Shotcrete Boiled Water Absorption

By Louis-Samuel Bolduc and Marc Jolin

One of the benefits of choosing the shotcrete process over pump-and-pour systems is the rapidity of execution. Indeed, this unique placement technique ensures a quick application because very little formwork is required. The major difference, however, is that (in the case of shotcrete) the nozzleman plays an important role in the quality of the in-place concrete. For example, the nozzleman is responsible for the air velocity, the nozzling technique, the amount of water added (in dry-mix shotcrete), and the amount of set accelerator added at the nozzle (in accelerated wet-mix shotcrete). In addition to the usual compressive strength measurements of shotcrete, it is not uncommon in the industry to perform boiled water absorption (BWA) tests, as described in ASTM C642, to evaluate the overall quality of the shotcrete placement.

The subject of BWA measurement in shotcrete is the source of animated discussions both around the construction site and in technical committee meetings. The issue at hand is that contract documents often require the contractors to comply to a minimum value of compressive strength (ASTM C1604) and a maximum value of BWA (ASTM C642). Contrary to what is often conveyed in the industry, however, there is no direct relationship between the compressive strength of concrete and its BWA (refer to Fig. 1). Indeed, some parameters affect the BWA but do not necessarily affect the mechanical properties.

One can observe that the correlation is quite poor in Fig. 1, especially when the range between 4000 and 6500 psi (28 to 45 MPa) is considered (typical values for shotcrete). This is because the parameters that influence the shotcrete BWA are not fully correlated with the compressive strength. The potential problem on the job site is that to comply with the specified BWA, contractors and engineers end up in an iterative and expensive process trying to fix the mixture design. Which parameters to modify, however, are not well understood.

The debate intensifies when it comes to the choice of the maximum acceptable value itself. What is an acceptable BWA value? What is the limit beyond which the in-place shotcrete is too porous? Which parameters must be modified to reduce BWA values?

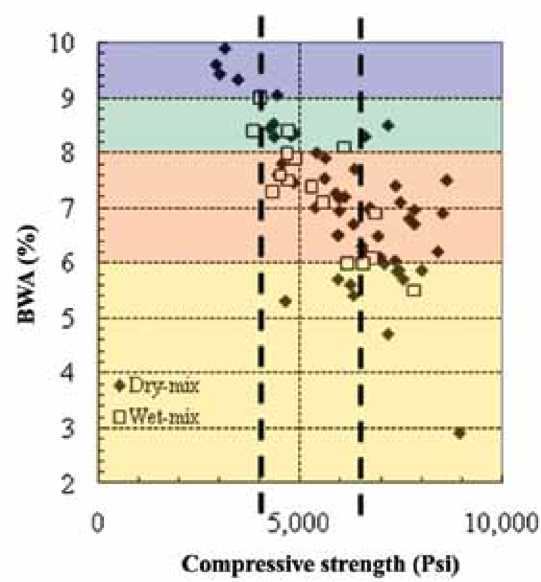


Fig. 1: BWA versus compressive strength (values compiled from projects at Laval University, Quebec City, QC, Canada)

It is the objective of this paper to provide some information that will hopefully help answer those questions. The first part of the article presents the mechanisms through which fluid can migrate through the concrete pore spaces. The second part presents some results from a study that was undertaken by the shotcrete team at Laval University.

Transport Mechanisms

Shotcrete is a porous material that comprises a solid matrix and a network of interconnected pores. The shotcrete porosity covers a wide range of pore size diameters (Neville 2000):

- The gel pores are smaller with a nominal diameter of approximately 8×10^{-5} to 12×10^{-5} mil (2 to 3 μm);
- The capillary pores have a median size of 0.05 mil (1.3 μm);

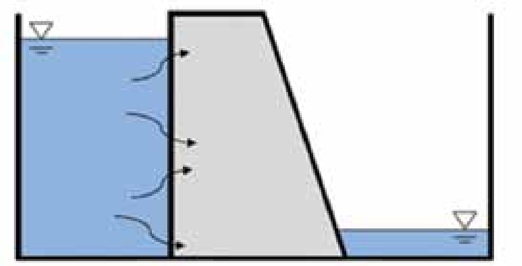


Fig. 2: Permeability

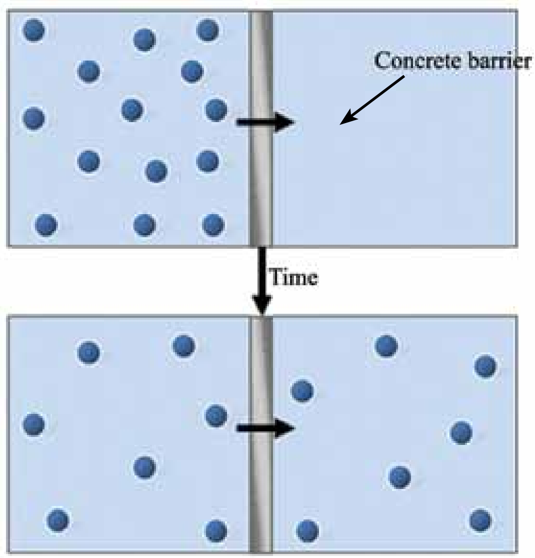


Fig. 3: Ionic diffusion

- The entrained air bubbles have a diameter of approximately 2 mil (50 μm); and
- The entrapped air and the compaction voids can reach the magnitude of over 1 in. (25.4 mm).

To illustrate the difference between the pore size diameters, comparing the gel pores to the compaction voids would be like comparing the size of a human to the size of Mars!

The porosity is therefore very complex, and the mechanisms controlling the movement of fluid (or contaminants) in the porosity received a lot of interest from researchers in the last decades. Why? Because most durability issues are related to these mechanisms (called transport mechanisms or transport properties). For example, reinforcement corrosion is initiated by the ingress of chloride, or by carbonation (which begins with the ingress of carbon dioxide in the concrete porosity). To make durable concrete, it is crucial to understand the material transport properties. The transport mechanisms can be roughly divided into three categories.

Permeability: movement of fluid (liquid or gas) resulting from a pressure (illustrated in Fig. 2).

The term permeability is widely used when it comes to the ingress of fluids in concrete. However, strictly speaking, a pressure must be involved to have the right to use the word permeability. Numerous test methods are available to measure the permeability of concrete, but none of them is standardized by an official standard organization.

Ionic diffusion: movement of ionic species resulting from a concentration gradient (illustrated in Fig. 3). Thermodynamic principles dictate that equilibrium must be established when a system is unstable. For instance, when concrete is immersed in water with a high concentration of salt, the chloride concentration in the concrete pore solution is lower than that of the salted solution. Consequently, the ionic species present in the salted water will migrate into the concrete pores, through the pore solution, until equilibrium is reached. The experimental evaluation of diffusion coefficient is laborious and time consuming. However, the research community came up with the rapid chloride penetration test (RCPT) (ASTM C1202) that can give a quick evaluation of the concrete diffusivity.

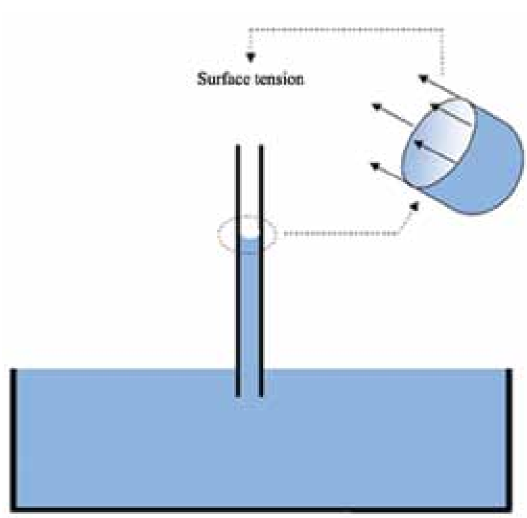


Fig. 4: Capillary absorption

Capillary absorption: suction of water resulting from the surface tension exerted in the capillary porosity (illustrated in Fig. 4). When a capillary tube is immersed in water, the level rises. In concrete, capillary pores behave like a series of tubes. When a concrete sample is immersed, the capillary void system slowly fills with water. In North America, the principal test procedure to evaluate the capillary absorption is ASTM C642 (also known as the BWA test). This test also provides the volume of permeable voids (VPV). The difference between these two parameters is that BWA represents the mass ratio of water absorbed in the sample, whereas the VPV

Table 1: Mixtures Composition

Study	Mixtures	*w/cm*	Cement Type GU, lb/yd³ (kg/m³)	Sand (0 to 5 mm), lb/yd³ (kg/m³)	Crushed stone (2.5 to 10 mm), lb/yd³ (kg/m³)	High-range water-reducing admixture, mL/m³	Air-entraining admixture, mL/m³
Air content	65/35-500-3	0.40	843 (500)	1796 (1066)	967 (574)	0	0
	65/35-500-13	0.40	843 (500)	1796 (1066)	967 (574)	0	750
Aggregate gradation	50/50-450-5	0.45	758 (450)	1363 (809)	1363 (809)	1800	0
	65/35-450-5	0.45	758 (450)	1773 (1052)	954 (566)	2700	0
	80/20-450-5	0.45	758 (450)	2180 (1294)	544 (323)	3600	0
Paste volume	65/35-390-5	0.45	657 (390)	1909 (1133)	1028 (610)	4600	0
	65/35-450-5	0.45	758 (450)	1773 (1052)	954 (566)	2700	0
	65/35-530-5	0.45	893 (530)	1592 (945)	858 (509)	1060	0

Note : 1 mm = 0.04 in.

represents the volumetric ratio of water absorbed in the sample. Therefore, the two results measure the same porosity, but are expressed differently.

The purpose of this section is only to give a quick overview of the main transport mechanisms used to describe concrete. The interesting observation here is there is no single test or concept available to evaluate every transport property. For example, it is important to calculate the permeability of the concrete in a dam because an important pressure gradient is involved. Conversely, a concrete pier in salt water will need to resist corrosion by both limiting ionic diffusion and capillary suction.

The complete understanding of these mechanisms is beyond the scope of this study. The reader can refer to several interesting publications to find more information (Glasser et al. 2008; Samson et al. 2005; Nilsson 2003; Hall 1994).

Research Program

A research project was undertaken by the shotcrete team at Laval University to further investigate this subject. The experimental program put forward consists of the production and characterization of several concrete mixtures, both cast and sprayed. One objective of this study is to investigate the influence of shooting parameters and mixture characteristics on shotcrete BWA. This will allow for the optimization of mixture proportions, and for the understanding of the parameters that influence BWA. The shooting parameters investigated include the dry- and wet-mix processes and, in the case of dry-mix, the consistency and predampening were studied. The mixture characteristics studied were the aggregate gradation and the binder composition. The following section presents results regarding the influence of the air content, the cement paste volume, the aggregate gradation, and the water-cementitious material ratio (*w/cm*). A more detailed analysis and report can be found in Bolduc et al. (2010).

Results

It is difficult to control and study one specific parameter of shotcrete. Thus, to evaluate the influence of targeted mixture characteristics, several concrete mixtures were cast. Table 1 presents the mixture composition and Table 2 presents their fresh and hardened properties. In the mixture identification, the first term is the sand/stone ratio, the second term is the cement content (kg/m), and the last term is the targeted air content. The *w/cm* was kept constant within each study.

Air Content

The first investigated parameter was the air content. A priori, one can think that the more air bubbles are present, the higher the BWA will be. This is not the case. Indeed, it is shown in the literature (Fagerlund 1993) that if a concrete sample is immersed, the air void system does not saturate under normal atmospheric pressure. To verify this statement, two mixtures were cast; one with and one without an air-entraining admixture (AEA). From Table 2, one can observe that when the air content goes from 3.6 to 11.5%, the BWA only increases from 0.8%, which is not significant. Obviously, extended conclusions cannot be drawn from this study because only two mixtures were produced. This experimentation, however, shows that small variations of air content within mixtures will not significantly affect the BWA.

Aggregate Gradation

The second parameter studied is the influence of the aggregate gradation. It is shown in the literature that the interfacial transition zone (ITZ) between aggregates and the cement paste is more porous than the bulk paste (Neville 2000).

Table 2: Test Results

Study	Mixtures	Fresh properties		Hardened properties	
		Slump, in. (mm)	Air content, %	Compressive strength, psi (MPa)	Boiled water absorption, %
Air content	65/35-500-3	1-3/8 (35)	3.6	7498 (51.7)	5.8
	65/35-500-13	2 (50)	11.5	4931 (34.0)	6.6
Aggregate gradation	50/50-450-5	8 (200)	3.0	6193 (42.7)	6.5
	65/35-450-5	6 (150)	5.0	6773 (46.7)	6.6
	80/20-450-5	7-3/8 (188)	7.0	6222 (42.9)	6.5
Paste volume	65/35-390-5	2-3/8 (60)	6.0	6135 (42.3)	5.7
	65/35-450-5	6 (150)	5.0	6773 (46.7)	6.6
	65/35-530-5	9-1/4 (235)	2.0	6527 (45.0)	7.6

Accordingly, the hypothesis is that a finer aggregate gradation leads to a greater specific surface of aggregates, and thus to a larger volume occupied by the ITZ. Moreover, experience in the laboratory showed that mortar always absorbs more water. To verify this assumption, three mixtures were cast with sand/stone ratios of 50/50, 65/35, and 80/20 (refer to Aggregate gradation row in Tables 1 and 2). The other parameters were kept constant. Figure 5 presents the graph of the BWA against the aggregate gradation fineness.

The graph clearly shows that the aggregate gradation does not have a significant influence on the BWA. It seems that the porous ITZ is not reached by the water during a BWA test. Therefore, another explanation is needed to explain the higher BWA values obtained with mortars.

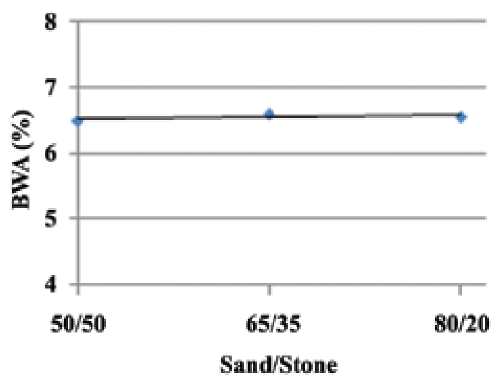


Fig. 5: Influence of the aggregate gradation

Paste Volume

In this study, the paste (or the cement paste) is considered as the product created by the combination of the water and the binder. It is often conveyed in the literature that shotcrete mixtures have a higher paste volume compared to conventional concrete. To evaluate the influence of the paste volume on concrete BWA, three mixtures were cast. The only variable parameter was the cement content: 24, 28, and 33 lb/ft^3 (390, 450, and 530 kg/m^3). The *w/cm* was kept constant, so the paste volumes were, respectively, 29.9%, 34.8%, and 42.3%. Figure 6 presents the graph of BWA as a function of the paste volume.

The graph shows that the correlation between these two parameters is practically linear; the higher the paste volume, the higher the BWA. The next step is obviously to produce shotcrete samples and verify how the aforementioned findings can apply to shotcrete.

w/cm ratio

The *w/cm* is the mass ratio between the amount of water in the mixture and the amount of cementitious materials (cement + supplementary cementitious materials). For conventional concrete, it is well known that this parameter affects the volume of capillary voids. For a given cementitious content, an increased amount of water will increase the capillary porosity, and consequently increase the BWA. To verify that this statement is still valid for shotcrete, 13 different mixtures were sprayed (both dry- and wet-mix) (Bolduc et al. 2010). The in-place *w/cm*, aggregate gradation, and paste volume were evaluated with the microwave method (Nagi and Whiting 1994). Figure 7 presents the BWA results as a function of the *w/cm*.

Taken globally, the results in Fig. 7 show a poor correlation between BWA and *w/cm*. The reader, however, can observe that when the three aggregate gradations used in the project are considered separately, the correlation greatly increases. The first gradation (ACI #1) is the one recommended by ACI Committee 506 (2005) for mortars. The second gradation (MTQ) is the granular distribution specified by the Ministry of Transportation of Quebec (Canada), somewhat located between gradations ACI #1 and ACI #2. The third gradation (ACI #2) is recommended by ACI Committee 506

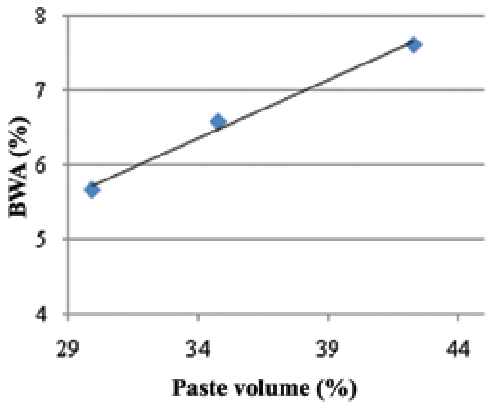


Fig. 6: Influence of the paste volume

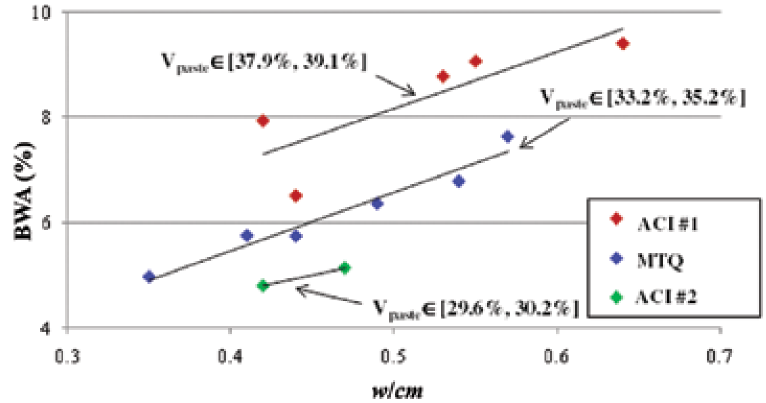


Fig. 7: BWA versus w/cm

(2005) for shotcrete containing coarse aggregates up to 3/8 in. (10 mm).

The graph shows that fine aggregate gradation (ACI #1) leads to higher BWA values (6.5 to 9.5%). The MTQ gradation brings BWA values that are between 5.0 and 7.5%, and the ACI #2 gradation leads to lower BWA values, which are around 5.0%. Because of the results presented in the Aggregate Gradation section, the aggregate gradation cannot be held responsible for the BWA variation between ACI #1, MTQ, and ACI #2 because it was shown that the fineness of the gradation does not influence the absorption.

To explain the difference between the three trend lines of Fig. 7, the paste volume must also be considered. Indeed, the in-place paste volumes from every mixture were compiled and an interesting conclusion was made. The ranges of in-place paste volumes are clearly distinct for every aggregate gradation. The ACI #1 gradation had the highest in-place paste volumes, ranging from 37.9 to 39.1%. The mixtures with MTQ gradation had in-place paste volumes from 33.2 to 35.2%, and the two mixtures with ACI #2 gradation led to paste volumes of 29.6 to 30.2%. In other words, a conclusion that can be drawn from these observations is that, in shotcrete, the initial aggregate gradation influences the in-place paste volume. The difference between the three trend lines is now easier to explain as it was shown in the Paste Volume section that the BWA is highly correlated with the cement paste volume.

More results and analyses were extracted from those 13 shotcrete mixtures. Details and further discussion can be found in Bolduc et al. (2010).

Discussion

Why is the BWA test specified?

Going back to the beginning of the paper, there is more than one answer to this question. Most would say that the BWA test is specified to assess the quality of the shotcrete placement. For example, it is commonly accepted in the industry that poorly compacted shotcrete, or material overdosed with set accelerator, will be identified with a BWA test. Some would also say that this test gives an idea of the shotcrete durability. Others suggest that it provides an indication of the overall shotcrete quality. Obviously, this is a topic that needs clarification.

The porosity measured in a BWA test mostly reflects the volume occupied by the capillary voids. Results presented in this paper show that mixtures with high paste volumes and high *w/cm* show an increased BWA, because a larger volume of voids accessible to water is present. In addition, other parameters are known to increase the volume of capillary voids, such as the use of porous aggregates and set accelerators. It is therefore clear that more than one parameter can affect the BWA of shotcrete, not only its placement. Is every parameter that increases BWA detrimental to the quality of shotcrete? The answer to this question is not necessarily. For example, Fig. 7 shows that three mixtures with a very good *w/cm* (0.45) can produce three very different values of BWA (5, 6, and 7.5%). These different BWA results are caused by the amount of paste present, not the quality of the paste itself.

Quality Indicators

In the 1980s, Morgan et al. (1987) compiled hundreds of BWA test from many shotcrete projects in North America. In their publication, the authors proposed quality indicators (Table 3) based on ASTM C642 results, which were used on various projects in Western Canada.

This classification system is very useful because it is simple and it can give, as its name reflects, a rapid appreciation of the overall shotcrete quality. Based on the results and discussion presented previously, however, it is clear that this indicator does not give a complete picture for all types of shotcrete mixtures. Moreover, based on the discussion surrounding the results found in Fig. 7, it seems that Table 3 should be adjusted to take into account the type of shotcrete produced (ACI #1 gradation as opposed to ACI #2 gradation).

Table 3: Morgan's Quality Indicators

Sprayed concrete quality	Permeable void volume, %	Boiled water absorption, %
Excellent	<14	<6
Good	14 to 17	6-8
Fair	17 to 19	8 to 9
Marginal	>19	>9

Conclusions

The main objective of this paper was to present new information regarding the BWA test in the shotcrete industry. A short review was presented in the first part of the article, where the three main transport mechanisms are briefly described: permeability, ionic diffusion, and capillary absorption. The second part of the article shares some results obtained from a recent study at Laval University. The main conclusions that can be drawn from this study are:

- The air content and the aggregate gradation do not directly influence shotcrete BWA;
- The paste volume and the *w/cm* both have a significant influence on shotcrete BWA; and
- Because of the placement process itself, the initial aggregate gradation affects the in-place paste volume, which in turn has an important effect on the absorption.

The authors consider that the BWA test is a quick and easy procedure to evaluate if the shotcrete microstructure was damaged or if the quality of the in-place material is affected. Owners and engineers responsible for the specifications, however, must clearly understand the different parameters that influence the BWA. High absorption does not necessarily mean poor quality shotcrete. Relevant specifications are crucial to guide contractors, but also to assure sound shotcrete applications.

References

ACI Committee 506, 2005, "Guide to Shotcrete (ACI 506R-05)," American Concrete Institute, Farmington Hills, MI, 40 pp.

ASTM C642, 2006, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete," ASTM International, West Conshohocken, PA, 3 pp.

ASTM C1202, 2005, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 6 pp.

ASTM C1604, 2005, "Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete," ASTM International, West Conshohocken, PA, 5 pp.

Bolduc, L.-S.; Jolin, M.; and Bissonnette, B., 2010, "Evaluating the Service Life of Shotcrete," *Proceedings of the Third International Conference on Engineering Developments in Shotcrete*, E. S. Bernard, ed., Queenstown, New Zealand. (accepted for publication)

Fagerlund, G., 1993, "The Long Time Water Absorption in the Air Pore Structure of Concrete," Lund Institute of Technology, Division of Building Materials.

Glasser, F. P.; Marchand, J.; and Samson, E., 2008, "Durability of Concrete—Degradation Phenomena Involving Detrimental Chemical Reaction," *Cement and Concrete Research*, V. 38, pp. 226-246.

Hall, C., 1994, "Barrier Performance on Concrete: A Review of Fluid Transport Theory," *Materials and Structures*, V. 27, pp. 291-306.

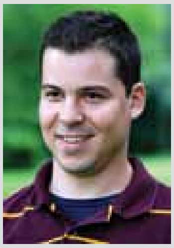
Morgan, D. R.; McAskill, N.; Neill, J.; and Duke, N. F., 1987, "Evaluation of Silica Fume Shotcrete," *Proceedings of the International Workshop on Condensed Silica Fume in Concrete*, Montreal, Canada, 34 pp.

Nagi, M., and Whiting, D., 1994 "Determination of Water Content of Fresh Concrete Using a Microwave Oven," *Cement, Concrete and Aggregates*, V. 16, pp. 125-131.

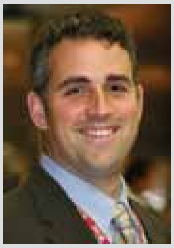
Neville, A. M., 2000, Propriété des bétons, ed., Eyrolles, Paris, 806 pp. (in French)

Nilsson, L.-O., 2003, "Durability Concept: Pore Structure and Transport Processes," *Advanced Concrete Technology*, V. 2, Chapter 8, J. Newman and B. S. Choo, eds., Elsevier.

Samson, E.; Marchand, J.; Snyder, K. A.; and Beaudoin, J. J., 2005, "Modeling Ion and Fluid Transport in Unsaturated Cement Systems in Isothermal Conditions," *Cement and Concrete Research*, V. 35, pp. 141-153.



***Louis-Samuel Bolduc** is a civil engineer with CEP Forensic Consulting Inc., a firm specializing in the field of forensic engineering and sciences. Over the last year, Bolduc has worked as a Research Engineer for the Research Center on Concrete Infrastructures in Quebec City. He has been involved in projects related to shotcrete compaction, service life prediction, and particle dynamics. He received his master's degree in civil engineering from Laval University, Quebec City, Canada. He is an associate member of ACI Committee 506, Shotcreting, and ACI Subcommittee 506A, Shotcrete—Evaluation.*



*ASA Director and ACI member **Marc Jolin** is an Assistant Professor in the Department of Civil Engineering at Laval University. He received his PhD from the University of British Columbia, Vancouver, BC, Canada, in 1999. An active member of CRIB, he is currently involved in projects on set accelerators, reinforcement encasement quality, new admixtures, and rheology of fresh shotcrete. Jolin is Secretary of ACI Committee 506, Shotcreting, and Chair of C660, Shotcrete Nozzleman Certification. His research interests include infrastructure durability and service life prediction.*