Evolution of Shotcrete Materials in the Past 20 Years

By Nicolas Ginouse and Simon Reny

Shotcrete has evolved significantly since the early 1900s. We've certainly achieved remarkable progress since the early 1980s when volumetric batching of sand and cement was the norm. This simple technology had its uses, but volumetric batching often led to inaccurate (and usually high) cement contents. High cement contents, combined with a lack of coarse aggregate, resulted in high shrinkage values, resulting in increased cracking potential and porosity. Advances in traditional cast concrete mixture designs have translated well to mixtures placed using the shotcrete process. In this article, we discuss the evolution and sophistication of shotcrete materials primarily governed by industry demand for high-quality, durable, and robust solutions for a wide range of new construction, repair, retrofit, and ground support applications. New chemical admixtures, additives, pozzolan, and cement technology have provided numerous technological breakthroughs for the shotcrete industry. The shotcrete industry has embraced

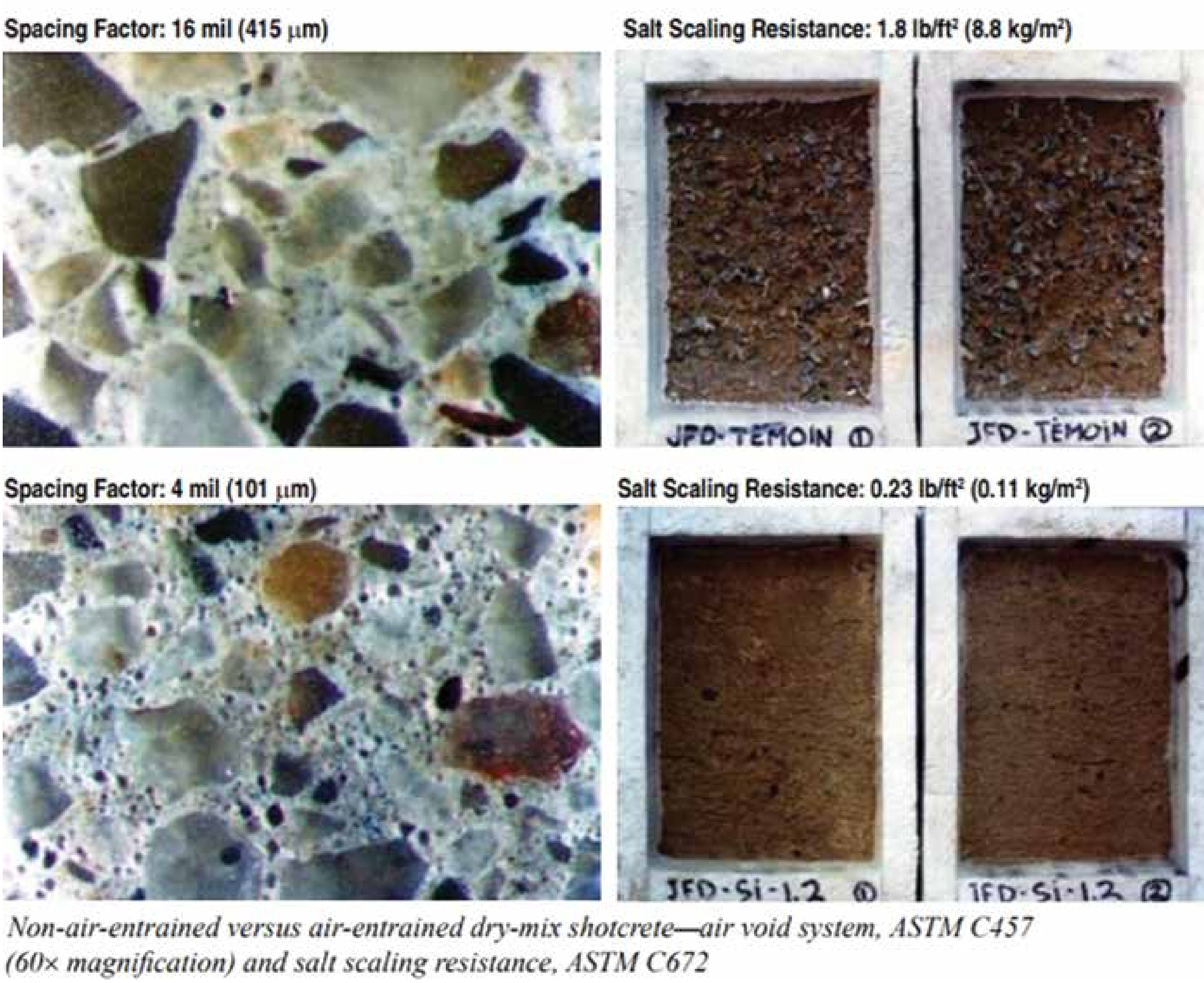

Fig. 1: Effect of air-entraining in dry-mix shotcrete[2]

these technological breakthroughs and left the old sand and cement days, with all its potential weaknesses, behind.

POWDER AIR ENTRAINMENT

In 1996, the addition of air entrainment in wet-mix shotcrete was not new. However, the introduction of powder air-entraining admixtures in the dry-mix shotcrete was a new phenomenon. It was widely assumed that dry-mix shotcrete durability could only be achieved with silica fume, proper compaction, and low water-cement ratio (*w/c*) (all of which resulted in low permeability). Studies completed at the University of Laval in Quebec City, QC, Canada, however, proved that the addition of air entrainment in dry-mix shotcrete was not only feasible but it also consistently provided significantly improved long-term durability.[1] Figure 1 shows how dramatically salt scaling resistance can be improved using proper dosages of air-entraining additives, which stabilized air void systems and reduced the air void spacing factors.[2] This technology has been adopted by many Specifiers, especially those in northern climates where concrete structures are exposed to extensive freezing-and-thawing cycling. Since 1996, thousands of structures throughout North America have been successfully repaired using dry-mix shotcrete mixtures that are enhanced with powder air-entraining admixtures.

MACRO-SYNTHETIC FIBERS

Although high-volume macro-synthetic fibers were used in wet-mix shotcrete applications as far back as 1988, and even earlier for concrete slab applications, the length and shape of macro-synthetic fibers made them impractical for dry-mix applications. The use of macro-synthetic fibers adapted well to wet-mix shotcrete formulations, primarily because of the similarities in the mixture design, but as reported by Morgan and Rich[3] in 1998, attempts to use macro-synthetic fibers in dry-mix shotcrete applications failed for a variety of technical reasons. To adapt macro-synthetic fibers to the dry-mix shotcrete process, it took almost another decade of research. Dufour et al.[4] developed a solution that was immediately adopted by some Canadian mines to improve flexural toughness and reduce wear on shotcrete equipment. In the construction of the pedestrian tunnel connecting Billy Bishop Island Airport to the mainland in downtown Toronto, ON, Canada, macro-synthetic fibers were chosen over steel fibers to avoid compromising the waterproof membrane (Fig. 2), as reported by Croutch.[5]

IMPACT AND ABRASION RESISTANCE

Over the past 20 years, many studies have been completed to improve the resistance of shotcrete linings to impact and abrasion. Primary applications included mining industry examples such as ore pass and ore bin linings. Other applications included the rehabilitation of cold climate lighthouses and other marine structures subject to impact by ice flows. Studies proved that dry-mix shotcrete applications using an optimized mixture design, combining the proper cementitious matrix with hard aggregates and steel fibers at the optimum dosage, provided a durable protective lining even if exposed to aggressive abrasion and impact.

These high-performance dry-mix shotcrete mixtures were first used to repair a lighthouse on the St. Lawrence River (as reported by Gendreau et al.[6]), and the technology has gained acceptance on numerous other high-impact or high-abrasion applications. Ease of application and long-term performance led to its use on numerous projects across North America.[7] Today, most ore passes in Canadian mines are excavated and lined using high-performance, high-dosage, steel-fiber shotcrete to ensure the long-term performance of these critical infrastructures[8] (Fig. 3).

SELF-CONSOLIDATING WET-MIX SHOTCRETE FOR MINING APPLICATIONS

After the development of flowable/pumpable self-consolidating concrete, similar wet-mix shotcrete materials were

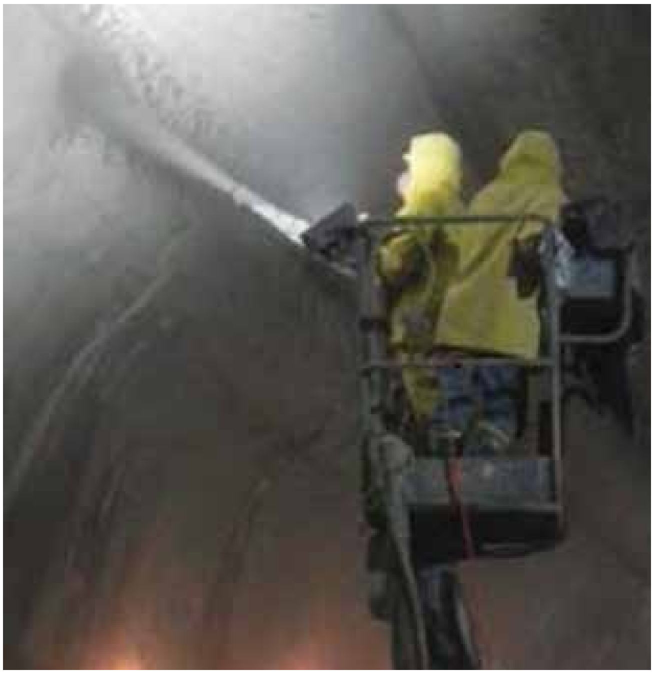

Fig. 2: Application of macro-synthetic fiber shotcrete in the Billy Bishop Pedestrian Tunnel[5]

Fig. 3: Construction and installation of protective shotcrete lining for critical ore pass in a Northern Quebec gold mine

introduced in 2003 at deep, hard rock mines in Québec, Canada, to address material delivery challenges.[9] For these applications, shotcrete mixtures were mixed on the surface before being dropped several thousand feet (m) through a steel pipe (slick line) and then transferred to an agitator truck for underground delivery and placement. This innovative solution was possible using advanced technology high-range water-reducing admixtures, viscosity modifiers, and hydration control admixtures and significantly increased shotcrete placement production at these depths. The development and application of these admixtures for mining and tunneling applications undoubtedly contributed to the increased use of wet-mix shotcrete.

These advanced admixture technologies have expanded into preblended, prepackaged, self-consolidating wet-mix materials, supplied in bulk or bagged formats. This technology, where all components are preblended in dry form, provided further flexibility and allowed shotcrete crews to produce their own shotcrete “on demand,” simply by adding water to the dry, preblended material[10] (Fig. 4). These products have been successfully used in many operating mines across North America.

ULTRA-RAPID-STRENGTH DRY-MIX SHOTCRETE

Initially introduced in Canada in 2013 for mining applications, ultra-rapid-strength dry-mix shotcrete was developed to accelerate the underground development cycle (drill, blast, muck, shotcrete) to improve productivity. Shotcrete mixtures produced with this new technology provide—in only 2 hours—the same 24-hour compressive strength values achieved with portland cement-based shotcrete mixtures[11] (Fig. 5). This innovative technology combines a shotcrete mixture using a very reactive ettringite-based cement using the dry-mix process and allows proper and consistent placement without the risk of blocked hoses. This technology has also been combined with macro-synthetic or steel fibers to overcome challenging ground support applications and to provide more rapid impact and abrasion resistance solutions.

Fig. 4: Mobile concrete mixing unit integrated with a lifting system for bulk, preblended concrete, and shotcrete material bags[10]

ENGINEERED HIGH-PERFORMANCE, FIBER-REINFORCED DRY-MIX SHOTCRETE

Initially developed and used in Japan for civil applications, this technology was introduced in Canada a few years ago for mining applications in areas of considerable seismic activity and extremely poor ground conditions. In many of these situations, conventional fiber-reinforced shotcrete possessed limited effectiveness due to poor resistance to spalling under these conditions (Fig. 6). The extremely high flexural and tensile toughness provided by this innovative mixture design technology has provided an effective protective lining for areas affected by blasting.[12]

SUSTAINABLE DRY-MIX SHOTCRETE USING SUSTAINABLE MATERIAL

As in traditional concrete mixtures, sustainable and recycled materials including aggregates,[13] recycled glass filler, blast-furnace slag, plastic (Fig. 7), rubber (Fig. 8), and others[14] have been shot using the dry-mix shotcrete process. By nature, dry-mix shotcrete does not require pumpability as a mixture characteristic and therefore provides a unique ability to

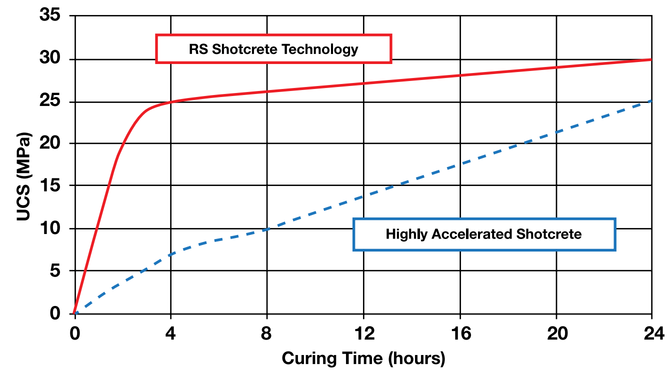

Fig. 5: Typical strength development curve of King RS Shotcrete Technology versus highly accelerated portland-cement-based shotcrete[10]

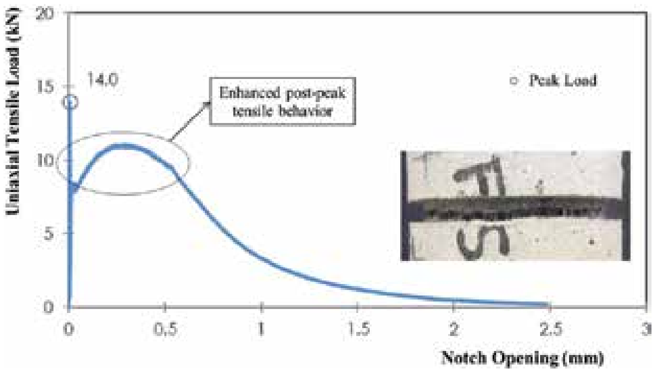

Fig. 6: Post-peak tensile behavior of an engineered high-performance fiber-reinforced dry-mix shotcrete[11]

spray extremely complex materials. Many of these materials would be impossible to pump with a conventional concrete pump due to their high viscosity, rapid reactivity, or unstable rheology. Current research is developing analysis tools that can evaluate the environmental impact of shotcrete mixtures with the objective to optimize sustainability.

Development of Highly Crack-Resistant Shotcrete

When used in repair, shotcreted materials can be subjected to high restrained shrinkage conditions. Shotcrete's ability to accommodate the restraint without cracking is critical to ensuring long-term durability. There are a limited number of testing methods to evaluate cracking potential of cast concrete or mortars. These test methods designed for casting materials require modification to make them suitable for

Fig. 7: Shotcrete core containing shredded recycled plastic[14]

Fig. 8: Shotcrete core containing recycled rubber beads[14]

concrete placed using the shotcrete process. Recent studies detail the adaptation of existing test methods to shotcrete mixtures to determine crack resistance of the material as shot.[15] The test method uses molds in ring form as per AASHTO T 334 (Fig. 9 and 10) and reproduces restrained shrinkage conditions. The development and use of this test method for shotcrete paves the way for mixture design optimization and improvement of the crack resistance and durability of shotcrete materials.

Conclusions

Over the past 20 years, new shotcrete materials technology has evolved faster than in the previous 100 years. These technological developments have produced dramatically improved quality and superior performance of shotcreted materials. This evolution of materials has served the shotcrete industry well, and together with advancements in equipment design, improved training and education, certification of shotcrete nozzlemen, and recognition of qualified shotcrete crews and contractors

Fig. 9: Sketch from the AASHTO T 334 restrained ring test[15]

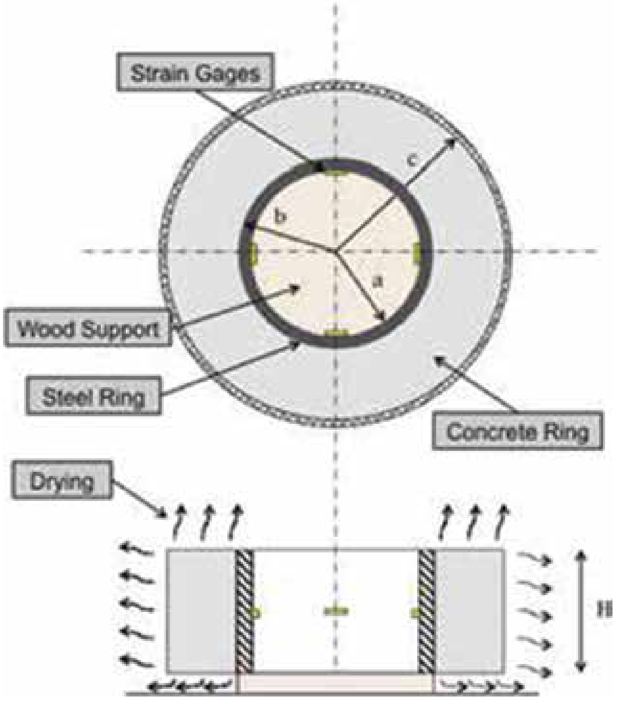

Fig. 10: Modified AASHTO T 334 restrained ring test orientation during shooting allows proper consolidation of the test specimen[15]

has led to sizable growth in the shotcrete industry. Moving forward, our industry must take advantage of these new, commercially available and innovative shotcrete materials and technologies. Most of the technologies presented in this brief article have been used successfully and are lightyears ahead of the old sand/cement mixtures developed at the beginning of the 20th century.

References

1. Beaupré, D.; Dufour, J.-F.; Lamontagne, A.; and Pigeon, M., "Powdered Air-Entraining Admixture in Dry-Mix Shotcrete," *Proceedings of the ACI/SCA International Conference on Sprayed Concrete/Shotcrete, Sprayed Concrete Technology for the 21st Century*, Edinburg, Scotland, Sept. 1996, pp. 1-7.

2. Dufour, J.-F., "Effects of Air-Entraining Admixtures on the Durability of Dry-Mix Shotcrete," master's thesis, Laval University, Quebec, QC, Canada, 1996, 176 pp.

3. Morgan, D.R., and Rich, L., "High Volume Synthetic Fiber-Reinforced Shotcrete," The First International Conference on Synthetic Fiber-Reinforced Concrete, Orlando, FL, Jan. 16, 1998.

4. Dufour, J.-F.; Trottier, J.-F.; and Forgeron, D., "Behaviour and Performance of Monofilament Macro-Synthetic Fibres in Dry-Mix Shotcrete," *Proceedings*, Shotcrete for Underground Support X, Whistler, BC, Canada, 2006, pp. 194-205.

5. Croutch, M., "Pedestrian Tunnel at Billy Bishop Toronto City Airport," *Shotcrete*, V. 16, No. 4, Fall 2014, pp. 38-40.

6. Gendreau, M.; Beaupré, D.; Lacombe, P.; and Montigny, J. D., "Use of Dry-Mix Shotcrete to Repair a Lighthouse Structure," *Shotcrete*, V. 2, No. 4, Fall 2000, pp. 16-20.

7. Reny, S., and Giroux, P., "Pointe de la Prairie Lighthouse," *Shotcrete*, V. 8, No. 4, Fall 2006, pp. 30-32.

8. Larsen, J.; Thibodeau, D.; and Hutter, J., "A History of Shotcrete Use at Vale Inco," *Shotcrete*, V. 11, No. 2, Spring 2009, pp. 14-21.

9. Milette, D., and Lessard, M., "Development of a Wet Mix Shotcrete for a Deep Mine," *Shotcrete*, V. 9, No. 1, Winter 2007, pp. 16-23.

10. Ginouse, N.; Clements, W.; and Rand, S., "Innovative Shotcrete Technologies for Advancement in Tunneling," *Proceedings of Tunneling Association of Canada 2016 Annual Conference*, Ottawa, ON, Canada, 2016.

11. Reny, S., and Ballou, M., "New Advancements in Dry Mix Shotcrete Using Rapid Set Cement in Lieu of Accelerator Admixtures in Tunnels, Shafts and Pipe Liners," *Proceedings of North American Tunneling Conference*, Los Angeles, CA, 2014, pp. 223-235.

12. Ginouse, N.; Reny, S.; and Jolin, M., "Engineered Fiber Reinforced Shotcrete for Efficient and Fast Ground Support Installation," *Proceedings of Shotcrete for Underground Support XII*, Singapore, 2015.

13. Sawoszczuk, P.; Nokken, M.; and Jolin, M., "Sustainable Shotcrete Using Blast-Furnace Slag," *Shotcrete*, V. 15, No. 4, Fall 2013, pp. 32-37.

14. Gagnon, A.; Fily-Paré, I.; Jolin, M., "Rethinking Shotcrete Mixture Design through Sustainable Ingredients," *Shotcrete*, V. 18, No. 4, Fall 2016, pp. 28-31.

15. Girard, S.; Jolin, M.; Bissonnette, B.; and Lemay, J.-D., "Measuring the Cracking Potential of Shotcrete," *Concrete International*, V. 39, No. 8, Aug. 2017, pp. 44-48.

Nicolas Ginouse *is a Research and Development Engineer for King Packaged Materials Company and Associate Professor at Laval University, Quebec City, QC, Canada. His research interests include all the aspects involved in shotcrete technology, whereas his expertise contributes to the development of new cementitious materials for mining, tunneling, architectural, and repair applications. Ginouse received his degree in mechanical and industrial engineering from Art et Métiers Paritech, Paris, France, in 2010 and his PhD in civil engineering from Laval University in 2014. He is a member of ACI Committees 239, Ultra-High-Performance Concrete, and 506, Shotcreting.*

Simon Reny*, P.Eng, is the Business Development Manager, Canadian Markets, King Shotcrete Solutions. Reny began his career at King in 2004 as a Technical Sales Representative after receiving his degree in civil engineering from Laval University. Then, as Manager of Technical Services, he helped build a strong technical team to serve both internal and external customers. After 6 years in that position, Reny is now responsible for the sale of King Construction Products throughout the Canadian mining and construction markets. He is a member of ACI Committee 506, Shotcreting, Chair of the ACI Shotcreting-Evaluation Subcommittee; and a member of the American Shotcrete Association.*