Shotcrete for Ground Support: Current Practices in Western Canada

Part I of II

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

Historically, in Western Canada, the stabilization of rock slopes and construction of excavations have been achieved using methods such as soldier piles and lagging or construction of cast-in-place concrete retaining walls. In the case of reinforced cast-in-place concrete, there is a requirement for erection of formwork, fixing of reinforcement, pouring the concrete mixture, and vibration to ensure good concrete consolidation and steel encapsulation. These methods have proven to be relatively inefficient and costly in many cases. In recent decades, however, the use of shotcrete for ground support has seen increased use, as shotcrete has allowed for economical construction of excavations and slope stabilization. Advances in shotcrete technology include improvements in materials, mixture formulations, and methods of application. These advances have led to shotcrete that provides greater ease of application, superior performance, and overall economy compared with many of the traditional forms of ground support in many projects in Western Canada (and elsewhere in the world).

Figure 1: Application of shotcrete for support of stressed tie-back construction excavation in Vancouver, B.C.

Figure 2: View of finished top-down construction stressed tie-back shotcrete supported excavation.

Examples of Applications

Shotcrete has been used for a wide range of ground support applications in Western Canada. The following are some examples.

Support of construction excavations

Shotcrete has been regularly used for temporary support of construction excavations. Figure 1 shows an example of such an application in Vancouver, B.C. Figure 2 shows a view of a finished shotcrete-lined construction excavation at another project in Vancouver, B.C. Shotcrete is usually mesh- or rebar-reinforced and used in conjunction with stressed tie-back anchors to produce a self-supporting shotcrete-lined ground system. The fast and continuous nature of shotcrete application in construction excavations make it a preferred and economical choice for such use.

Rock slope stabilization

Shotcrete has also been frequently used for rock slope stabilization, particularly in the rockslide- and landslide-prone mountainous regions of British Columbia. Figure 3 shows the application of shotcrete for rock stabilization at the Stave Falls Hydroelectric Project, Mission, BC. The shotcrete is usually steel- or synthetic fiber-reinforced and used in conjunction with rock bolts, as can be seen in Figure 3. Examples of this type of shotcrete application include: Highway 99, B.C.; Stave Falls portals, Mission, B.C.; Highway 3, B.C.; Trans-Canada Highway and Rail Lines in the Thompson and Fraser Valleys.

Lining of water conveyance channels or creeks

Shotcrete has been used in various instances for water channel or creek bed lining for the purpose of providing erosion control. Figure 4 shows a view of a steel fiber-reinforced shotcrete-lined creek bed with embedded boulders at Harvey Creek in Lions Bay, B.C.

Other applications of shotcrete for ground support in Western Canada include: construction of permanent soil-nailed walls, containment berms around oil and liquid natural gas tanks, and stabilization of deteriorating quality rock tunnel and portals.

Specifications

Most civil engineering ground support projects require the development of technical specifications for the shotcrete work. This is irrespective of whether it is a traditional *consultant design, contractor bid* project or a *turnkey design-and-build* project. There are two general approaches to preparing specifications for shotcrete: *prescription-based* and *performance-based*.[1]

In prescription-based specifications, the engineer typically sets out in detail all the requirements for shotcrete materials, mixture proportioning, as well as equipment type and method of batching, mixing, supplying, and applying shotcrete. The engineer/owner is then prepared to accept the resulting performance (in terms of compressive strength and other physical properties achieved) with these prescription mixes. Quality assurance (QA) measures are usually implemented to verify that the specified details are attained.

In performance-based specifications, the engineer provides detailed specifications regarding the required performance of the end product, but only general guidance regarding the materials and methods to be used.[2] The selection of the precise type of equipment, materials, and proportions is left to the contractor. The engineer may specify the shotcreting process (wet- or dry-mix) to be used and any special materials, such as silica fume, air-entraining admixtures, accelerators, and steel or synthetic fibers to be used. The contractor is made responsible for all quality control (QC) testing; and the engineer monitors the work, including review of the contractor's QC test results, as part of the QA program.

In general, performance-based specifications are preferred over prescription-based specifications, as the former type encourages contractor innovation and the introduction of new technology, and generally results in the lowest-cost shotcrete installation to the owner. An example of performance-based specifications used for a hydroelectric pressure headrace tunnel lining at Stave Falls, B.C., is shown in Table 1.[1]

In certain instances, however, prescription-based specifications may actually be advantageous where the engineer is prepared to take the responsibility for the shotcrete performance. In such cases, the engineer has the freedom to quickly modify parameters of the mixture or spraying technology, and the contractor need not charge a risk premium for unpredictable situations or requirements outside the envelope of routine construction practice.

Figure 3: Shotcrete application for rock slope stabilization at Stave Falls Hydroelectric Project, Mission, B.C.

Figure 4: Use of shotcrete for erosion control at Harvey Creek, Lions Bay, B.C.

Materials and Mixture Designs

Materials

The materials used in shotcrete are essentially the same as those used in conventional cast-in-place concrete. There are, however, some differences in the proportioning of ingredients arising from the different application processes. While conventional concrete is poured into forms and then consolidated, shotcrete is consolidated by the impact process and then has to stay adhered to the substrate without sagging, sloughing, or falling out. For shotcrete, higher-than-normal cementitious materials contents (360 to 480 kg/m^3, 606 to 757 lb/yd^3) are typically used, and the gradation of aggregates usually falls within the limits specified by ACI 506R-90 (95).[4] These gradations recommended by ACI 506R-90 (95) contain considerably less coarse aggregate and finer composite aggregate gradations than conventionally cast concretes.

Table 1: Shotcrete performance specification, Stave Falls, B.C., hydroelectric project[1]

Property	Age, days	Specified limits
Maximum water-cement ratio		0.45
Air content, as-shot, % (CSA A23.2-4C)		4.0 ± 1.0
Slump, mm [in] (CSA A23.2-5C)		80 ± 30 [3 ± 1]
Minimum compressive strength, MPa [psi] (CSA A23.2-14C)	7 28	30 [4350] 40 [5800]
Maximum boiled absorption, % Maximum volume of permeable voids, % (ASTM C642)	7 7	8.0 17.0
Minimum flexural strength, MPa [psi] (ASTM C1018)	7	4.0 [580]
Minimum flexural toughness (ASTM C1018 and Ref. 3)	7	Toughness Performance Level III
Shotcrete core grade (ACI 506.2-95)*		Mean < 2.5 Individual < 3

**Note: the new ACI C660 Shotcrete Nozzleman Certification standard requires that, for five extracted cores, no individual core grade is > 3 and no more than two core grade 3's.*

Over the past two decades, significant developments in shotcrete materials technology have led to a wider range of applications for shotcrete.[5] These developments include:

Use of supplementary cementing materials

The use of supplementary cementing materials, such as fly ash and silica fume, in shotcrete mixture design has gained wider popularity in the industry.[6] In ternary blends of cementing materials (portland cement, fly ash, and silica fume), the fly ash increases paste volume, thereby improving pumpability and shootability; and the silica fume enhances adhesion and cohesion of the mixture and reduces rebound. Silica fume (typically at between 8 to 15% by mass of cement) also provides the ability for greater build-up thicknesses of shotcrete in a single pass and improves hardened shotcrete properties such as strength and durability.[7, 8] Silica fume is particularly beneficial in dry-mix shotcrete because of the reduction in overall and fiber rebound.

Use of chemical admixtures

Water reducers and superplasticizers are commonly used at dosages similar to those in conventional concretes to control the water demand of mixtures, particularly those containing silica fume. Accelerators (chemical accelerators and rheology modifiers) have been used in many underground shotcrete applications to enhance stiffening of the shotcrete and promote early-age strength development. Air-entraining admixtures are employed to achieve higher-than-normal air contents (8 to 10%) at discharge into the pump for enhancement of the pumpability and shootability of the mixture[9] and to improve frost resistance. Hydration-controlling admixtures can also be used to provide shotcrete with extended working life. Shrinkage-reducing admixtures represent a new generation of chemical admixtures that are finding increased use in shotcrete. It has been demonstrated that these admixtures are very effective in reducing drying shrinkage and mitigating restrained drying-shrinkage induced cracking.[10]

Use of fiber reinforcement

Steel fibers have routinely been incorporated into wet- and dry-mix shotcretes to provide system ductility, such as increased crack resistance, energy absorption, impact resistance, and ability to continue to carry load if cracked. These attributes are collectively referred to as *toughness*. The effectiveness of any steel fiber to impart toughness to the shotcrete depends on several factors, including the aspect ratio (length/ equivalent diameter), the fiber geometry, the type of fiber deformation (end or continuous), the tensile strength of the steel, and the fiber addition rate. In Western Canada, most steel fiber-reinforced shotcrete applications have used steel fiber-addition rates in the 50 to 70 kg/m^3 (84 to 118 lb/yd^3) range with 55 kg/m^3 (93 lb/yd^3) being common. It should, however, be recognized that the in-situ fiber content will be lower than the as-batched quantities due to fiber rebound, particularly in dry-mix shotcrete. Rebound of the steel fibers can be greatly reduced by using proper nozzling technique, using correct mixture designs, and applying the right material exit velocity.

Synthetic fibers at high-volume addition rates (0.5 to 1.5% by volume) have found increasing use in a wide range of ground support applications. Most of the new-generation synthetic fibers are either monofilament type fibers or bundled assemblies of fine fibers with a monofilament appearance, with a chemical composition of either polypropylene (and polyolefin) or polypropylene/polyethylene blends. Tensile strengths of as much as 610 MPa (88 ksi) are exhibited by the latter type of fiber. Some of these fiber types have a slight fibrillating characteristic upon mixing and shooting. The post-crack toughness imparted by synthetic fibers can be equivalent or even superior to that provided by steel fibers or welded wire mesh fabric, particularly at large deformations.[11] In addition, their chemically inert nature and lightweight and nonabrasive properties have made them a material of choice for many shotcrete applications, including ground support. Technological advances for these fibers have produced more user-friendly fibers that can be readily added to wet-mix shotcrete without balling problems. Their use in dry-mix shotcrete, however, is still limited. Further research is needed to optimize synthetic fibers for dry-mix shotcrete applications.

Mixture Proportioning

As described in the previous section, due to the way shotcrete is placed and consolidated and to the required performance of these mixtures, the proportioning of materials for shotcrete mixtures is carried out differently than for conventional cast concretes. Table 2 provides a summary of shotcrete mixture design concepts. The specific proportions depend on the performance requirements of the particular project, availability of materials, and experience of the designer and contractors. An example of a shotcrete mixture design for a 0.75% vol. synthetic fiber-reinforced wet-mix shotcrete is shown in Table 3. These proportions are typical for many ground support shotcrete applications in Western Canada. The performance of such a mixture is discussed in the "Performance" section of this paper.

Table 2: Shotcrete mixture design concepts

Material	Proportions	
Portland cement	360 to 450 kg/m^3	606 to 757 lbs/yd^3
Silica fume	30 to 50 kg/m^3	50 to 84 lbs/yd^3
Fly ash	30 to 60 kg/m^3	50 to 101 lbs/yd^3
Coarse and fine aggregate	ACI 506.2 Gradation No. 1 or No. 2	
Water demand	160 to 190 L/m^3	32 to 38 gal/yd^3
Steel fibers	50 to 80 kg/m^3	84 to 135 lbs/yd^3
Synthetic fibers	7 to 13 kg/m^3	11.8 to 21.9 lbs/yd^3
Water-reducing admixtures	1 to 1.5 L/m^3	33 to 51 fl.oz./yd^3
Superplasticizer	2 to 5 L/m^3	67 to 168 fl.oz./yd^3
Air-entraining admixtures	0.2 to 0.6 L/m^3	7 to 20 fl.oz/yd^3
Shrinkage-reducing admixtures	1 to 2% by mass of cement	
Accelerator	2 to 5% by mass of cement	
Hydration-control admixtures	1 to 3 L/m^3	33 to 102 fl.oz./yd^3

Table 3: Typical synthetic fiber-reinforced wet-mix shotcrete proportions

Material	Mass, kg/m^3	Mass, lbs/yd^3
Portland cement	400	673
Silica fume	45	76
Fly ash	30	50
Coarse aggregate (10-2.5mm) [SSD]	450	757
Sand [SSD]	1210	2035
Synthetic fibers	7.0	11.8
Water	180	303
Water-reducing admixture [L]	1.2	40 fl.oz.
Superplasticizer [L]	1.5	51 fl.oz.
Air-entraining admixture as required for air content, at pump as-shot	 7 to 10% 3.5%	 7 to 10% 3.5%
Total	**2325**	**3910**

Shotcrete Application

Site Planning

In the application of shotcrete for ground support, as in any other field project, good planning is essential for efficient and safe working conditions.[12] Planning starts with proper site setup to facilitate mobilization of equipment and personnel to perform the shotcrete operations in an effective manner. One key requirement in the proper site setup is that the shotcrete equipment be close to the work. Doing so will minimize hose lengths to be used and will require smaller volumes of air to move the material.

Crew organization and personnel selection on the job are also important for the success of shotcrete application. The minimum size of a shotcrete crew should consist of a foreman, nozzleman, finisher, assistant nozzleman, blowpipe operator, gunman or pump operator, mix operator, and laborers.[12] Some of the functions on a site may be combined depending on the particular project.

Scaffolds or other means of lifting are required where these will permit the nozzleman to move closer to the work in order to properly encapsulate the steel. Such equipment should allow the nozzleman to move around freely, not pose any obstruction on the progress of the works, and be stable.

Shotcrete Application

Prior to the application of shotcrete, it is crucial to properly prepare the receiving surface. Even correctly applied shotcrete may be compromised if the substrate is not properly prepared. Surface preparation involves removing any loose material or debris, removing any cracked or unsound substrate, sandblasting or hydroblasting if necessary, and thawing any frozen surfaces, followed by bringing the surface to a saturated surface dry (SSD) condition. If there is any doubt, it is generally better to err on the dry side rather than having too damp a surface. The objective is to achieve a stable, sound, rough, and nonabsorptive surface that will enhance bond of the applied shotcrete.

Batching, mixing and supply of the shotcrete mixture can be done in several ways depending on the particular method of application (wet- or dry-mix) and the location of the project. The following are the most common forms of shotcrete supply used in Western Canada.

Wet-Mix Shotcrete	Dry-Mix Shotcrete
• Central mixture batching with transit mixer supply. • Transit mixer batching and supply. • Volumetric site batching.	• Central or transit mixture batched, transit mixer supply. • Volumetric site batching. • Dry-bagged premix materials in paper bags (30 kg) or bulk bin bags (1000 to 1600 kg)

There is a growing tendency towards the use of pre-blended materials, particularly for dry-mix shotcrete or for remote locations. The use of pre-blended materials allows for convenient supply of shotcrete to the site as well as excellent quality control of the shotcrete mix proportions.

The quality of the applied shotcrete is dependent on the skill and application technique of the nozzleman. In the case of dry-mix shotcrete, this is particularly critical, as the nozzleman controls the amount of water to be introduced to the shotcrete stream at the nozzle. ACI 506R, "Guide to Shotcrete,"[4] and ACI Concrete Craftsman Series 4, "Shotcrete for the Craftsman," provide detailed guidelines for the proper application of shotcrete by the nozzleman. These include control of mixing water, nozzle velocity, nozzling technique and manipulation, gunning, shooting multiple layers, encapsulation of reinforcement, and controlling rebound and overspray. Over the years, certification of nozzlemen has become a standard for many projects. ACI Committee C 660, Shotcrete Nozzleman Certification, has developed a Shotcrete Nozzleman Certification Program, which is sponsored by the American Shotcrete Association.[13] Through such programs, it is now possible for designers to write into their specifications a statement that only "ACI Certified Shotcrete Nozzlemen" will be allowed to apply shotcrete on the job.

Quality Assurance and Quality Control

An important component of quality assurance involves the prequalification of nozzlemen and preconstruction trials. This process involves a demonstration of skill in constructing test panels, whereby the nozzleman intended for work on the project shoots test panels at the orientation (vertical, horizontal or overhead), together with the reinforcement configuration expected on the job. Cores are then extracted from the test panels and graded according to the ACI 506.2 core grading system. Preconstruction testing is also beneficial to establish the performance of intended shotcrete mixtures and resolve any difficulties with equipment and procedures used.

On-site quality control should be carried out throughout the duration of the project and consists of several aspects, as follows:[12]

- shop drawing review to verify compliance with project requirements;
- testing plastic shotcrete properties (slump and air content) for wet-mix shotcrete;
- mechanical sounding to detect any possible delaminations in hardened shotcrete;
- tensile bond strength tests (if specified);
- in-situ tests such as coring and nondestructive testing; and
- shooting of test panels on a predetermined

frequency to determine physical properties of the shotcrete, e.g., compressive strength, flexural strength, and toughness (for fiber-reinforced shotcretes), boiled absorption and volume of permeable voids.

Curing

Proper curing of the applied shotcrete is essential to aid in the hydration process, and so that the potential strength and durability can be developed. The best method for curing is moist curing with water for at least 7 days while maintaining a temperature above 5° C (40° F). Curing compounds can be used but are not as good as moist curing. No additional shotcrete should be placed over an existing layer—unless the curing compound has been removed by sandblasting or high-pressure water blasting.

See the next issue of Shotcrete for Part II.

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.