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Evaluating the service life of shotcrete

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ABSTRACT: Over the last decades, extensive research has been conducted to describe and predict the service life of reinforced concrete structures. Several models, some of which are extremely sophisticated, are available today to evaluate and predict the ingress of contaminants into concrete porosity. Unfortunately, the current state of knowledge regarding shotcrete durability, and especially service life prediction, is limited. Criteria have been proposed to relate the quality of in-place shotcrete to its Boiled Water Absorption (BWA). However, these criteria are mostly based on job site observations, and they require more fundamental scientific support. Moreover, the BWA test measures the volume of capillary voids present in concrete, while it is recognized that contaminant ingress, a major durability concern, is mostly caused by diffusion.

The main objective of this research program is to study the relevance of the BWA test to estimate shotcrete durability. Emphasis is placed on shotcrete transport properties. An experimental program was put forward, where 17 shotcrete mixtures (wet and dry-mix) were sprayed in a controlled laboratory environment. The STADIUM™ software is used to model chloride ingress in shotcrete. Results show that BWA alone is not a sufficient parameter to estimate shotcrete service life. It is poorly correlated with diffusion coefficients which are more important in terms of durability.

1 INTRODUCTION

Durability of concrete infrastructure is a growing concern throughout the world. Deterioration mechanisms include mainly freeze-thaw cycling, shrinkage cracking, sulphate attack, and alkali-aggregate reactions. However, in the case of reinforced concrete, the most expensive durability problem is unquestionably associated with chloride-induced corrosion. Steel corrosion results in cracking and spalling of the concrete cover, which leads to further damage caused by amplified ingress of aggressive agents. If the initiation of reinforcement corrosion is detected early, maintenance and repair operations are simple and the associated cost could be minimized. On the other hand, if reinforcement corrosion has reached the point where it has caused significant cracking and spalling of the concrete, repair is more complex and expensive. To avoid this situation, owners and managers often adopt a *service life prediction* approach to anticipate the maintenance operations on their structures to optimize their investment.

Over the last decades, intensive research was conducted to understand how contaminants penetrate into the porosity of cementitious materials and how steel corrosion is initiated within concrete. Numerous models are now available to help infrastructure managers planning rehabilitation operations on their facilities. Those models are based on a thorough scientific approach. They take into account the environmental conditions in the vicinity of the structure, and the chemical and physical properties of the material. All this research activity not only helped managers in the decision making process, but it also contributed to the understanding of the mechanisms that controls contaminant transport in concrete (or concrete transport properties).

On the other hand, in the shotcrete industry, specifiers often prescribe, in addition to compressive strength, a maximum value of boiled water absorption (BWA). This requirement, initially used to evaluate the quality of the shotcrete placement, has somehow evolved into what many specifiers see as a durability criterion. In the case of conventional cast concrete, this practice was discredited by some authors (De Schutter & Audenaert 2004; Audenaert et al. 2006) because BWA results (which indicate capillary absorption) are poorly correlated with other transport properties (such as ionic diffusion and water permeability). Faced with this situation, a project was undertaken in the Shotcrete Laboratory at Laval University, Quebec, Canada. The objectives behind this study are threefold: generate data on shotcrete transport properties; investigate the influence of mix design/shooting parameters on shotcrete transport properties; and offer guidelines for specifiers to help specify relevant material properties. The article ends with a discussion on the relevance of the BWA test as a durability criterion.

2 RESEARCH SIGNIFICANCE

When shotcrete is specified, for repair or for a new structure, engineers must generally comply with a minimum value of compressive strength (ASTM C1604) and a maximum allowable boiled water absorption (ASTM C642). Contrary to what is sometimes conveyed in the industry, there is no direct relationship between the compressive strength of shotcrete and its BWA. Figure 1 presents BWA results as a function of the compressive strength, obtained from several dry and wet shotcrete mixtures sprayed at Laval University in different projects over the years.

Although a trend is observable, Figure 1 shows that a poor correlation exists between the BWA and the compressive strength. One can observe that between 25 and 45 MPa, absorption values range from 5.3% to 9.1%, which represents a large spread (see next paragraph). It is obvious that the parameters influencing shotcrete BWA are not totally understood and appropriately taken into account. Therefore, in order to comply with the absorption criterion specified, mixture designers must often make adjustments based on limited knowledge, which may result in an iterative and expensive process.

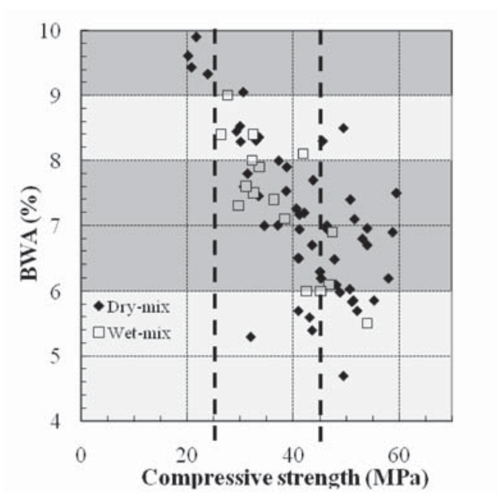

Figure 1. Compressive strength vs BWA.

Table 1. Morgan's Quality Indicators (Morgan et al. 1987).

Sprayed concrete quality	Permeable void volume (%)	Boiled absorption (%)
Excellent	<14	<6
Good	14–17	6–8
Fair	17–19	8–9
Marginal	>19	>9

The shaded regions presented in Figure 1 reflect the most current state of knowledge concerning shotcrete absorption and durability issues. Indeed, in the 1980s, Morgan et al (1987) proposed qualitative criteria to relate the quality of in-place shotcrete to its boiled water absorption (Table 1).

This classification system is widely used because it is a simple test that relates to the overall quality of the material. Even though these criteria are simple and practical, they do not explain the relationship between the absorption of shotcrete, and its resistance to the penetration of aggressive agents.

3 RESEARCH PROGRAM

A research program was put together to study the transport properties of shotcrete. The project was divided in two parts. In the first part, the influence of mixture design and shooting parameters was investigated. In the second part, the relevance of the BWA test as a durability criterion is discussed.

Twelve shotcrete mixtures (dry and wet-mix) were designed for this project. Mixture variables include the binder composition, the aggregate gradation, and the presence of admixtures and fibres. Three aggregate gradations were used in this project: ACI#1 (mortar), ACI#2 (concrete), and a third identified as MTQ (since it is specified by the Ministry of Transportation of Quebec) which falls between ACI#1 and ACI#2 (see Figure 2).

For the dry process, since the nozzleman adjusts the amount of water added to the mix, the W/Cm ratio is not known. Therefore, as pointed out by Armelin (1997) and Jolin (1999), the material

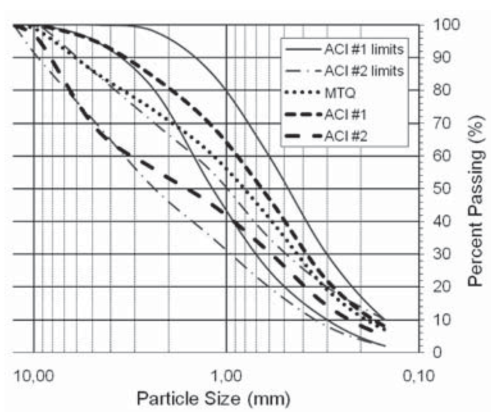

Figure 2. Particle size distributions (limits per ACI 506 (2005)).

consistency is the targeted parameter in dry-mix shotcrete. In this project, several mixtures were sprayed at two consistencies (low and high water content) to represent what is encountered on job sites. All mixtures were sprayed within a practical range of consistencies. The effect of pre-dampening was also studied. Table 2 presents the chemical composition of the cementitious materials used in this project. Tables 3 and 4 present both the *initial* and *in-place* composition of the different mixtures produced in this study. The *in-place* composition was determined following the procedure proposed by Nagi & Whitting (1994). The mixture identification follows this code: the first letter identifies

Table 2. Chemical composition of cementitious materials (%).

Element	Cement 1 *Type MS* (%)	Cement 2 *Type GU* (%)	Silica Fume (%)	Fly Ash *Type C* (%)
CaO	63.2	62.5	1.0	27.7
SiO_2	20.3	19.7	96.3	32.5
Al_2O_3	4.8	4.6	0.2	19.2
SO_3	3.4	3.4	0.4	2.8
Fe_2O_3	3.2	3.1	0.1	6.0

Table 3. Initial mix composition.

Mix	Description	Process	Aggregate gradation
CD1	Type GU, 10% silica fume	Dry	MTQ
CD2	Type GU, 10% silica fume, predampened	Dry	MTQ
CD3	Type GU, 10% silica fume Synthetic fibres, powdered AEA	Dry	MTQ
CD4	Type GU, no SCM's	Dry	MTQ
CD5	Type GU, 25% fly ash	Dry	MTQ
MD1	Type GU, 10% silica fume	Dry	ACI#1
MD2	Type GU, 12% silica fume	Dry	ACI#1
MD3	Type GU, 15% silica fume	Dry	ACI#1
MD4	Type GU, 12% silica fume Synthetic fibres, powdered AEA	Dry	ACI#1
CW1	Type MS, 8% silica fume Naphtalene HRWRA 4 ml/kg Cm	Wet	ACI#2
CW2	Type MS, 8% silica fume Naphtalene HRWRA 12 ml/kg Cm	Wet	ACI#2
MW1	Type GU, 12% silica fume Naphtalene HRWRA 10 ml/kg Cm	Wet	ACI#1

Table 4. In-place mix composition.

Mix	W/Cm	Binder content (kg/m^3)	Aggregate content (kg/m^3)	Paste volume (%)
CD1	0,35	511	1604	34,7
	0,54	385	1648	33,4
CD2	0,49	415	1633	34,0
	0,57	392	1608	35,2
CD3	0,37	505	1662	35,3
	0,51	423	1663	35,5
CD4	0,44	437	1703	33,2
CD5	0,41	451	1724	33,4
MD1	0,42	522	1594	39,1
	0,64	395	1596	38,3
MD2	0,44	508	1527	39,1
	0,53	447	1525	38,4
MD3*			N/A	
MD4	0,47	460	1603	36,8
CW1	0,42	405	1744	30,2
CW2	0,47	372	1809	29,6
MW1	0,55	433	1493	37,9

*Results unavailable because of equipment breakdown during the testing operation.

whether the mixture is a concrete ("C") or a mortar ("M"), and the second letter classifies the process ("D" for dry-mix and "W" for wet-mix). Results for the mixture MD3 are unavailable because of an equipment breakdown during the testing operation. One should observe that out of the 12 initial mixtures (Table 3), some were sprayed at two different consistencies (Table 4). Thus, 17 different *in-place* mixtures were produced in this study.

Shotcreting activities took place in Laval University's shotcrete laboratory using full-size equipment in a controlled environment. The dry-mix gun used in this project was a rotating barrel ALIVA 246, with a 38 mm (1.5 in) interior diameter hose. The water ring is located 3.0 m (10 ft) upstream from the nozzle. For wet-mix shotcrete, the fresh concrete was pumped using an Allentown Powercreter 10, combined with a 50 mm (2 in.) interior diameter hose, and shot with a ACME nozzle (Figures 3 and 4).

The experimental investigation included the evaluation of the compressive strength (ASTM C1604), the BWA and volume of permeable voids (ASTM C642), and the chloride penetration using the Rapid Chloride Penetration Test (ASTM C1202) and chloride migration test (ASTM C1202 modified). The procedure and theoretical background related to the migration test can be found in the paper by Samson et al (2003). This last experiment is necessary to determine diffusion

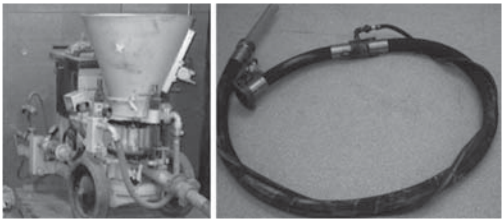

Figure 3. Dry-mix gun and nozzle.

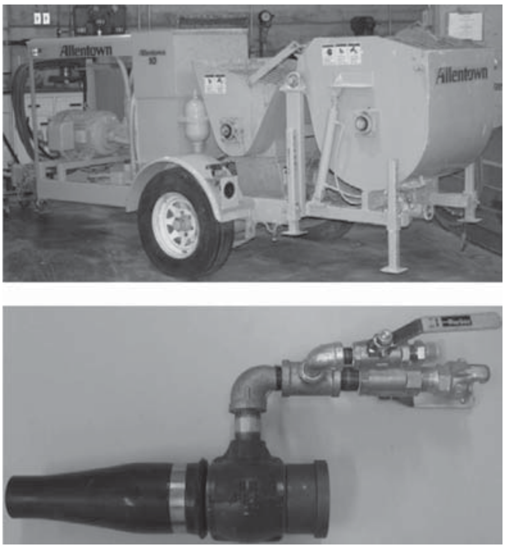

Figure 4. Wet-mix pump and nozzle.

coefficients, a requirement of the service life prediction software STADIUM™. The diffusion coefficient is a critical parameter characterizing the displacement of ionic species into the porosity of porous materials such as concrete.

4 RESULTS

Test results from this project are presented in Table 5 & 6. For clarity purposes, only diffusion coefficients for hydroxyl ions (OH^-) are shown. This choice is arbitrary but it allows for direct comparisons. Moreover, the diffusion coefficients of every ionic species are all related by the same proportional constant, the material tortuosity τ (Samson et al. 2003). This parameter characterizes the intricacy of the path that ions must travel in cementitious materials.

The following sections analyse the results from these tables to better understand what affects BWA in shotcrete.

Table 5. Test results.

Mix	Consistency	UCS* 28d (MPa)	RCPT** (C)	OH^- Diffusion coefficient ($\times 10^{-11}$ m²/s)
CD1	Dry	68,3	431	1,64
	Wet	55,4	922	3,21
CD2	Dry	59,1	830	3,54
	Wet	50,0	1300	4,66
CD3	Dry	52,2	435	1,45
	Wet	39,5	1418	3,48
CD4	In between	48,2	5471	13,60
CD5	In between	53,8	2725	3,76
MD1	Dry	52,5	1119	2,54
	Wet	42,5	2043	5,05
MD2	Dry	75,3	234	0,88
	Wet	54,8	1036	3,51
MD3	In between	53,1	724	2,63
MD4	Wet	51,7	666	1,56
CW1	–	61,4	689	2,69
CW2	–	53,6	713	2,13
MW1	–	53,4	862	2,95

* UCS: Unconfined Compressive Strength.
** RCPT: Rapid Chloride Penetration Test.

Table 6. Test results.

Mix	Consistency	BWA (%)	Volume of permeable Voids (%)	Bulk density (dry) (T/m³)
CD1	Dry	5,0	11,4	2,29
	Wet	6,8	15,0	2,20
CD2	Dry	6,4	14,2	2,23
	Wet	7,7	16,6	2,17
CD3	Dry	6,0	13,3	2,19
	Wet	7,5	15,9	2,12
CD4	Dry	5,7	13,0	2,26
CD5	Dry	5,7	13,0	2,27
MD1	Dry	7,9	17,1	2,15
	Wet	9,4	19,6	2,08
MD2	Dry	6,5	14,4	2,21
	Wet	8,8	18,6	2,12
MD3	Dry	7,6	16,3	2,15
MD4	Wet	7,2	15,5	2,15
CW1	–	4,8	11,2	2,32
CW2	–	5,1	11,8	2,29
MW1	–	9,1	19,2	2,11

4.1 *Boiled water absorption*

Previous results from this project (Bolduc et al. 2009) showed that the paste volume has a considerable influence on cast concrete BWA (Figure 5, top). Results also showed that the aggregate grada-

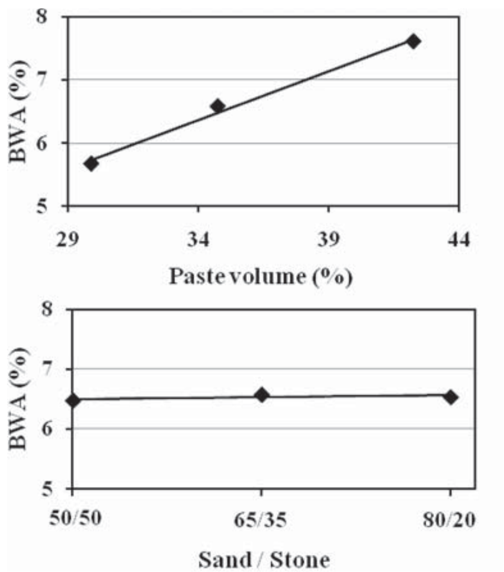

Figure 5. Influence of paste volume (top) and aggregate gradation (bottom) on BWA.

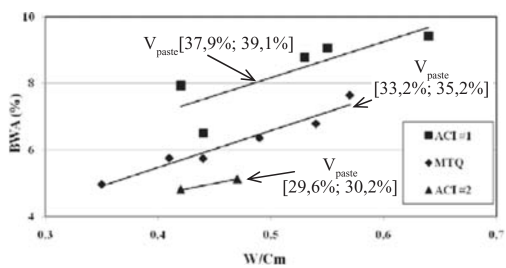

Figure 6. BWA vs W/Cm ratio.

tion alone does not have a significant influence on cast concrete BWA (Figure 5, bottom).

One of the main parameters known to affect the absorption of concrete is the W/Cm ratio. During the hydration process, the relative proportions of water and cementitious materials have a great influence on the capillary porosity. Figure 6 illustrates the relationship between the BWA and W/Cm ratio, for the mixtures sprayed in this project. Results from both dry and wet-mix shotcrete are presented in this graph. However, in this section, results from 13 mixtures are analysed. Indeed, mixtures CD3 and MD4 are not shown on this graph because they are commercial mixtures that contain powdered air entraining admixture and polypropylene fibres, for which exact in-place composition could not be determined. Mixture MD3 is not on the graph either: the W/Cm ratio has not been evaluated because of equipment failure.

At first glance, the correlation between these two parameters is quite poor. However, when the three aggregate gradations used in this project are considered separately (ACI#1, MTQ, and ACI#2), the correlation is increased, as shown in Figure 6. In other words, the graph shows that mortar (ACI#1) leads to higher BWA in comparison with the MTQ gradation, which have a higher BWA compared with ACI#2. One should be careful and keep in mind the results from Figure 5, and not conclude that finer aggregate gradations lead to higher BWA. It was shown in Figure 5 (bottom) that the fineness of the particle size distribution does not have an impact on concrete BWA. Obviously, another step is needed to explain the difference between the three lines in Figure 6.

The rational for these observations is as follows. Figure 5 (top) shows that BWA is directly related to the paste volume. The analysis of results for the shotcrete mixtures is interesting because the range of paste volumes is clearly distinct for the three aggregate gradations (as shown in Figure 6). The mortar (ACI#1) led to paste volumes between 37.9% and 39.1%, MTQ gradation led to values between 33.2% and 35.2%, and ACI#2 brought paste volumes between 29.6% and 30.2% (paste contents expressed here exclude the volume occupied by air bubbles). The conclusion is that it is the *initial aggregate gradation* that has an impact on the in-place paste volume, which has, in turn, an effect on shotcrete BWA. Therefore, two parameters are needed to explain BWA: the in-place paste volume and the paste quality (as expressed by the W/Cm ratio).

4.2 *Chloride ingress*

The ingress of chloride ions is the root cause related to most reinforced concrete deterioration (Neville 2000). Since the traditional method to evaluate chloride ion penetration (ASTM C1543/ ASTM C1152) is time consuming (ie. ponding for 3 months minimum), the research community has designed over the years accelerated procedures to assess the penetrability of cementitious materials (ASTM C1202). The Rapid Chloride Penetration Test (or RCPT) is a measure of the electrical conductance of concrete that gives an indication of its ability to resist chloride ion penetration. Table 7, presented in ASTM C1202, relates the charge that passed through the sample in 6 hours to the chloride ion penetrability. The higher values denote a higher penetrability, and therefore an expected reduced durability.

It is well known in the literature that chloride ion penetrability is influenced by the W/Cm ratio. Figure 7 presents the relationship between RCPT

Table 7. ASTM C1202 classification system.

Charge passed (C)	Chloride ion penetrability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
<100	Negligible

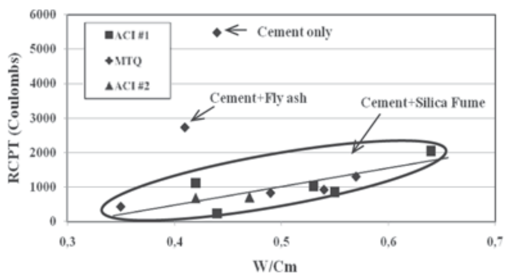

Figure 7. RCPT vs W/Cm ratio.

results and W/Cm ratios for the shotcrete mixtures sprayed in this project.

Two conclusions can be drawn from this graph. The first one is that contrary to the BWA test, there is no distinction between the three aggregate gradations/paste contents. The binder content is obviously more significant. The second one is that RCPT and W/Cm ratios are poorly correlated. However, observation of the mixture designs shows that the two points higher than 2500 coulombs do not contain silica fume. Excluding these two points, the correlation is much better. This graph reveals the strong influence of silica fume on the electrical conductivity of cementitious materials.

In the presence of silica fume, the analysis of RCPT results can be misleading. As pointed out by Torii & Kawamura (1994), the presence of silica fume leads to a decrease in the hydroxyl ion concentration in the pore solution, which reduces the overall electrical conductivity of the material. Therefore, RCPT results underestimate the real chloride ion penetrability when silica fume is used in the mixture. This is the reason why the modern approach is to estimate diffusion coefficients to predict the chloride ingress. Just as for the BWA test, the RCPT is not adequate, by itself, to properly describe the penetrability of shotcrete.

5 DISCUSSION

This section presents a discussion on the relevance of using the BWA test as a durability criterion. Here, the term *durability criterion* only refers to the ingress of contaminants into the shotcrete porosity and excludes other deterioration mechanisms. The main objective of this section is to determine if the BWA is pertinent to estimate chloride penetration. The first step taken here is to observe the correlation between RCPT and BWA (Figure 8).

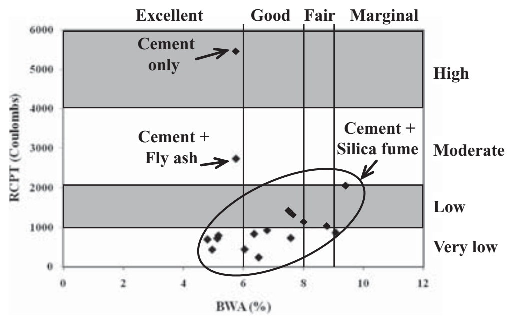

Figure 8. Relationship between RCPT and BWA.

The classification system proposed by Morgan (1987), where the BWA is related to the overall shotcrete quality, is shown on the graph. The regions identified on the right-hand side indicate the chloride penetrability, as presented in the ASTM C1202 standard. Again, the correlation between these parameters is low. This can be explained by the fact that both properties are not similarly affected by changes in the porosity. As pointed out by Sato & Agopyan (2001), there is a difference between the total volume of pores and pore dimension. While the BWA is more affected by the size of the *accessible* pores in the concrete surface, the RCPT test will be most affected by the connectivity of the pores, and a lot less by their size. In terms of chloride ion transport, both size and connectivity of the porous system in the concrete are considered to have a significant influence.

Two important observations can be made from Figure 8. First, if only the mixtures with *Very low* penetrability are considered (lower strip on the graph), the BWA classification ranges from *Marginal* to *Excellent*. On the other hand, if only the mixtures classified as *Excellent* are analyzed, the chloride penetrability ranges from *Very low* to *High* as soon as the binder type is changed. Even if only two mixtures were tested without silica fume, the authors believe the results show the obvious influence of the binder composition. These observations are very important because, depending on the environmental condition surrounding the shotcrete application, two situations can occur:

- High-quality shotcrete (*Very low* penetrability) can be rejected because it does not meet the absorption criterion specified, or
- Poor quality shotcrete (*High* penetrability) might be accepted because it presents an adequately low BWA value.

It is believed that both cases present a poor assessment of the real material quality/durability. Owners and specifiers should consider a larger range of parameters when selecting material specifications such as the environmental exposure, the type of structure considered (above or below ground, etc.) and particularly previous performance records for a given mixture design.

6 CONCLUSION

Based on an extended experimental research program where 17 shotcrete mixtures (wet- and dry-mix) were sprayed and characterized, the following conclusions can be drawn.

The *initial* aggregate gradation has a direct impact on the *in-place paste volume*, which is, in turn, a parameter that affects significantly the shotcrete boiled water absorption. This observation is valid for both wet- and dry-process shotcrete.

Rapid chloride penetration test results are greatly influenced by the presence of silica fume, and to a lesser extent, by the presence of fly ash. Supplementary cementing materials do not seem to affect significantly the shotcrete boiled water absorption.

The boiled water absorption test alone is not a reliable parameter for estimating shotcrete durability, such as chloride-induced corrosion. This test is poorly correlated with RCPT and diffusion coefficients, which are more relevant in terms of chloride transport.

A more thorough approach is needed to understand all the implications of the shotcrete placement process on the durability of the resulting in-place concrete. The effect of parameters such as set accelerators, material velocity or the presence of compaction voids are not yet fully understood in terms of resulting in-place composition and significance to the long-term durability of the shotcrete. More effort is needed to better understand the pneumatic placement process itself and also to actually model and predict the long-term behavior of shotcrete exposed to harsh environments.

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