Understanding Wet-Mix Shotcrete: Mix Design, Specifications, and Placement

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by Marc Jolin and Denis Beaupré

The purpose of this article is to examine the use of modern wet-mix shotcrete in underground environments. A critical review is provided of aspects such as mixture design, specifications, and placement. More specifically, the intent of this article is to identify the limits of the wet-mix shotcrete process, examine actual mix designs, discuss the various methods of determining (and specifying) the early-age properties of shotcrete (< 1 day), and review shotcrete placement properties, especially pumping the fresh concrete. The presentation treats various subjects taking into account actual field practices as well as the results of on-going research at Laval University, QC, Canada.

Introduction

Maintenance of the stability of an underground opening often requires the engineer to specify some sort of support system. Generally, this support system takes the form of a composite structure, which can include rock bolts, welded wire mesh, steel sets, lattice girders, and/or shotcrete. If shotcrete is included as an element of the support system, it can play different roles. First, it can be used as a simple protective layer to isolate the exposed rock from the ambient air. It can also be used as a structural layer, where it is used in combination with rock bolting and/or steel sets or lattice girders. In this case, shotcrete is structural in the sense that it offers support between the rock bolts and the steel sets or lattice girders. This type of support is intended to provide local stability of the excavation and prevent fallouts of blocks of rock. Finally, shotcrete can be used in some openings to provide a complete structural support, a shell action, to the surrounding ground. These generally thicker shells of shotcrete, working mostly in compression, are usually reinforced and may also incorporate fibers.

In this paper, it is assumed that wet-mix shotcrete has been selected as an element of the support system. Different aspects related to the design, specifications, and placement of wet-mix shotcrete in an underground environment are examined. More specifically, the wet-mix shotcrete process is assessed by examining the following items:

- Batching, mixing, and pumping wet-mix shotcrete (all the way to the nozzle);
- Placing wet-mix shotcrete; and
- Testing and evaluating in-place wet-mix shotcrete.

In other words, the reader is shown some of the possibilities of the wet-mix shotcrete while keeping a critical eye open, either for misconceptions often found in the concrete industry or for new and useful information originating from recent shotcrete research.

Batching, Mixing, and Pumping Wet-Mix Shotcrete

This part of the shotcrete process is probably the one that benefited most from recent advances in the concrete admixture technology. Indeed, it is now possible to mix and pump concretes that will reach 60 MPa (8700 psi) compressive strengths thanks to the use of high-range water reducers and superplasticizers that allow mixtures to be designed with water/cementitious material ratios (*w/cm*) as low as 0.35. It is also now possible to produce robust and flexible mixtures that will not cause unwanted surprises when it is time to pump, even with significant amounts of steel or synthetic fibers included in the mix.

Keeping in mind the pumpability requirements, two important approaches have been increasingly used in the past few years to increase the robustness against potential pumping problems: the optimization of the aggregate phase and the use of the concept of temporary high initial air content. These two approaches are discussed in the following sections.

Pumping Wet-Mix Shotcrete: Optimization of the Aggregate Phase

Batching and mixing a high-quality and pumpable wet-mix shotcrete is not always a simple task, particularly when high dosages of fibers are used. Using a classic mix design approach for conventional concrete may result in non-pumpable or difficult to pump concretes. Adding fibers to ordinary wet-mix shotcrete can produce similar effects. Also, keep in mind that the addition of a superplasticizer does not always result in a more workable mixture. A common factor behind these all too common observations is aggregate packing, which represents how densely the aggregate particles are packed or, by corollary, the amount of voids between the aggregate particles. The shape and combined particle size distribution of the aggregates used are the main parameters affecting the aggregate packing density. As far as the designer is concerned, the fine/coarse aggregates ratio is often the only parameter left to choose once the aggregate supply has been selected.

In concrete technology, the particles include the fine aggregate, the coarse aggregate(s), and the fibers (if any are used). Water, cement, other cementitious materials, and air constitute the paste phase that lubricates the particles. To make concrete or shotcrete, not only must all the space (voids) between the particles be filled with cement paste, but some extra paste must also be added to provide the desired level of workability. Normally, there is an optimum fine/coarse aggregate ratio (and aggregate gradation) that minimizes the amount of voids in the aggregate skeleton, thus minimizing the amount of paste required to fill the voids. Extra paste is required, over and beyond that required to fill the voids, and its presence affects the workability or, in this case, the pumpability of the wet-mix shotcrete (Chapdelaine and Beaupré 2000).

Figure 1 shows the void content for various proportions of coarse aggregates (as a fraction of the total combined aggregate mass) for three mixtures containing 0, 1, and 2% (by volume) of synthetic macrofibers. Each mixture has a minimum void content that indicates optimum particle packing. The optimum ratio depends upon the shape and gradation of both the fine and coarse aggregates and the fiber type and content. When fibers are present, the aggregate packing is modified, which leads to a different optimum coarse/total aggregate ratio and void content. These curves were obtained with standard concrete sand and a 10 mm (0.394 in.) maximum size crushed granite coarse aggregate.

In Figure 1, the mixture without fibers having a coarse/total aggregates content of 47% has a void content of 29%. In practice, this mixture should contain 29% of cement paste plus approximately 6% of extra paste* in order to have good pumpability (Chapdelaine and Beaupré 2002). For the same ratio, the paste content should be increased when fibers are present; 1% of fibers not only moves the optimum toward a mixture richer in sand, but increases the void content to 35% (35% + 6% = 41% paste requirement for good pumping). This is only an example; one should remember that these numbers are affected not only by the aggregates used, but also by fiber geometry and content. However, it illustrates the importance of this concept. Also, to limit rebound, the optimum coarse aggregates content will most probably lie closer to 25% of the total combined aggregate.

Having a minimum paste content to fill the voids between aggregates and fiber particles is an essential factor with respect to concrete pumpability. As implied in Fig. 1, there are two ways of achieving this: either increase the paste content (increase cement, water, or air content) and/or reduce the aggregate void content by optimizing the fine/coarse aggregate ratio. The two options

*This value of 6% is good practice. It will be affected greatly by hose diameter and layout.

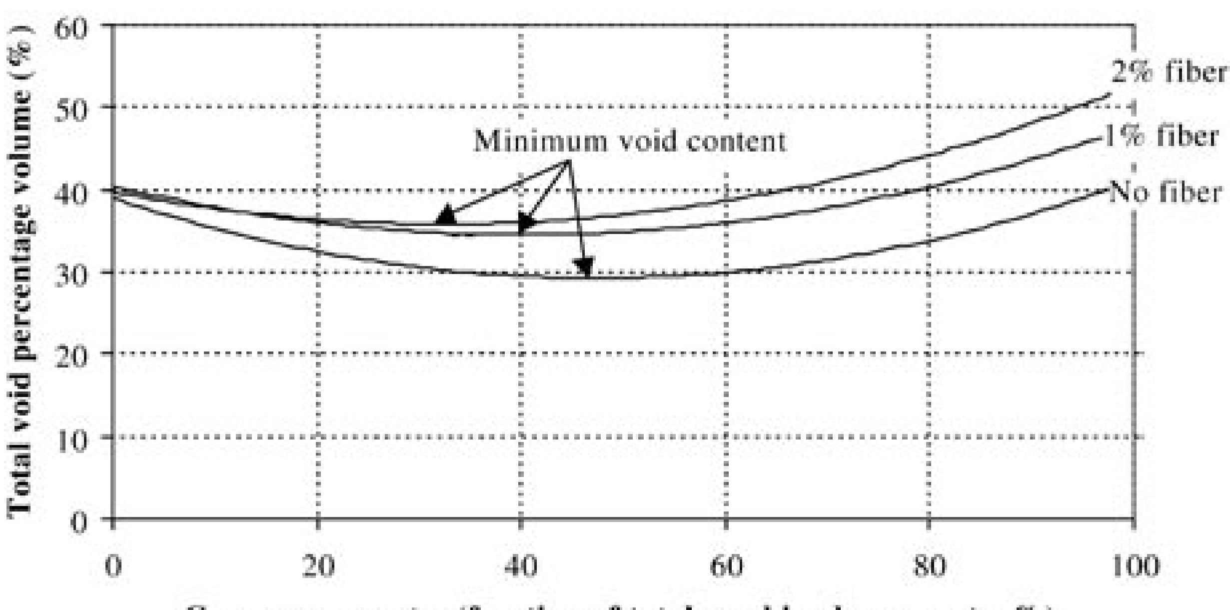

Figure 1: Packing curves for mixtures with different fiber contents.

have the same effect: increasing the workability (and pumpability) of the concrete mixture. However, there are limits related to cost, mechanical, and durability considerations as to how much the paste content can be increased. Because of the beneficial effects on material costs, shrinkage, durability, and mechanical properties, minimization of voids in the aggregate skeleton and hence the paste required in the mixture should always be implemented first.

Determining the void content of the aggregate phase is easy to do and is described in basic soil mechanics manuals. The curves in Fig. 1 are simply built by testing different combinations of fine aggregate, coarse aggregates, and fibers (when required).

Pumping Wet-Mix Shotcrete: High Initial Air Content

The placement of high-strength wet-mix shotcrete is sometimes complicated by the compromise required between pumpability and shootability requirements. At the pump, a relatively fluid concrete that will be easy to pump is required; at the nozzle, a stiff material is desired so it does not sag or slough on the wall. Most of the time, the simplest solution is to add a set-accelerator at the nozzle and/or adapt the application schedule to allow sufficient time for initial stiffening of the in-place material before the next layer of shotcrete is applied. Due to the stringent quality requirements of modern shotcrete, however, limiting the amount of accelerator to what is strictly required for reaching stability and early strength requirements is by far a better method because accelerators can downgrade shotcrete quality. An alternative was sought where wet-mix shotcrete could be applied in relatively thick layers (100 to 150 mm, 4 to 6 in.) without the use of set-accelerators. (More information supporting this accelerator limitation is presented later in this paper in the section Dosage of Set Accelerator).

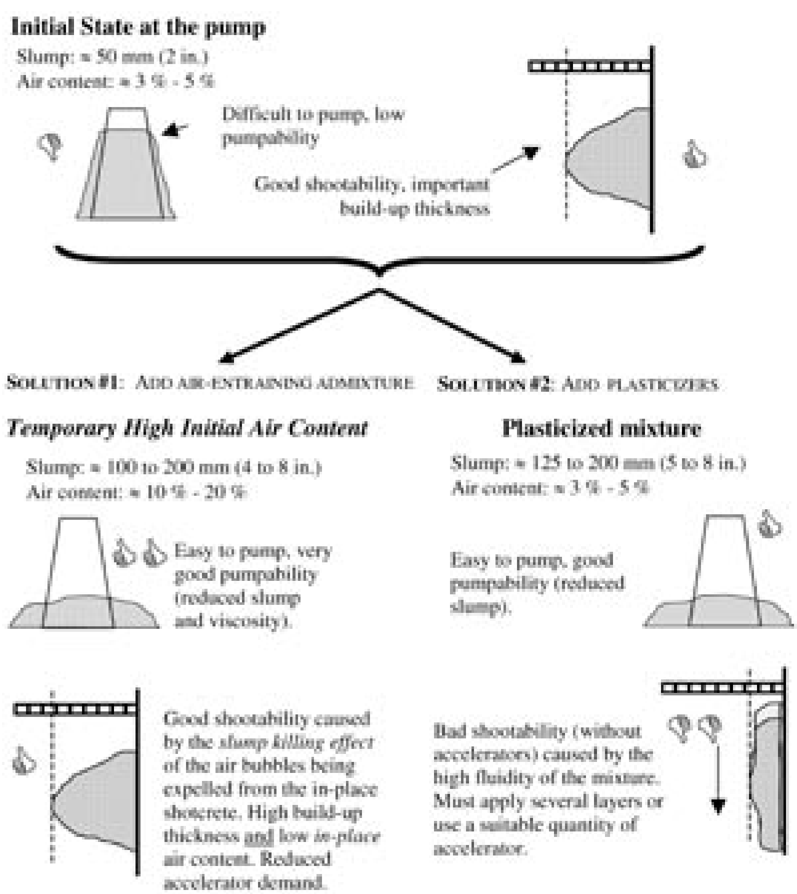

Figure 2: Schematic of the Temporary High Initial Air Content.

In 1994, Beaupré developed the Temporary High Initial Air Content concept. This concept is a clever and simple system by which the workability of the fresh concrete is increased to meet the pumpability requirement by introducing a large amount of entrained air bubbles into the mix, instead of relying on water-reducing admixtures to increase workability. The trick is that during pumping and particularly during shooting, a large amount of air is lost due to the compaction process. This reduces the slump of the in-place shotcrete, thus increasing the shootability of the shotcrete (Fig. 2). This air loss upon impact on the shooting surface is often referred to as a slump killing effect. This method of shotcrete production has been used in a number of applications with success over the past 5 years.

The technicalities of this concept are simple. Instead of adjusting the plasticizer's content (normal or high-range water reducers and superplasticizers) to produce a 75 to 100 mm (3 to 4 in.) slump at the pump, the plasticizer content should be reduced so as to produce a 25 to 50 mm (1 to 2 in.) slump. The air-entraining admixture is then incorporated to produce the slump required for pumping, typically between 75 and 150 mm (3 to 6 in.). Remember that the slump killing effect works best if there is a high initial air content at the pump, typically between 10 and 20%. One should not be afraid to batch the shotcrete with this high air content as it will be reduced to 3 to 6% in the in-place shotcrete due to the compacting effect. Hence, it will not result in the negative effect on compressive strength associated with high air content. Table 1 shows a typical mix design used with this technology for a high performance shotcrete. Table 2 shows a typical test results obtained with this mixture.

Placing Wet-Mix Shotcrete

It is common in the underground environment to use robotic arms to hold and manipulate the nozzle. The nozzleman controls the position of the nozzle remotely, increasing his safety. However, application becomes more difficult due to greater distance between the nozzleman and the surface. In any case, the task of applying shotcrete,

Table 1: *Typical wet-mix shotcrete composition using the Temporary High Initial Air Content concept*

Ingredient	Quantity for 1 m³
Cement	400 kg (880 lb)
Silica fume	40 kg (88 lb)
Fine aggregate	1110 kg (2447 lb)
Coarse aggregate (max 10 mm [3/8 in.])	460 kg (1014 lb)
Water	180 kg (396 lb)
Water-reducing admixture	1500 ml (51 fl oz.)
Superplasticizer	5000 ml (170 fl oz.)
Air-entraining admixture	2500 ml (84 fl oz.)

Table 2: *Typical test results for the mix described in Table 1*

Slump before pumping	220 mm (8.5 in.)
Air content of fresh shotcrete before pumping	17%
Air content on hardened in-place shotcrete	5.3%
Compressive strength (28 d)	48 MPa (7000 psi)

whether by hand or with a robot, should be performed by an experienced nozzleman. A certification program that verifies the basic knowledge of the nozzleman and his ability to properly apply well-compacted shotcrete (even behind obstacles such as reinforcing bars or rock bolt plates) is greatly encouraged. A shotcrete nozzleman program now exists, developed by ACI International, that can easily be adapted to the underground environment.

Most applications of wet-mix shotcrete in the underground world require the use of some kind of set-accelerating admixture. Some important technical points concerning the placement phase are discussed. One concerns the distribution of the accelerator in the in-place shotcrete, and the other concerns the quantity of accelerator added to the mixture.

Distribution of the Set Accelerator

The actual distribution of the set-accelerator within the in-place shotcrete mass has rarely been studied. In evaluating the setting time of wet-mix shotcretes, it has been noted that the measurements can be quite variable, depending upon the precise location of the penetration test on the shotcrete surface. Also, some job site experiences have shown that some areas of the wet-mix surface do not set at the same rate. This can be explained by an uneven distribution of the accelerating admixture within the in-place shotcrete due to the intermittent or pulsating nature of most pumping operations and the (hopefully) steady supply of the set-accelerator to the shotcrete at the nozzle. Problems of variable accelerator distribution in the shotcrete can also arise when the entry point of the admixture at the nozzle is not properly designed.

As shown in Fig. 3, the concrete dual piston pump produces a pulsating flow compared with the regular stream of the additive pump feeding the accelerator to the nozzle. A nonuniform dispersion of the accelerator in the in-place wet shotcrete with such pumping equipment can thus be expected. To determine the degree to which the different flow

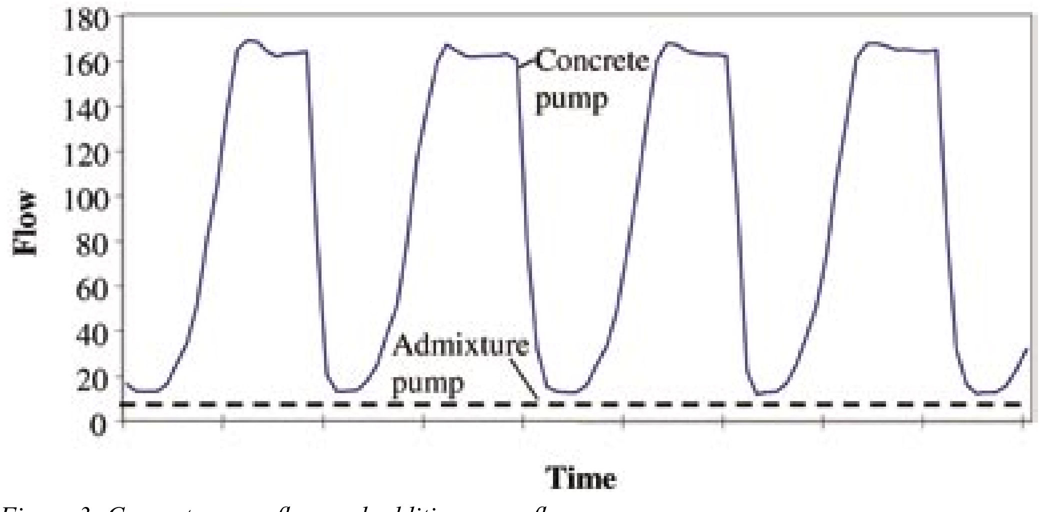

Figure 3: Concrete pump flow and additive pump flow.

rates generate a nonuniform dispersion of the accelerator, an evaluation method was developed that allowed visual observation of the dispersion of accelerator in the matrix. The approach consisted of substituting the accelerator with a product that enabled a distinction to be made between the areas of high and low concentrations of the product. The solution consists in replacing the accelerating admixture with a phosphorous solution. Under a high emission UV light, the phosphorous particles are excited and produce a glowing tint.

A small-scale trial was first conducted on conventional concrete samples. A visual inspection was performed and, as shown in Fig. 4 and 5, the first results revealed that the difference in coloration produced by the phosphorous solution can be significant and easily perceived.

In Fig. 4 and 5, the same amount of solution was incorporated in approximately 2.5 kg (5.51 lb) of concrete. The samples shown in Fig. 4 received a minimum amount of mixing whereas the samples in Fig. 5 were thoroughly hand mixed.

A large-scale test was conducted in the laboratory at Laval University. A shotcrete dual piston pump creating a pulsating stream of concrete at the nozzle and a typical accelerator pump that produced a constant feed of the substituting product were used. The phosphorous solution was added at a dosage of 5% by mass of cement. The visual test revealed a uniform dispersion of the substituting product throughout the entire 50 kg (110.23 lb) of sample produced. Further investigations should be done on the subject. Various types of pumps should be tested to evaluate the influence of the type of equipment on the uniformity of accelerator dispersion.

Dosage of Set Accelerator

The dosage of the accelerator is a very important aspect of shotcrete technology. The claim is sometimes made that some accelerators do not affect the long-term strength or other properties of shotcrete. In fact, it is not only the type of accelerator that is important with respect to long-term properties, but also the dosage (Bessette et al. 2001), as is briefly discussed as follows.

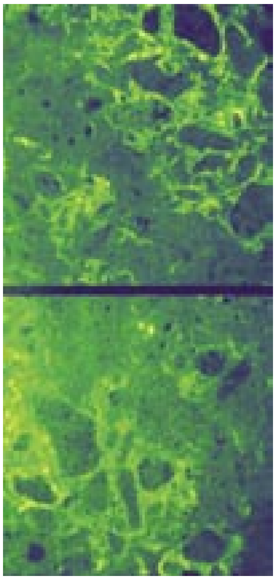

Figure 4: Nonuniform dispersion.

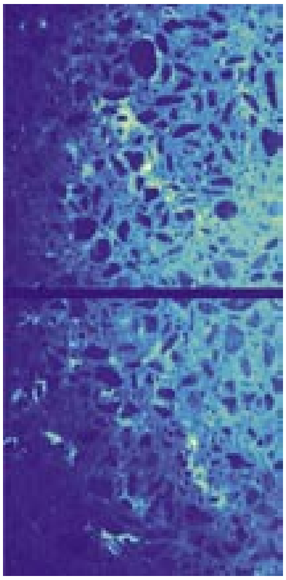

Figure 5: Uniform dispersion.

Figure 6 presents the results of the strength development of seven accelerated and one plain reference shotcrete. The compressive strengths at 4, 8, and 24 h were measured using the ends of beams while the strengths at 7, 28, and 56 days were measured on cores extracted from shotcrete panels. All accelerating admixtures increased the early-age compressive strength at 4 and 8 h when compared with the reference shotcrete. For example, increases in early strength development of the order of 200% were obtained with products A and B at 8 h. However, compressive strengths at 28 and 56 days show marked reductions for some mixtures when compared with the reference mixture (up to 55% reduction for Mix C-12%). Thus, the final strength is highly dependent on both the type and dosage of the accelerating admixture. It is therefore recommended to minimize the amount of set-accelerator added to any wet-mix shotcrete mixture to limit these long-term reductions in compressive strength. Similar reductions in quality can be measured for absorption and drying shrinkage, where the values can be increased (while you want to keep them as low as possible) as much as 100 and 50%, respectively. More information on this subject can be found on these tests in Bessette et al. (2001) or Beaupré and Jolin (2002).

Therefore, it is important to not only select the right type of accelerator (compatible with the cement and admixtures, early strength development, and shelf life) but also to limit the accelerator dosage to the amount required to ensure the stability of the fresh shotcrete layer and to meet the early and later age strength and other performance requirements. Using this approach, everyone will be working toward attaining higher quality in-place wet-mix shotcrete.

Early Strength of Wet-Mix Shotcrete

Recent years have seen an increasing number of methods being used to determine the (sometimes very) early strength of shotcrete. In some cases, compressive strength values have been obtained as early as 4 h to allow a shorter work cycle, especially in mining or tunnelling operations. The question that arises from such an extreme case is quite important from an engineering point of view: Is the value of the compressive strength given to the mining engineer corresponding to the compressive strength, as a material property, he or she is expecting? Or, in other words, are we really

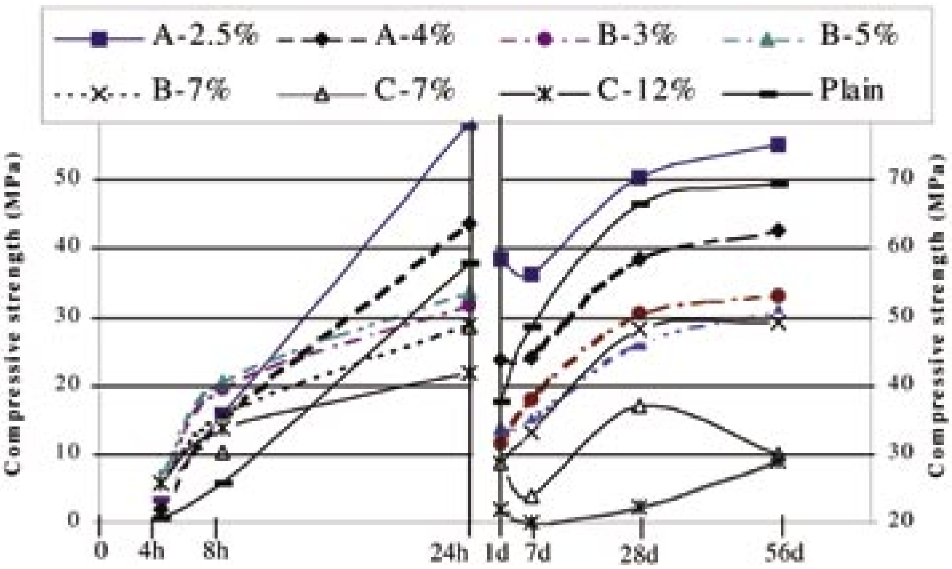

Figure 6: Evolution of compressive strength of shotcretes with different types and dosages of accelerators.

measuring the compressive strength in those early age tests?

Normally, coring of shotcrete test panels cannot be done before the concrete has reached a minimum compressive strength of approximately 8 to 10 MPa (1160 to 1450 psi). Below that strength, other indirect testing methods are used, such as the end beam test (Heere and Morgan 2002), vane shear tests (Beaupré and Jolin 2002), penetration test (Austrian Concrete Society), pullout test (Austrian Concrete Society), or a combination of penetration and pullout tests.

Depending on the real strength of the material and the size of the largest aggregate, some methods perform better than others. It is not the intent of this paper to review in detail the pros and cons of those methods. One important point, however, should be stressed. All of the aforementioned methods use some kind of correlation factor to convert their measurements into equivalent unconfined compressive strength values (as measured on a core). Care should be taken when interpreting the data obtained, especially when the results are used to make decisions on whether construction activities can be resumed or not. In this case, some serious questioning is required about the real significance of the measured property.

The specifier and the designer should make sure they agree on early compressive strength requirements and on the test method by which these early strengths should be acquired. Indeed, recent experiences seem to indicate that there might be some significant discrepancies between the values obtained for early compressive strength from the different testing methods mentioned. It is the intent of the authors to initiate a research project on the subject to verify and validate the accuracy of different methods.

Conclusions

This paper provides some information about a complex field. To summarize, one should remember that shotcrete is not only concrete on a vertical or overhead surface, but a special application method that requires special attention to details. Properly preparing, mixing, and placing wet-mix shotcrete is not a simple task. It is the hope of the authors that the information given in this paper will help in the production of quality wet-mix shotcrete and thus increase the number of projects where wet-mix shotcrete is preferred over conventional concrete construction. This will only be possible if the material—concrete—and the method of placement—spraying—are well understood by the specifier, designer, and contractor. Mistakes can be avoided by increasing the robustness of key parts of the process and by adequately training the crews, especially the nozzleman, performing the job.

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ACI member Marc Jolin obtained his PhD from the University of British Columbia, Vancouver, British Columbia, Canada, in 1999. He is working as a research associate in the Department of Civil Engineering of Laval University, Quebec, Canada. He is a member of ACI Committees 506, Shotcreting; C 660, Shotcrete Nozzleman Certification; Certification Programs Committee; and Internet Advisory Committee. As part of the Industrial Chair on Shotcrete and Concrete Repairs, his main research activities cover the shotcrete process. Jolin is currently involved in projects on set-accelerators, reinforcement encasement quality, new admixtures, and rheology of fresh shotcrete. His more recent research interests include infrastructure durability and life cycle.

ACI member Denis Beaupré completed a PhD at the University of British Columbia in 1994. He is currently teaching in the Civil Engineering Department at Laval University. He is a member of ACI Committees 236, Material Science of Concrete; 304, Measuring, Mixing, Transporting, and Placing Concrete; 506, Shotcreting; and C 660, Shotcrete Nozzleman Certification. Beaupré's research interests include rheology, self-consolidating concrete, repair, pumping, and all aspects of shotcrete technology.