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Shotcrete for Underground Support XII | Proceedings

2015

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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. Unfortunately, the current state of knowledge regarding sprayed concrete durability, and especially service life prediction, is limited. Although the test methods used change from one country or jurisdiction to the other, criteria have been proposed to relate the quality of in-place sprayed concrete to its boiled water absorption, its susceptibility to chloride ions penetration or its permeability. Unfortunately, the available criteria are mostly based on empirical job site observations and have many drawbacks, and they require more fundamental scientific development to be reliably used as durability indicators, if indeed applicable.
Following a first project that concentrated on North American shotcrete mix designs, this second paper concentrates on wet-mix shotcrete mixtures incorporating a set-accelerating admixture at various dosages. The main objective of the research program reported is first to study the relevance of boiled water absorption and permeability tests to estimate sprayed concrete durability. The results guide us to a more fundamental aspect of the study with emphasis on sprayed concrete mass transfer properties. The experimental program included more than 11 distinct shotcrete mixtures sprayed in a fully controlled laboratory environment with different addition rates of set-accelerating admixtures. The results are quite interesting and should draw the industry's attention. It demonstrates the highly positive effect of high-speed pneumatic consolidation of sprayed concrete on its durability. The results also show the importance of limiting the amount of set-accelerating admixture added to shotcrete in order to maintain long-term compressive strength and durability. In this context, the paper concludes with a discussion on a suggested approach for the evaluation of shotcrete during construction, and proposes means to adapt the project specifications accordingly.

INTRODUCTION

Shotcrete is generally defined as a pneumatic method for placing concrete. The main difference between shotcrete and conventional concrete resides in their placement and consolidation methods. Conventional concrete is placed by gravity and usually consolidated using vibration, whereas sprayed concrete is applied under pressure and consolidated through the high velocity impact of the incoming spray particles. This unique pneumatic placement method allows for vertical and overhead applications on irregular surfaces with little or no formwork.

Sprayed concrete can be applied following two different processes: the *dry-mix* process and the *wet-mix* process. The latter uses fully mixed concrete that is transported to the nozzle using a concrete pump; compressed air is added at the nozzle to provide sufficient velocity for placement. This method is well adapted for large volume production (as commonly found in ground support applications). In most cases for overhead wet-mix process applications, a set-accelerating admixture is added at the nozzle to promote rapid initial stiffening and/or early strength development and thus prevent fall-outs. In all cases, an experienced and trained nozzleman along with the appropriate equipment are paramount for a quality application, low rebound, homogeneous shotcrete and good bond to the substrate.

Wet-mix sprayed concrete is extremely popular and largely used as part of the ground support system in tunnels and other types of underground openings. The absence of formwork, the good bond characteristics and the possibilities to reach high early compressive strength make it a perfect tool in modern excavation work. Given the situation where more and more wet-mix shotcrete is being used as final lining (as opposed to temporary support followed by segmented precast concrete elements), it is of interest to explore the long-term performance of such shotcretes, particularly in the presence of set accelerators, which are known to have a negative impact on the development of long-term mechanical strength (Bessette 2001).

WET-MIX SPRAYED CONCRETE

The challenges encountered in wet-mix shotcrete placement are to make sure that the sprayed material will bond well to the surface, produce minimum rebound and have the in-place material setting quickly enough to eliminate dangerous fallouts and promote high early strength. For this last requirement, a liquid set-accelerating admixture, adjusted for dosage through a separate pump, is often added at the nozzle.

This paper attempts to bring some understanding and information on how the addition of a set-accelerating admixture, sometimes at very different dosages than expected, will affect the short and long-term behaviour of the in-place material. Indeed, in order to meet not only the usual strength requirements, but also the service life expectations, one needs to take a step back and analyse the complete process, from mixture design to placement, and from initial strength development to maintenance and repair considerations. It is a fact very few will argue with: in the shotcrete industry nowadays, sustainability requirements mean bringing service life and durability requirements to the front row.

SERVICE LIFE

Service life prediction is quite a wide subject and can be quite complex. It should first be said that the discussion presented here concentrates on the concrete material as opposed to the structure itself. That being said, it allows for a simplified definition of service life as the response, or performance, of the concrete in given exposure conditions. This performance, in turn, needs to be specified and related to acceptance criteria that will vary in accordance with the type of structure considered, the exposure conditions and the level of damage tolerated before some intervention. For example, in a given environment, the critical chloride ion concentration for at at reinforcement depth could be selected as a criterion, while in some other environments, the depth of carbonation would be more appropriate.

This paper could go in depth, describing at length test procedures and analyze how the results relate to sprayed concrete durability or how mixture design affects those tests results. Instead, it appears more profitable to concentrate on the material properties themselves, to really emphasize the importance of the role played by cement paste and understand what it means for the durability of concrete.

Shotcrete, as ordinary concrete, is a porous material that comprises a solid matrix, and a network of more or less interconnected pores. The shotcrete porosity covers a wide range of pore size diameters that vary from a few nanometres to a several millimetres in some cases (Neville 2008). The pore structure is therefore very complex, and the mechanisms controlling the movement of water (and potential contaminants) within the pores have received a lot of interest from researchers over the last decades. Why? Because most durability issues are related to these exchange mechanisms (generally referred to as *transport mechanisms* or *transport properties*). In order to make concrete durable, it is crucial to understand the material transport mechanisms, which can be roughly divided into three categories:

- **Permeability**: *Movement of fluid (liquid or gas) resulting from a pressure gradient* (illustrated in Figure 1).

The term *permeability* is widely used when it comes to the ingress of fluid in concrete. However, strictly speaking, a pressure gradient must be involved in order to have *permeability*-related transport.

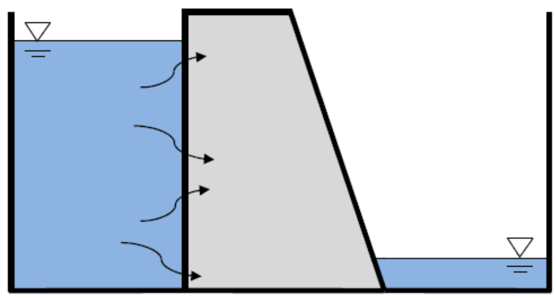

Figure 1 – Permeability

- **Ionic Diffusion**: *Movement of ionic species within concrete resulting from a concentration gradient* (illustrated in Figure 2).

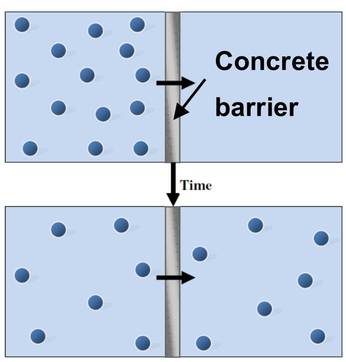

Figure 2 – Ionic Diffusion

Thermodynamic principles dictate that equilibrium must be re-established when a system is characterized by uneven conditions (temperature, moisture content, ionic concentration, etc.). For instance, when concrete is immersed in highly concentrated salt water, the chloride concentration in the concrete pore solution is lower than that of the salt solution. Consequently, the ionic species present in the salt water will migrate into the concrete porosity, through the pore solution, until equilibrium is reached. This mechanism also includes water vapour diffusion in the case of partially saturated media.

- **Capillary absorption**: *Suction of water resulting from the surface tension exerted in the capillary porosity* (illustrated in Figure 3).

In concrete, capillary pores act like capillary tubes. When a capillary tube is immersed in water, it is well known that the liquid rises into the tube. Accordingly, when a concrete sample is immersed, the capillary void system slowly fills with water. In North America, the usual test procedure to evaluate the capillary absorption of concrete is ASTM C642 (also known as the *boiled water absorption,* BWA, test). It is, in fact, a measurement of the porosity accessible to water.

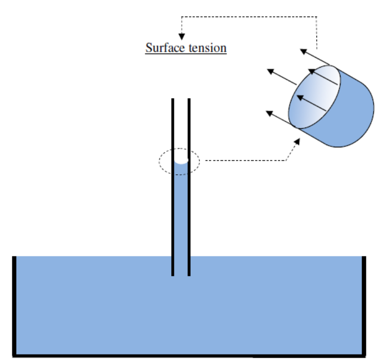

Figure 3 – Capillary absorption

The purpose here is to provide an overview of the main transport properties controlling durability and service life of concrete structures. Indeed, the complete understanding of these mechanisms is way beyond the scope of this text. The reader can refer to various in-depth publications to find more information (Hall 1994, Nilsson 2003, Samson et al. 2005, Glasser et al. 2008)

The next task is to find a way to *specify* what is expected from the concrete used in the design. Two approaches are available: the use of *performance-based* specifications (ex.: *the concrete member shall last 50 years without corrosion of the reinforcement*) or the use of classic *prescriptive* specifications (ex.: *the concrete shall have a compressive strength of 30 MPa at 28 days*). The reality is that many specifications nowadays incorporate some of both, with performance criteria to ensure long-term serviceability and durability of the structure, together with usual concrete properties specified to facilitate day-to-day quality control operations. Although the latter is relatively simple and well established, it fails to address adequately the service life considerations. Then again, the challenge of identifying, *selecting* and *evaluating* performance criteria cannot be overstated. This selection must take into account factors such as the exposure conditions, the expected maintenance (including all types of interventions, from preventive actions to rehabilitation) over the lifespan of the structure, the importance of the structure, the anticipated risks and the economic constraints.

SERVICE LIFE AND SPRAYED CONCRETE

Most of the damage found in concrete and sprayed concrete can be attributed to physical degradation of the hardened cement paste (e.g. freeze-thaw damage), the ingress of aggressive phases (e.g.: chloride ions with steel corrosion) or the formation of deleterious expansive products resulting from a reaction between the aggregates and some cement paste compounds (e.g. AAR). Unfortunately, a combination of these phenomena is most often encountered, with the hardened cement paste degradation facilitating for instance further ingress of water and other aggressive phases, and vice-versa (e.g.: sulphate attack), thus resulting in further amplified and accelerated damage.

Given the importance of hardened cement paste quality on the durability of concrete, it is interesting to refer here to the findings of Bolduc in his research project (Jolin et al. 2011). In their work, two important features were revealed with regard to sprayed concrete. First, for a given water/binder ratio, the measured porosity (or water absorption) of the sprayed concrete is directly related to the *volume* of paste in the mixture (Figure 4). Secondly, it was shown that the *in-place volume of cement paste* is closely related to the mixture design (especially the aggregate gradation) and the method of placement (Figure 5). These observations support what many nozzlemen and practitioners already know intuitively: the mixture design and method of placement control, to various degrees, the placement kinetics, i.e. rebound and consolidation, leading to *given in-place concrete composition* and properties. It also explains why a single concrete material property (in this case the porosity or water absorption) may not be sufficient to completely represent the “quality” of sprayed concrete; indeed, it can be seen in Figure 5 that a given value of BWA recorded for shotcrete may actually correspond to a wide range of paste’s water/binder ratio values.

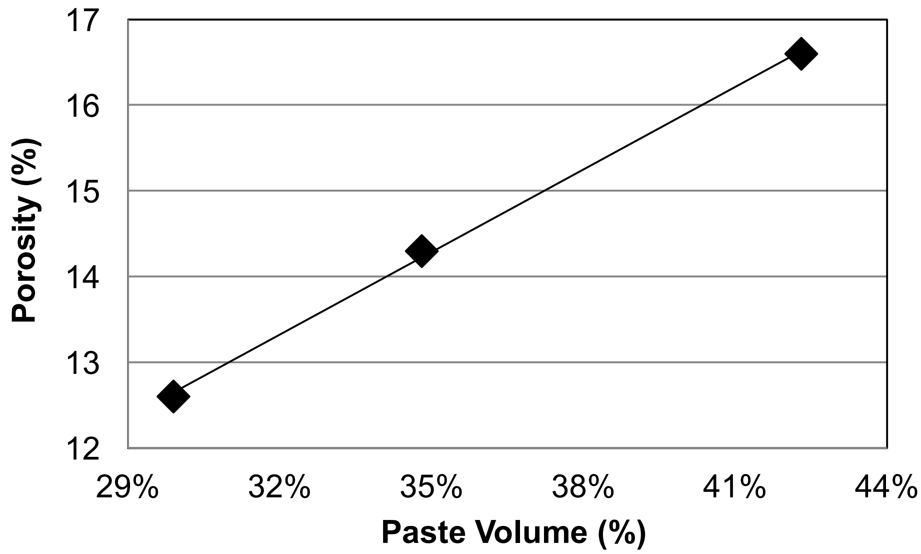

Figure 4. Influence of paste volume on porosity (Jolin et al. 2011)

Bolduc in his research project (Jolin et al. 2011) showed that the pneumatic placement method plays an important role on the quality of the in-place concrete and normally improves the durability of the in-place concrete.

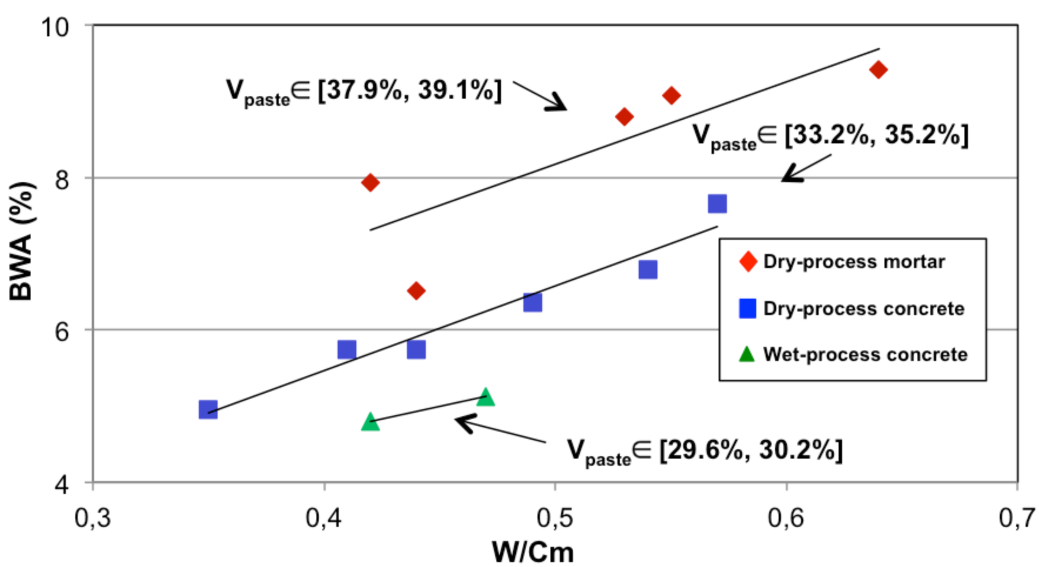

Figure 5. Relationship between the water to cementitious materials ratio of the mixture and the boiled water absorption for both types of shotcrete processes (Jolin et al. 2011)

EXPERIMENTAL PROGRAM

All shotcretes were produced in the *CRIB Shotcrete Laboratory* at Laval University in Quebec City, Canada. As described hereafter, this unique facility allows to produce wet-process shotcrete year-round, under well-controlled conditions, using full-size industrial equipment.

EQUIPMENT AND MIXTURE DESIGN

The wet-mix shotcrete mixtures were produced with a Allentown/Putzmeister *Powercreter 10* pump hooked up to 15.2 m long pipe having a 50 mm interior diameter (Figure 6). It is equipped with an integrated mixer allowing batch sizes ranging from 80 to 120 liters and two high-pressure hydraulic pistons. This equipment is similar to what is usually used in the industry with the exception of the electric motor that replaces the usual factory diesel motor.

Figure 6. Allentown/Putzmeister *Powercreter 10* wet-mix process shotcrete pump

For the shotcreting operations, the end of the hose is mounted with a 50 mm nozzle, as shown in Figure 7 (a). With this nozzle, compressed air is introduced in 8 different locations around the circumference of the shotcrete stream. This nozzle also allows the incorporation of the set accelerator directly in the air flow, which allows for a uniform distribution of the admixture. The incorporation of the set accelerator is performed with an automated *Allentown A10* admixture pump (Figure 7 (b)).

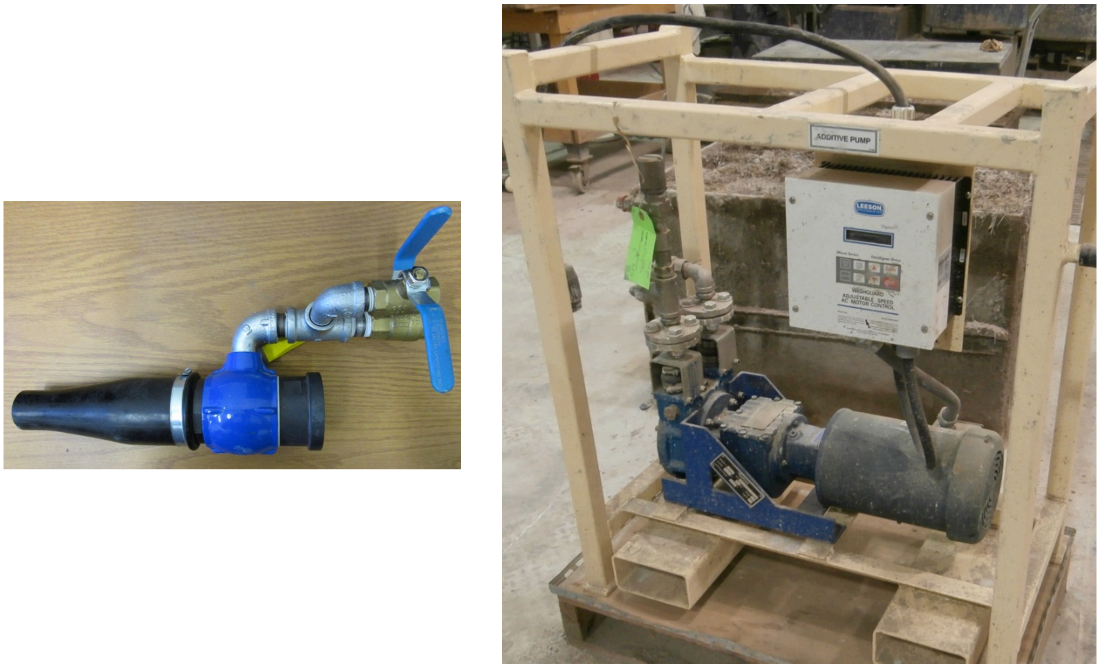

Figure 7. (a) Wet-mix shotcrete nozzle and (b) admixture pump.

All shotcrete mixtures produced in this project used two base mixtures, one containing only ordinary Portland cement (referred to as OPC) and one containing silica fume (referred to as SF). Each mixture is identified with respect to its base mixture (OPC or SF) and the percentage of set-accelerating admixture i.e. mixture OPC – 6 contains only Portland cement as binder and has 6% of set accelerator (by mass of binder). Table 1 presents actual composition of both mixtures. The set-accelerator is a alkali-free aluminum sulfate-based admixture available worldwide.

Table 1 Wet-mix constituents

Constituents	*OPC*	*SF*
Portland Cement [kg/m^3]	440.6	393.8
Silica Fume [kg/m^3]	---	34.4
Sand [kg/m^3]	1006.8	1014.7
Gravel 2.5-10 mm [kg/m^3]	703.2	708.8
Water [kg/m^3]	222.1	216.6
Set accelerator [kg/m^3]		
0	---	---
6	24.7	24.0
11	48.5	50.5
16	68.3	71.5

TESTING PROGRAM

The goal of the testing program is to evaluate the effect of set accelerator in wet-mix shotcrete on service life. To do so, durability related test were conducted, mainly porosity (ASTM C642 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete)(ASTM 2013) and chloride penetration tests (ASTM C1202 Standard Test Method for Rapid Chloride Penetration Test and ASTM C1543 Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding) (ASTM 2010, ASTM 2012a). Compressive strength (End Beam Test and ASTM C1604 Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete)(Heere and Morgan 2002, ASTM 2012b) was measured to evaluate the effect of the set accelerator on early and long term mechanical properties.

Boiled water absorption and volume of permeable voids

The standard test method ASTM C642 - *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete* covers the determination of specific gravity, absorption, and volume of voids in hardened concrete. The boiled water absorption and volume of permeable voids are used in the industry as an indicator of the shotcrete quality. Table 2 presents guidelines proposed in the literature, and that are generally accepted in the industry (Morgan et al. 1987) and Table 3 shows the actual results yielded in the present project.

Table 2: Suggested indicators of shotcrete quality (Morgan et al. 1987)

Shotcrete Quality Indicator	*Boiled absorption (%)*	*Volume of permeable voids (%)*
Excellent	<6	< 14
Good	6 – 8	14 – 17
Fair	8 – 9	17 – 19
Marginal	> 9	> 19

Table 3: Absorption and volume of permeable voids

Mixtures	*Boiled absorption (%)*	*Volume of permeable voids (%)*	*Rating per Table 3*
OPC – 0	6.74	15.0	*Good*
OPC – 6	6.53	14.5	*Good*
OPC – 11	6.56	14.6	*Good*
OPC – 16	8.11	17.5	*Fair*
SF – 0	6.45	14.4	*Good*
SF – 6	7.50	16.4	*Good*
SF – 11	7.57	16.6	*Good*
SF – 16	8.53	18.4	*Fair*

Chloride Penetration Test

Two test procedures were used to evaluate chloride penetration. The first one is ASTM C1202 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (ASTM 2012a)* commonly referred to in North America as the *RCPT* test. Table 4 presents chloride ion penetrability index (as found in ASTM C1202) and Table 5 presents the results recorded for each mixture.

Table 4. Chloride ion penetrability index (ASTM C1202)

Charge Passed (coulombs)	*Chloride Ion Penetrability*
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

Table 5. ASTM C1202 Results

Mixtures	*Charge Passed (coulombs)*	*Chloride Ion Penetrability*
OPC – 0	3851	Moderate
OPC – 6	5980	High
OPC – 11	5230	High
OPC – 16	7655	High
SF – 0	685	Very Low
SF – 6	922	Very Low
SF – 11	1252	Low
SF – 16	1050	Low

The second test evaluating chloride penetration is the ASTM C1543 *Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding (ASTM 2010)*. In this particular test, a reservoir is built on top of the specimen and it is filled with a 3% NaCl solution. Table 6 presents the results for the recorded for the different mixtures after 3 months of testing.

Table 6. ASTM C1543 Results after 3 months of ponding

	Depth of layers [mm]			
Mixtures	*10-20*	*25-35*	*40-50*	*55-65*
	Chloride ion concentration (w. Cl / w. cement %)			
OPC – 0	1.13	0.00	0.00	0.00
SF – 0	0.54	0.00	0.00	0.00
SF – 6	0.97	0.32	0.00	0.00
SF – 11	0.83	0.65	0.19	0.00

Mixture OPC – 6 and OPC – 11 could not be tested as the ponding solution was seeping thought the specimen in less than 10 minutes. This could be explained by the fact that the capillary pore network in those mixtures was still connected even after 56 days of curing. The C1543 test could neither be performed on the extremely fast setting of mixtures OPC – 16 and SF – 16, as their peculiar rheological characteristics did not allow proper finishing of the test specimens.

Compressive Strength Tests

Compressive strength was determined for all mixtures. First, early age compressive strength (6 and 24 hours) was evaluated using the *End Beam Test*. Specimen to be tested are shot directly into rectangular steel molds (75×75×350 mm). The beam specimens are stripped and then tested by applying a compressive load against a 100×100 mm steel bearing plate placed on top of the specimen (see setup in Figure 8). Both ends of the beam are tested at each age.

Figure 8. End Beam Test setup

Compressive strength was subsequently determined at 3, 7, 28 and 56 days, using each time three cores obtained in accordance with ASTM C1604 - *Obtaining and Testing Drilled Cores of Shotcrete*. The cores were 75 mm in diameter and 150 mm in length (nominal size). Table 7 summarizes the average compressive strength results obtained for the tested mixtures.

Table 7. Average compressive strength results

Mixtures	Average compressive strength results [MPa]					
	6h	24h	3d	7d	28d	56d
OPC – 0	---	23.6	24.6	29.4	36.6	39.1
OPC – 6	---	23.0	24.6	28.1	35.7	38.4
OPC – 11	---	21.3	30.2	34.0	37.4	44.5
OPC – 16	1.3	16.0	24.5	28.3	35.9	35.0
SF – 0	---	24.1	28.9	35.8	49.2	49.3
SF – 6	5.6	21.5	26.3	34.7	46.9	45.0
SF – 11	5.6	23.6	27.5	34.4	46.2	47.5
SF – 16	7.8	18.8	20.6	29.5	38.4	41.1

DISCUSSION

Based on the test results presented above, two broad observations can be put up front. The increase of set-accelerator seems to alter the quality of shotcrete, as revealed by the porosity and chloride penetration tests. Conversely, based upon the same tests, the use of silica fume is observed to improve the overall quality of shotcrete produced.

An important finding that needs to be looked at in more details is the impossibility to test the OPC-6 and OPC-11 (and most probably OPC-16, if the specimens could have been finished adequately) in the ponding test (ASTM C1543), as the samples leaked before the test could even be started. This means that upon filling the reservoir located on top of the specimens (approximately 300×200×90 mm), the water found its way to the bottom and started leaking within less than 10 minutes (the sides of the specimens are covered in epoxy to promote a unidirectional gradient). This means that the porosity of those shotcrete samples was interconnected, a situation abnormal after 56 days of wet-curing, which can only be attributed to the presence of the accelerator. The latter presumably "*froze*" the microstructure too rapidly, creating an inhomogeneous system with alternating denser and more porous paste areas (similar findings were reported for dry-mix shotcrete (Jolin et al. 1997)). In practice, as an example, would the same shotcrete be sprayed on a saturated tunnel wall, water would percolate through the surface of the lining on a permanent basis. Although the service life prediction modeling still has to be completed in this project, it would be of little interest to compute complex ionic diffusion factors or water vapor transmission coefficient for these particular shotcrete mixtures when in fact, they would simply let the water seep through in a matter of minutes!

The experimental elephant in the room

A lot of efforts are put into the careful selection of aggregates and cement, on the proper mixture design, and also on the QA/QC testing. Unfortunately, experience demonstrate that not all shotcreting equipment is equal when the homogeneity of the in-place shotcrete is considered. In fact, there would be much to say about the use of the accelerator pump (and the dosage of the accelerator, as can be concluded from the results presented before). Indeed, while shooting, the intermittent arrival of concrete at the nozzle resulting from the concrete pumping action (pistons and s-valve movement) and the high pressure accelerator input at the nozzle (preferably through the air inlet and then air ring to facilitate dispersion) create a situation where the risk for high inhomogeneity in accelerator dispersal in the in-place shotcrete is quite significant. In fact, a short study using the set-up described before where the accelerator was replaced with a fluorescent solution (observed under a black light) was undertaken to evaluate the resulting level of inhomogeneity. Figure 9 shows a representative 100×100 mm slice of shotcrete taken through the thickness of a test panel. As can be easily seen over the area of observation, the distribution of the "accelerator" within the in-place shotcrete is not at all homogeneous.

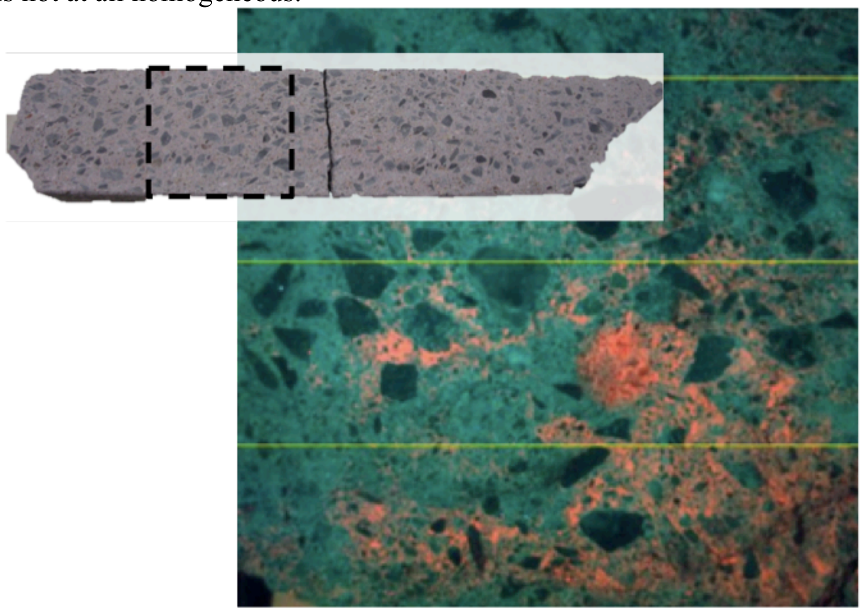

Figure 9: Distribution of a fluorescent solution through a 10 cm x 10 cm slice of shotcrete

The results of this short project are still being analyzed in order to extract quantitative data, but Figure 9 shows that there is indeed a risk for inhomogeneity in wet-mix shotcrete incorporating set-accelerators.

CONCLUSION

The research project reported in this paper was aimed at illustrating the potential influence of set-accelerators on wet-mix shotcrete properties and, by extension, service life. Based on the experimental results that were generated and the previous discussion, the following conclusions could be drawn:

- Service life prediction requires knowledge of the fundamental concrete/shotcrete transport properties, as well as selection of acceptance criteria for given exposure conditions (for ex.: chloride content at a 50 mm depth for a sea wall in Panama).
- The increase in set-accelerator content appears to alter the quality of the in-place shotcrete, as shown by the porosity and chloride penetration tests.
- The replacement of 8% of the OPC cement with silica fume produces shotcrete mixtures that are more robust against the accelerator dosage.

It is the hope of the authors that the results of this research project will help the industry in better understanding the challenges involved in predicting the service life of wet-mix accelerated shotcrete.

ACKNOWLEDGEMENTS

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC), King Shotcrete Solutions. and to the *Fonds de Recherche du Québec—Nature et Technologies (FQRNT)* for their financial support of this project.

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