRPSCL, a new standard was

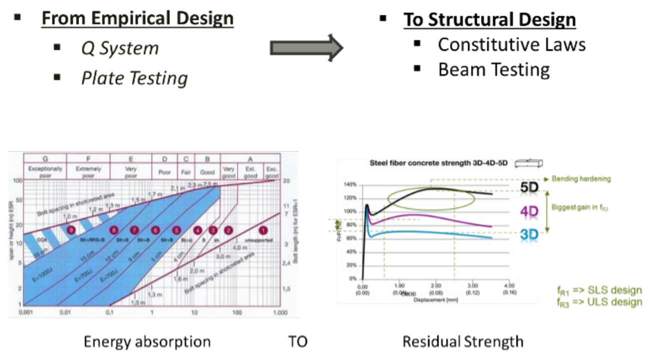

Fig. 4: Comparing Empirical to Structural Design

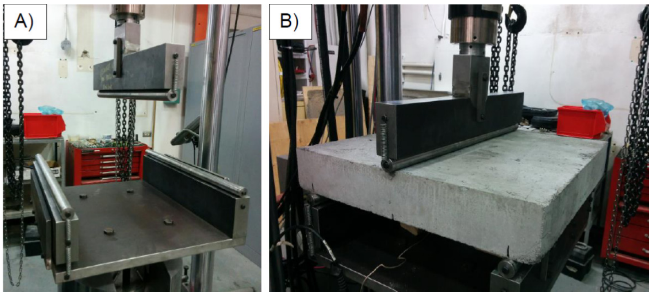

Fig. 5: A) Overview of 3PBT setup B) close-up during testing at Laval University

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 standard notched EN 14651 type beam test with the advantages of the EN 14488-5 panel test used for energy absorption The same molds are used for the residual panel test and, due to the larger cracked section, the scatter is lower than the cut beams. (Fig. 5)

The advantages of this new 3 point bending test on a notched panel method in SFRPSCL applications include:

- 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 as 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 equipment and setups used 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 — this eliminates the need to saw a beam out of a panel!
- The scatter will be lower than the current standardized beam tests because of the larger specimen size.
- The notch will provide a controlled cracking process, thereby reducing the risk of a sudden failure and fall.

- This test provides the required residual flexural strengths values needed forstructural designs.

Our hope in writing this article is that it encourages designers, contractors, and owners to specify and adopt the use SFRPSCL in future tunnel projects. Specifying permanent steel fiber-reinforced shotcrete linings in underground projects provides not just significant cost savings, but just as critical, helps us to significantly reduce the carbon impact of the underground construction industry and provide for a better environment and future for us all and our planet!

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