In-Service Performance of Macrosynthetic Fiber-Reinforced Tunnel Linings

By Ralf Winterberg and Axel G. Nitschke

This article introduces macrosynthetic fiber-reinforced concrete (MSFRC) and shotcrete (MSFRS) for tunnel linings and provides an overview of state-of-the-art design and testing methodologies that currently exist. In addition to the structural load bearing capacity of fiber-reinforced linings, design considerations with regard to long-term performance are presented, which is getting more and more into the focus of project owners, as well as their designers and consultants. Actual projects and recent research are presented with this regard, together with best practice design principles, including crack width control, corrosion and durability, and sustainment of performance with age.

Introduction

MSFRC and MSFRS have reached maturity as an engineering process and is widely used in all forms of tunnel linings. The technology is now commonplace for temporary and permanent ground support in both mining and civil tunnel applications. It has for instance become the standard form of reinforcement in the Australian underground mining industry, where 2014 literally marked the end of steel fiber use in shotcrete,[1] and has been used for over 80% of permanent tunnel linings in recent tunnel construction in Norway. Similarly, macrosynthetic fibers are becoming a standard solution for initial (or primary) tunnel linings in the United States. Recent examples are the Devil's Slide Tunnel and Caldecott Fourth Bore Tunnel in California and the Anacostia River Tunnel Inter-shaft Connector Tunnel in Washington, DC. In addition, an increasing number of tunnels are adopting shotcrete permanent linings using macrosynthetic fibers. Examples include the A3 Hindhead tunnel near Guildford in the United Kingdom and the North Strathfield Rail Underpass in Sydney, Australia.[2,3] A recent example of a MSFRC cast-in-place permanent tunnel lining in the United States is the Euclid Creek Tunnel in Cleveland, OH.[4]

Macrosynthetic fibers have the same approximate size as steel fibers, but are not to be mistaken with monofilament microsynthetic fibers, which serve a completely different purpose, as these are nonstructural fibers. Macrosynthetic fibers have typical lengths between 0.8 and 2.6 in. (20 and 65 mm) and typical equivalent diameters of 0.016 to 0.039 in. (0.4 to 1.0 mm). Due to their flexibility, they are much easier to handle, pump, and shoot than steel fibers, which are more prone to formation of blockages and wear and tear of pumping lines. The tensile strength and the Young's modulus are typically around 45 to 100 ksi (300 to 700 MPa) and 725 to 2000 ksi (5 to 14 GPa), respectively. The base material of macrosynthetic fibers is usually polypropylene.

Typical dosages for shotcrete primary ground support and initial tunnel linings are in the range of 5 to 10 lb/yd³ (3 to 6 kg/m³). Typical dose
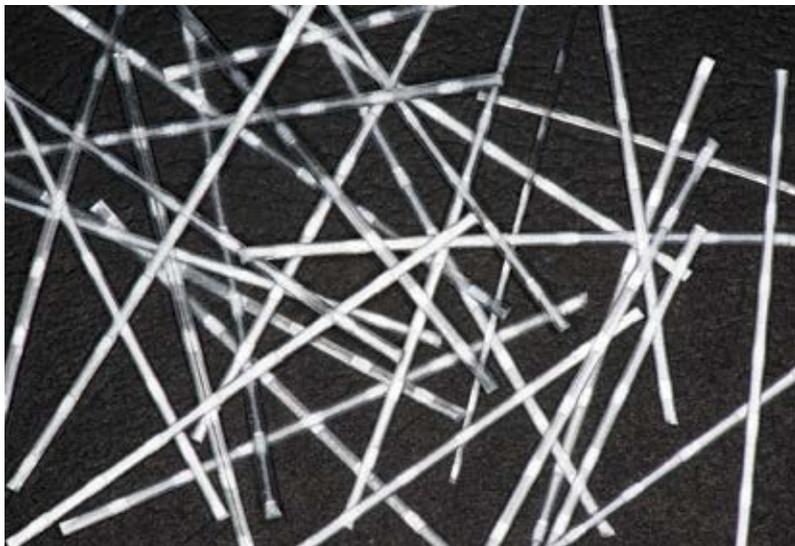

Fig. 1: EPC DucTil 57 Macrosynthetic Fiber

rates for shotcrete or cast-in-place concrete final tunnel linings are in the range of 8.5 to 15 lb/yd³ (5 to 9 kg/m³).

The physical properties of different macrosynthetic fibers vary greatly. For tunnel applications, only highly engineered macrosynthetic fibers with a tensile strength greater than 90 ksi (600 MPa) and a Young's modulus greater than 1450 ksi (10 GPa) should be used. These fiber characteristics are required to achieve and maintain the required structural performance.

Structural Considerations for Initial Tunnel Linings

Initial tunnel linings are applied immediately after excavation, typically using shotcreting as the installation process. The initial tunnel lining acts as a temporary support in combination with other support measures where it is usually the only support system installed in mining applications. In civil tunneling projects, typically an additional lining is installed which can be either cast-in-place concrete or a further shotcrete layer, and is referred to as secondary or final lining.

Applications for tunnel linings with a long service life have required further research and study to confirm that macrosynthetic fiber reinforcement meets typical project performance criteria dictated by tunnel designers. Current

research, as well as a number of major tunnel lining projects recently completed using macrosynthetic fiber reinforcement, confirm the very good performance of MSFRC and MSFRS for tunnel lining applications and a high potential for broader use.

Since the mid-1990s, multiple national bodies have developed guidelines for the use of fiber-reinforced concrete (FRC) and shotcrete (FRS); for example, in the United States 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.[5] 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.

One simplified design approach for FRS for initial ground support in hard rock mining and tunneling uses Barton's Q-chart approach,[6] which is based on the energy absorption capacity of the composite as determined by means of the square panel test according to EN 14488-5.[7] However, the square panel test (also known as EFNARC test) used in conjunction with the Q-chart method is no longer used in many countries given the numerous problems associated with this test method. Instead, the ASTM C1550 round panel test[8] has become the primary means of assessing post-crack performance for FRS and is therefore
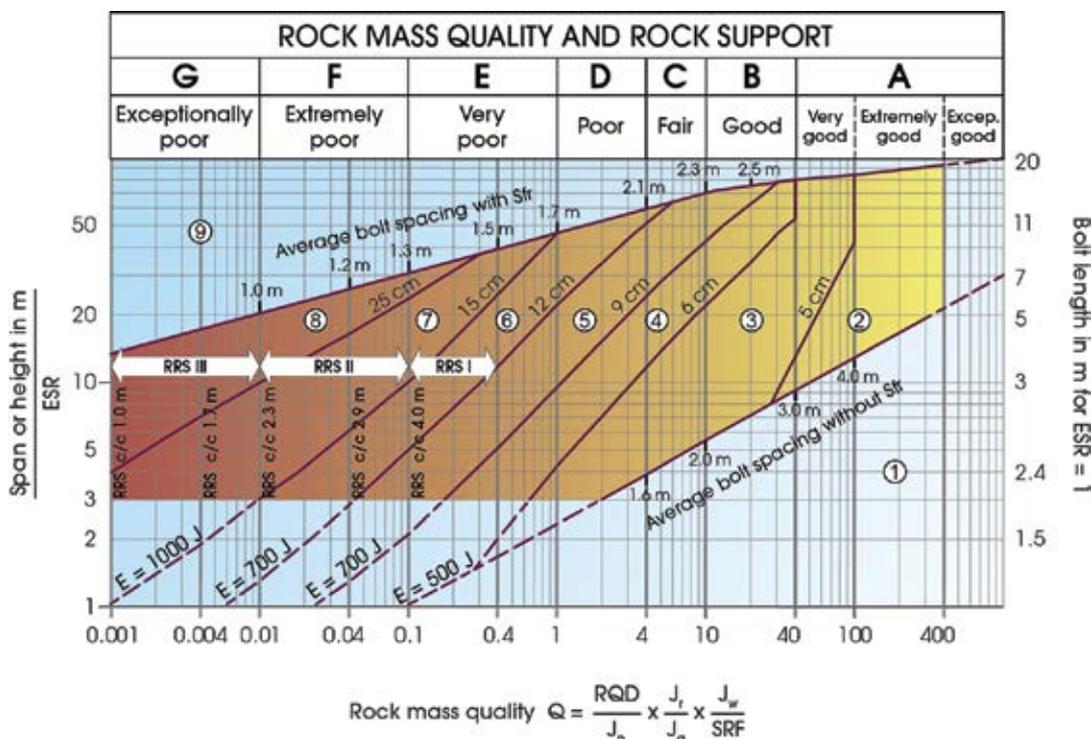

$$\text{Rock mass quality } Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

Fig. 2: Rock Mass Quality Chart or Q-Chart[6]

the preferred performance assessment tool used in the design of temporary tunnel linings based upon the Q-chart and other similar design approaches. The ASTM C1550 round panel test uses a 3 in. thick by 32 in. (75 mm thick by 800 mm) diameter round shotcreted specimen. A conversion factor of 2.5 was found to correlate the results from the different panel tests.[9] This means that, for example, a result of 740 ft-lb (1000 Joules) in an EFNARC panel relates to approximately 300 ft-lb (400 Joules) in an ASTM C1550 panel.

A classical design approach for fiber-reinforced concrete tunnel linings in civil tunneling applications is the use of Moment-Normal Force (M-N) interaction diagrams, which are obtained by equilibrium iterations on a given cross section.[10-12] The approach adopts and modifies classical 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.[10-12]

This approach generally provides structural gains for FRC and FRS versus unreinforced concrete, but typically the 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 loadbearing capacity in the post-cracking phase due to the elasto-plastic or ductile failure behavior of FRC,[10-12] which is similar to steel welded-wire-reinforced shotcrete. In tunnel linings, which are statically highly indeterminate, this ductile behavior allows for load redistribution, thereby increasing the structural capacity of the structure as a whole.

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 a ground support 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
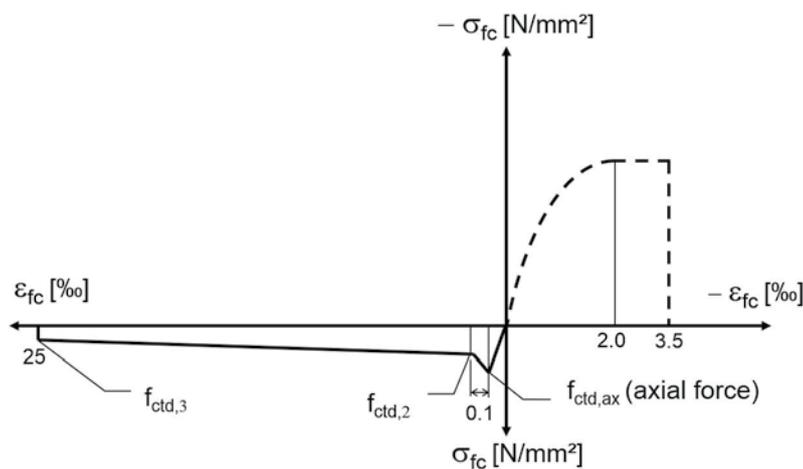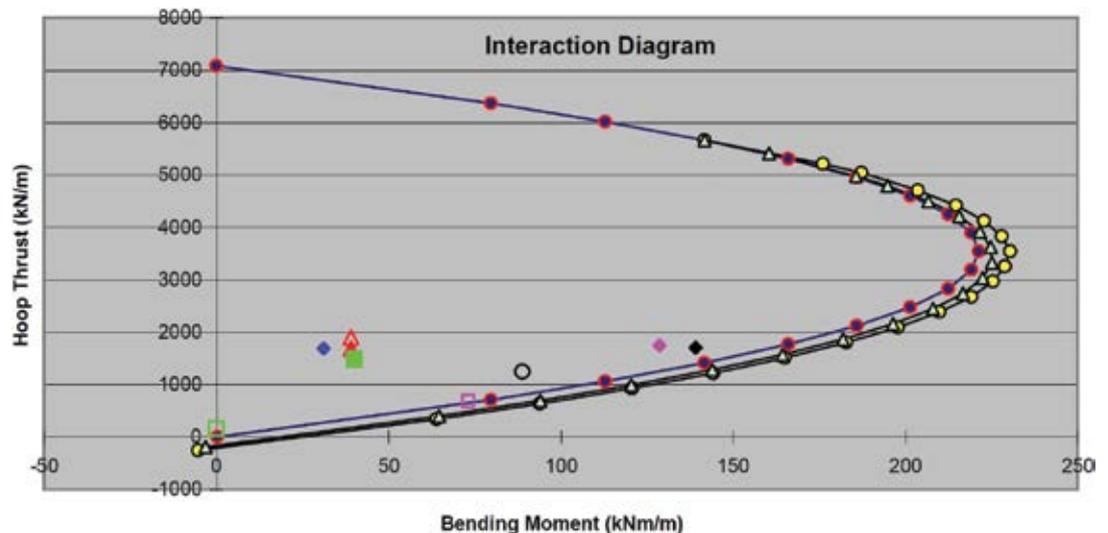
Fig. 3: Stress-strain curve of FRS

Fig. 4: M-N interaction diagram of FRS

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.

Structural Considerations for Final Tunnel Linings

For the structural design of final (or permanent) tunnel linings similar methods to the above may be applied. However, for final lining applications there are a number of additional factors design engineers must consider. While cracking and deformations may well be 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.

Durability and Corrosion

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, macrosynthetic 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 salt ingress to the reinforcement. Maximum acceptable crack widths are about 0.006 in. (0.15 mm) or just 0.004 in. (0.10 mm) as shown by recent in-place tests by Nordström[13,14] and Bernard.[15] In contrast, crack width control is not critical for durability when using macrosynthetic fibers since they are not susceptible to corrosion. Crack width limits might have to be considered though for water-tightness or structural capacity.

Embrittlement

Most shotcrete mixture designs 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.[15,16]

Embrittlement of FRC 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 research works have indicated that aging can lead to a significant loss of post-crack performance for steel FRC.[15-17] The change in behavior with age is due to a change from a ductile high-energy pull-out mode of post-crack fiber behavior into a brittle low-energy rupture mode of the fiber itself, because of rup-
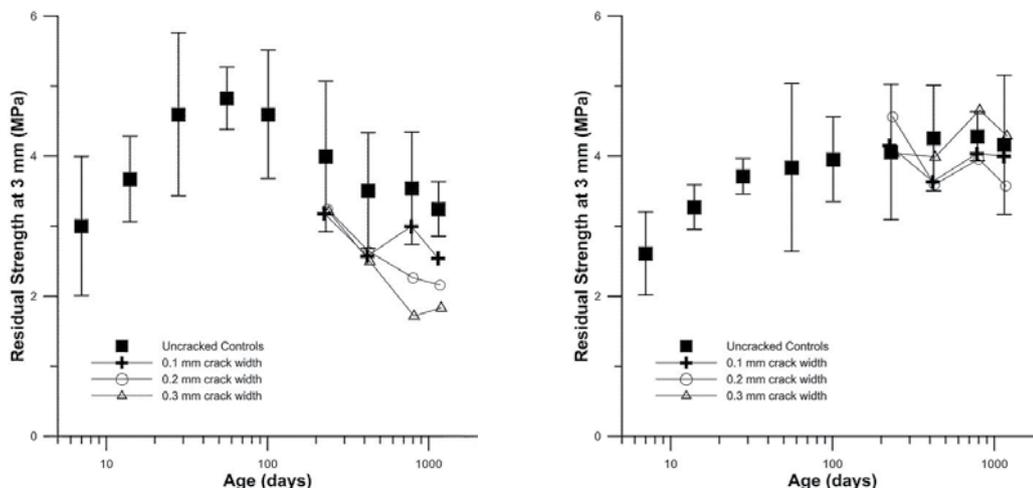

Fig. 5a,b: Corrosion and embrittlement leading to post-crack performance loss in steel FRC with age (left); where neither corrosion nor embrittlement effects occur in MSFRC (right)[16]

turing 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. For this reason, satisfactory performance at early ages (around 28 days) does not guarantee an acceptable performance of the aging steel FRC. The performance of steel FRC at crack widths in excess of 0.04 in. (1.0 mm) can decrease 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.[15,16]

MSFRC is largely unaffected by this phenomenon because 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 MSFRC evident at 28 days is therefore unaffected over time.

Creep Considerations

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 steel welded-wire reinforcement, steel fibers, or macrosynthetic fibers.[18] 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 steel welded-wire reinforcement or macrosynthetic fibers up to load ratios of 50% during a loading period of 100 days.

The requirement for long-term testing of MSFRC 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 macrosynthetic 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[19] show that the inclusion of macrosynthetic 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

The structural performance of MSFRC or MSFRS is able to meet or exceed that of welded-wire reinforcement or steel fiber-reinforced concrete for tunnel lining applications. Design methods for the structural load-bearing capacity are similar.

Macrosynthetic fibers are easy to pump and 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.

Macrosynthetic fibers are not susceptible to corrosion and do not have to meet stringent crack width limitations for durability. High-performance macrosynthetic 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.

The inherent isolated creep properties of macrosynthetic fiber reinforcement play a subordinate role in the long-term performance of tunnel linings because compression forces typically govern overall behavior. Due to the advantages discussed in this article, it is to be expected that macrosynthetic fibers will become more common in tunnel shotcrete and cast-in-place tunnel linings in the near future.

References

1. Bernard, E.S.; Clements, M.J.K.; Duffield, S.B.; and Morgan, D.R., "Development of Macro Synthetic Fiber Reinforced Shotcrete in Australia," *7th International Symposium on Sprayed Concrete – Modern Use of Wet Mix Sprayed Concrete for Underground Support*, Sandefjord, Norway, June 16-19, 2014.

2. Ireland, T. J., and Stephenson, S., "Design and Construction of a Permanent Shotcrete Lining – The A3 Hindhead Project, UK," *Shotcrete: More Engineering Developments*, E. S. Bernard, ed., CRC Press, Boca Raton, FL, 2010, pp. 143-152.

3. Gonzalez, M.; Kitson, M.; Mares, D.; Muir, B.; Nye, E.; and Schroeter, T., "The North Strathfield Rail Underpass – Driven Tunnel Design and Construction," *15th Australian Tunnelling Conference 2014*, Sydney, Australia, Sept. 17-19, 2014, pp. 369-374.

4. Carlson, J.E., Wotring, D.C., Auber, R.J., and Vitale, M.G., "Synthetic-Fiber Reinforcement for the Cast-in-Place Final Tunnel Liner at the Euclid Creek Tunnel Project," *Proceedings, Rapid Excavation and Tunneling Conference*, June 7-10, 2015, New Orleans, LA, pp. 882-889.

5. *Shotcreting in Australia: Recommended Practice*, second edition, Concrete Institute of Australia, Sydney, Australia, 2010, 67 pp.

6. Barton, N., and Grimstad, E., "The Q-System Following Thirty Years of Development and Application in Tunnelling Projects," *Rock Engineering - Theory and Practice, Proceedings of the ISRM Regional Symposium EUROCK 2004*, Salzburg, Austria, 2004, pp. 15-18.

7. BS-EN 14488, "Testing Sprayed Concrete," British Standards Institute, London, UK, 2006.

8. ASTM C1550-12, "Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)," ASTM International, West Conshohocken, 2012, 14 pp.

9. Bernard, E. S., "Correlations in the Behaviour of Fibre Reinforced Shotcrete Beam and Panel Specimens," *Materials and Structures*, RILEM, V. 35, No. 3, Apr. 2002, pp. 156-164.

10. Maidl, B.; Nitschke, A.; and Ortu, M., "Design of Steel Fiber Reinforced Concrete in Tunneling*," Final report DBV No. 211 and AiF no. 11427 N*, Fraunhofer IRB, Oberlainder, Germany, June 1999.

11. Nitschke, A., "Calculation of the Load-Bearing Behavior and Test Evaluation for Steel Fiber Reinforced Concrete in Tunneling—Presentation of a New Method," *Bauingenieur*, V. 74, Feb. 1999, pp. 82-90.

12. Nitschke, A., "Load-Bearing Behavior of Steel Fiber Reinforced Concrete in Tunneling," PhD dissertation, Ruhr Universität Bochum, Bochum, Germany, 1998.

13. Nordström, E., "Durability of Steel Fiber Reinforced Sprayed Concrete with Regard to Corrosion," *Proceedings, 3rd International Symposium on Sprayed Concrete*, Gol, Norway, Sept. 26-29, 1999.

14. Nordström, E., "Durability of Steel Fiber Reinforced Shotcrete with Regard to Corrosion," *Shotcrete: Engineering Developments*, E.S. Bernard, ed., CRC Press, Boca Raton, FL, pp. 213-217.

15. Bernard, E.S., "Age-Dependent Changes in Post-Crack Performance of Fibre Reinforced Shotcrete Linings," *Tunnelling and Underground Space Technology*, V. 49, 2015, pp. 241-248.

16. Bernard, E.S., "Age-Dependent Changes in Post-Cracking Performance of Fiber-Reinforced Concrete for Tunnel Segments," *15th Australian Tunnelling Conference 2014*, Sydney, Australia, Sept. 17-19, 2014, pp. 229-235.

17. Bjontegaard, O.; Myren, S.A.; Klemtsrud, K.; and Kompen, R., "Fiber Reinforced Sprayed Concrete (FRSC): Energy Absorption Capacity from 2 days age to One Year," *Seventh International Symposium on Sprayed Concrete*, Sandefjord, Norway, June 16-19, 2014, pp. 88-97.

18. Bernard, E.S., "The Influence of Reinforcement on Relative Creep Deformations in Shotcrete Linings," *Shotcrete*, V. 14, No. 4, Fall 2012, pp. 52-57.

19. Gilbert, R.I., and Bernard, E.S., "Time-Dependent Analysis of Macro Synthetic FRC Sections with Conventional Bar Reinforcement," World Tunnelling Congress (WTC 2015), Dubrovnik, Croatia, May 2015.

Ralf Winterberg specializes in fiber reinforcement for concrete and its application development. He received his MSc in civil engineering and his PhD on the cracking behavior of steel fiber-reinforced concrete from Ruhr University Bochum, Bochum, Germany. After serving as Technical Director and Managing Director in German companies, he started his own engineering company for the development of fiber-reinforced concrete solutions and applications in 2004. Since 2005, he has been working also as a consultant to the Fibre Division of Officine Maccaferri S.p.A., headquartered in Italy, supporting their worldwide subsidiaries in the technical market development of the Fibre Division. In February 2010, he joined Maccaferri Asia Headquarters in Malaysia as Business Development Manager and Technical Director of the Fibre Division Asia/Oceania. In July 2014, he joined Elasto Plastic Concrete, the market leaders in structural synthetic fiber-reinforcement, headquartered in Australia, to take up the role as Group Chief Engineer for their worldwide structure. Winterberg co-authored the "Steel Fibre Reinforced Concrete" guide to good practice by the German Concrete Association, and contributed to RILEM TC162-TDF, "Test and Design Methods for SFRC," as well as to CEN TC104 WG11, "Fibres for Concrete," for the harmonized European Standard EN 14889.

He chaired the Fibres Technical Committee of EFNARC and is member of ITA-AITES WG12, Shotcrete Use, and ITA-Tech AG, Support. Winterberg has published numerous papers and articles on the performance of fiber-reinforced concrete with a focus on structural and durability improvements and on the fire resistance of concrete. He further shared his knowledge and experience in numerous seminars in many countries.

Axel G. Nitschke is Vice President of Gail Zeidler Consultants. He received his MSc and PhD in civil engineering in 1993 and 1998, respectively, from Ruhr University Bochum and is a licensed professional engineer in Virginia and California. He has gained more than 20 years of in-depth, on-the-job experience in all aspects of underground construction, geotechnical engineering, and mining. He has worked on the engineering and construction of a large number of tunnel projects in Europe, the United States, Canada, and Colombia. He is well-experienced in all ground conditions, ranging from soft ground to hard rock, and the associated implications for design and construction methods. Nitschke has held key positions such as Senior NATM Engineer, Contract/Claims Manager, Risk Manager, Design Manager, and Project Manager.