Shotcrete for Ground Support: Current Practices in Western Canada

Part II of II

by Cesar Chan, Roland Heere, and Dudley R. Morgan

Editor's Comment: Part I of this article was published in the Winter 2002 issue of Shotcrete *and covered examples of applications, specifications, materials and mixture designs, and shotcrete application.*

Performance

Each ground-support project is unique and will likely have its own design and performance requirements. Performance requirements for shotcrete can generally be divided into two groups: fresh state parameters and hardened state parameters. The following briefly elaborates on the variables included in each of these groups.

Fresh Shotcrete Properties

Water/cementitious materials ratio

The water/cementitious materials ratio is one of the most important parameters controlling shotcrete quality and performance under long-term conditions. In cases where the shotcrete may be exposed to severe environments, the water/cementitious materials ratio would be limited to a specified maximum value, e.g., 0.40. Also, limiting the water/cementitious materials ratio helps reduce shotcrete shrinkage.

Air content

Having an adequate air content and air-void spacing factor in the as-placed shotcrete mixture has long been recognized as critical for frost resistance of wet-mix shotcrete. Usually, in wet-mix shotcrete, an as-batched air content of approximately 8 to 10% is used to achieve an as-shot air content of 3 to 5%. However, even if frost resistance is not a concern, there is a definite advantage in using a high air content during batching of shotcrete in that the air entrainment enhances the workability (slump) of the shotcrete. Upon impact on the receiving surface, the air content is reduced, resulting in a reduction in slump in the in-place shotcrete. In projects where the use of accelerators is specified, this *slump-killing* effect helps reduce the amount of accelerator required to provide slump reduction and shotcrete adhesion.[14]

Slump

The required slump of wet-mix shotcrete for a particular application depends on the specific mixtures used, and control of the slump at discharge into the pump is important. Too high a slump could cause sagging and sloughing of the freshly applied shotcrete, while stiff mixtures could create excessively high pumping pressures, wear of the shotcrete equipment, and *slugging*.[2] Typically, wet-mix shotcrete slumps in the range of 30 to 60 mm (1 to 2 in.) are used, although slumps as high as 90 mm (about 4 in.) can be properly shot without having to add rheology modifiers or accelerators at the nozzle.

Hardened Shotcrete Properties

Compressive strength

The compressive strength of shotcrete is important not only for structural reasons, but also as an indication of the potential shotcrete durability. Compressive strength tests are usually conducted on cores extracted from test panels or sometimes from the in-place shotcrete. Typical specifications for structural-quality shotcrete require minimum compressive strengths of 30 MPa (4350 psi) at 7 days and 40 MPa (5800 psi) at 28 days. Such compressive strength levels are readily achievable with the high cement contents in the mixture, particularly when silica fume is incorporated into the mixture design. A review of construction records for a number of large shotcrete projects in Western Canada revealed that average 28-day compressive strengths for silica fume-modified, dry-mix shotcretes were in the range of 45 to 55 MPa (6500 to 8000 psi).[14] Wet-mix shotcretes can attain similar or higher strength levels, particularly when low water/cementitious materials ratio mixtures are used in conjunction with water reducers and superplasticizers.

Early-age compressive strength development of shotcrete (particularly in the first 24 hours) can also be determined, especially for shotcrete containing accelerators. A draft ASTM test method describes the use of a set of three steel beam molds (dimensions 75 x 75 x 350 mm [3 x 3 x 14 in.]) where shotcrete is sprayed and then demolded after final set. The beams are then carefully placed in a portable test apparatus that compresses a square section of the beam to obtain the compressive strength of the shotcrete. For more information on this test method, refer to the Technical Tip on page 28 of this issue.

Boiled absorption and volume of permeable voids

The boiled absorption and volume of permeable voids of shotcrete, conducted according to ASTM C 642, provides a good indicator of shotcrete quality and durability. This test method readily detects shotcrete that has poor consolidation as a result of improper nozzling orientation, improper nozzling distance, or voids created by entrapment of rebound or overspray. The test also detects shotcrete that has been damaged by the excessive use of accelerators. Table 4 shows how the values for boiled absorption and volume of permeable voids can be used as indicators of shotcrete quality.

Table 4: Shotcrete quality indicators[16]

Boiled absorption, %	Volume of permeable voids, %	Suggested quality indicator
< 6	< 14	Excellent
6 to 8	14 to 17	Good
8 to 9	17 to 19	Fair
> 9	> 19	Marginal

Flexural strength

The flexural strength of shotcrete is normally determined using either the ASTM C 78 or ASTM C 1018 test methods on beams loaded under third-point loading. These beams, typically with dimensions 100 x 100 x 350 mm (4 x 4 x 14 in.), are diamond saw-cut from test panels and loaded on a 300-mm (12 in.) load span. Specifications for structural-quality shotcrete frequently require minimum flexural strengths of 4 MPa (580 psi) at 7 days, and sometimes 6 MPa (870 psi) at 28 days. At 7 days, the flexural strengths are commonly in the range of 11 to 14% of the corresponding compressive strength.

Toughness

As discussed in Part I, the "Materials and Mixture Designs" section, steel and synthetic fibers are added to shotcrete to enhance its toughness, which is defined as its energy-absorbing capacity. Without fibers, crack propagation in the plain shotcrete matrix occurs rapidly, resulting in brittle fractures that may potentially cause loss of structural integrity and serviceability. The use of fibers, coupled with recent innovations in fiber technology, has led to the production of shotcretes with exceptional pseudo-ductile characteristics, making these systems a preferred choice for many shotcrete applications.

A variety of different test methods have been developed in different countries to characterize the toughness of fiber-reinforced shotcretes. For more information and details on these test methods, refer to Reference 17. In Western Canada, as in the rest of North America, the ASTM C 1018 test method is the most widely used test method for design, specification, and QC of fiber-reinforced shotcrete in civil applications. This test method involves the use of beams tested in third-point loading, followed by the reporting of the following parameters:[18]

- first crack load and deflection and calculated flexural strength;
- ultimate load and flexural strength;
- toughness indices; and
- residual strength factors.

Significant concerns, however, have been raised relating to the means of interpreting toughness test data provided in the standard ASTM C 1018 test.[19] As a consequence, different methods of calculating and specifying flexural toughness have evolved. One such method, commonly used for fiber-reinforced shotcrete projects in Western Canada, is the Toughness Performance Level (TPL) method whereby the load-deflection response of a beam tested according to ASTM C 1018 is compared to a series of templates that are expressed as a percentage of the design flexural strength at 1/600 and 1/150 span.[3] Figure 5 shows an example of a steel fiber-reinforced shotcrete mixture plotted against these templates. (This TPL method has now also been adopted by the Austrians in their national standard for fiber-reinforced shotcrete.)

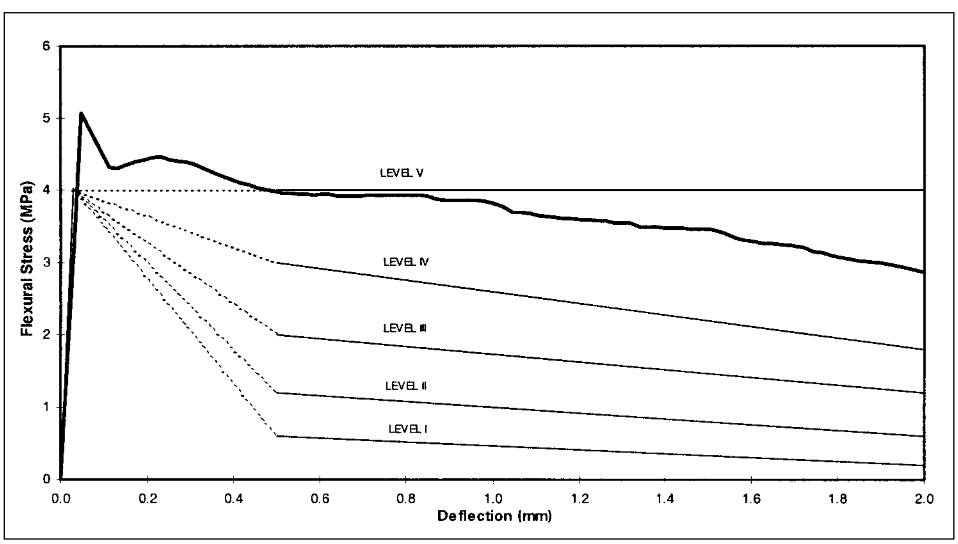

Figure 5: Steel fiber-reinforced shotcrete plotted against Toughness Performance Level templates.

A new draft ASTM standard test method, based on a test method developed by Bernard in Australia,[21] that uses a round determinate panel, is now available as an alternative method for characterizing toughness in fiber-reinforced shotcretes. The 800-mm-diameter (32 in.) by 75-mm-thick (3 in.) panels are statically, determinately supported on three swiveling supports and loaded at the center point. Toughness is then characterized by comparing the absorbed energy at a specified central deflection obtained from the load-central deflection curve. In one study, it was found that the round determinate panel test was able to sort out the relative behavior among various plain, mesh, steel fiber, and synthetic fiber types and addition rates in essentially the same way as the larger (more representative of field performance) South African water bed test.[20] This feature, together with the inherently low variability of the test, has led to this test method being specified for QA/QC purposes on ground support projects in Western Canada in the past couple of years.

Closure

Numerous ground-support projects in Western Canada have been successfully completed using conventionally reinforced and fiber-reinforced shotcretes. The preference for shotcrete in these projects over traditional cast-in-place concrete ground-support methods has been due to the technical and cost-effective advantages demonstrated by shotcrete in the design, construction, and utilization stages over other methods. Protection of the owner's investment, however, requires careful attention to details including the following items:

- Design of an appropriate ground-support/lining system;
- Development of a suitable set of shotcrete specifications;
- Careful selection of quality materials and appropriate preconstruction shotcrete mixture-design proportioning and optimization;
- Preconstruction qualification of the nozzlemen and shotcrete crew proposed for the project using review of submittals and preconstruction testing;
- Establishment and enforcement of a suitable QA monitoring and QC testing program during construction; and
- Adoption of a suitable long-term maintenance program to deal with any deterioration that develops with time from service conditions.

Numerous projects completed in Western Canada in the past couple of decades have demonstrated that, if such best practice is followed, then the owner should be provided with a high-quality durable structure with the lowest service-life cost.

References

1. Morgan, D. R., "Performance vs. Prescription Based Shotcrete Specifications," *Shotcrete Magazine*, V. 1, No. 1, Winter 1999, pp. 10-13.

2. Morgan, D. R., *Steel Fibre Reinforced Shotcrete for Underground Support: Civil Applications*, Australian Shotcrete Conference, Oct. 8-9, 1998, 19 pp.

3. Morgan, D. R.; Chen, L.; and Beaupré, D., *Toughness of Fibre Reinforced Shotcrete*, Shotcrete for Underground Support VII, Telfs, Austria, June 1995, published by ASCE, pp. 66-87.

4. ACI Committee 506, "Guide to Shotcrete (ACI 506R-90 (95)," American Concrete Institute, Farmington Hills, Mich., 1990, 41 pp.

5. Chan, C., and Morgan, D. R., "Shotcrete for Infrastructure Repair and Rehabilitation," *CE News Magazine*, Mar. 2000, pp. 66-71.

6. Morgan, D. R., "Use of Supplementary Cementing Materials in Shotcrete," *Proceedings*, International Workshop on the Use of Fly Ash, Slag, Silica Fume and Other Siliceous Materials in Concrete, W. G. Ryan, ed., Concrete Institute of Australia, Sydney, Australia, July 4-6, 1988, pp. 403-432.

7. Morgan, D. R., "Dry-Mix Silica Fume Shotcrete in Western Canada," *Concrete International: Design and Construction*, V. 10, No. 1, Jan. 1988, pp. 24-32.

8. Morgan, D. R.; Neill, J.; McAskill, N.; and Duke, N., "Evaluation of Silica Fume Shotcrete", *CANMET/CSCE International Workshop on Silica Fume in Concrete*, Montreal, Quebec, Canada, May 4-5, 1987, pp. 34.

9. Beaupré, D., and Mindess, S., "Compaction of Wet Shotcrete and Its Effect on Rheological Properties," *Proceedings*, International Symposium on Sprayed Concrete, Fagernes, Norway, Oct. 1993, pp. 167-181.

10. Morgan, D. R.; Here, R.; Chan, C.; Buffenbarger, J.; and Tomita, R., "Evaluation of Shrinkage-Reducing Admixtures in Wet and Dry-Mix Shotcretes," *Shotcrete: Engineering Developments*, E.S. Bernard, ed., Proceedings of the International Conference on Engineering Developments in Shotcrete, Hobart, Tasmania, Australia, Apr. 2-4, 2001, pp. 185-192.

11. Morgan, D. R.; Here, H.; McAskill, N.; and Chan, C., *System Ductility of Mesh and Synthetic Fibre Reinforced Shotcrete*, 3rd International Symposium on Sprayed Concrete, Gol, Norway, Sept. 26-29, 1999.

12. Gebler, S. H., "Construction Practice and Quality Control," *Sprayed Concrete: Properties, Design and Application*, Whittles Publishing, Scotland, 1995, pp. 204-228.

13. Morgan, D. R., "Shotcrete Guides and Specifications," *Shotcrete Magazine*, American Shotcrete Association, V. 2, No. 4, Fall 2000, pp. 8-11.

14. Morgan, D. R., "Special Sprayed Concretes," *Sprayed Concrete: Properties, Design and Application*, Whittles Publishing, Scotland, 1995, pp. 229-265.

15. Morgan, D. R.; McAskill, N.; and Here, R., *Proposed Method for Determination of Early-Age Compressive Strength of Shotcrete*, ASTM, San Diego, Calif., Oct. 1997, 12 pp.

16. Morgan, D. R., *Recent Developments in Shotcrete Technology—A Materials Engineering Perspective*, World of Concrete, Las Vegas, Nev., Feb. 1988, 55 pp.

17. Bernard, E. S., *Variability in Toughness Estimates for FRS Derived Using Beam and Panel Tests*, Australian Shotcrete Conference, Oct. 8-9, 1998, 8 pp.

18. ASTM C 1018-97, "Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)," *Annual Book of ASTM Standards 2000*, V. 04.02, ASTM, West Conshohocken, Pa., pp. 528-534.

19. Banthia, N., and Trottier, J. F., "Test Methods for Flexural Toughness Characterization of Fibre Reinforced

Concrete: Some Concerns and a Proposition," *ACI Materials Journal*, V. 92, No. 1, Jan.-Feb. 1995, pp. 48-57.

20. Morgan, D. R.; Here, H.; McAskill, N.; and Chan, C., "Comparative Evaluation of System Ductility of Mesh and Fibre Reinforced Shotcretes," *Shotcrete for Underground Support*, T. Celestino and H. Parker, eds., Sao Paulo, Brazil, Apr. 1999, published by ASCE, pp. 216-239.

21. Bernard, E. S., *Measurement of Post-Cracking Performance in Fibre Reinforced Shotcrete*, Australian Shotcrete Conference, Sydney, Australia, Oct. 8-9, 1998, 15 pp.

Cesar Chan is an Engineer-in-Training with AMEC Earth & Environmental Ltd. in Vancouver, British Columbia, Canada. He received his Master's Degree in civil engineering from the University of British Columbia in 1998. His thesis addressed the use of recycled aggregate in shotcrete. At AMEC, Mr. Chan has worked on various consulting, testing, research and development projects relating to concrete and shotcrete technology. He has also assisted in the English-Spanish translation of various shotcrete nozzleman training and certification materials.

Roland Heere is a Materials Engineer with AMEC Earth & Environmental Ltd. He graduated with a Master's Degree in civil engineering from the University of British Columbia. He has 7 years of experience in the field of shotcrete technology. His professional interests include fiber shotcrete and concrete technology, and materials testing.

Dudley R. (Rusty) Morgan is Chief Materials Engineer with AMEC Earth & Environmental Ltd. He is a civil engineer with over 35 years' experience in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructures. Dr. Morgan is a Fellow of the Canadian Academy of Engineering and the American Concrete Institute (ACI), and is Secretary of ACI Committee 506, Shotcrete. He is a member of several ACI, ASTM, and Canadian Standards Association (CSA) technical committees, and is a founding member of the American Shotcrete Association. Dr. Morgan has provided consulting services on concrete and shotcrete projects throughout North America and around the world.