Ageing of cement grouted joint by water and acidic flows for assessing dam foundation quality

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ABSTRACT
Cement grouting is widely used to maintain the safety of dams by reducing the water pressure in rock foundations and by improving its quality. However, little is known about the ageing of grouted joints. Some studies have suggested that erosion and dissolution caused by water flow are the main factors of degradation. This paper deals with a laboratory study assessing the performance of cement grout injection in rock or mortar test samples and submitted to a constant water (or acid) flow. Each sample was kept in a sealed box where a pump induced a flow at constant pressure. The degradation time ranged from two weeks to two months. The main decrease occurred on the cement grout surface, showing a modification on Barton's JRC and a global variation of the shear strength indeed. Finally, the study adds a new dimension to the grout degradation of dams, which offer an accelerated system of deterioration by flow.

RÉSUMÉ
Le coulis de ciment est largement utilisé pour maintenir la sécurité des barrages en réduisant la pression d'eau dans les fondations rocheuses et en améliorant sa qualité. Cependant, on sait peu de choses sur le vieillissement des joints. Certaines études ont suggéré que l'érosion et la dissolution causées par l'écoulement de l'eau sont les principaux facteurs de dégradation. Cet article constitue une étude en laboratoire évaluant la performance d'injections de coulis de ciment sur des échantillons de roche ou de mortier qui sont soumis à un écoulement constant d'eau ou d'acide. Chaque échantillon a été conservé dans un boitier étanche où une pompe induisait un débit à pression constante. Le temps de dégradation variait de deux semaines à deux mois. La principale diminution a eu lieu à la surface du coulis de ciment, montrant une modification du JRC de Barton et une variation globale de la résistance au cisaillement. Enfin, l'étude ajoute une nouvelle dimension à la dégradation du coulis des barrages, qui offre un système accéléré de détérioration par écoulement.

1 INTRODUCTION

In Quebec, many dams and dikes were built for the development of hydropower complexes providing energy to the population and the aluminum industry for the East of North America. Many dams have 40 to 50 years of age and some questions can be raised regarding the evolution of the original grouting (Bulota and Larivière 1991). The deterioration can be seen as the increase of the number of leaks in the foundations. However, the mechanisms of deterioration are not known, and the grout condition cannot be evaluated without drilling and examining the recovered core. Cement grouting is widely used to contribute to the stability of gravity dams by reducing the uplift pressure in the foundations and reducing water circulation that could affect the quality of the foundation. The purpose of this study is to determine with accelerated laboratory tests how the cement grout (2:1 ratio) has been degraded on a natural rock joint or replica joint at a constant flow.

All grout joints were analyzed using a scanning electron microscope (SEM) to ensure that there are no more than erosion and dissolution factors that cause degradation of the interface. It is important to consider that a significant decrease of the shear strength can result, in extreme cases, to the collapse of the structure. That is why it is required to understand how the degradation of the grout can change the mechanical behavior of dam foundations. However, little is known about the mechanisms of ageing of cemented joints. Some studies have suggested that erosion (mechanical) and dissolution (chemical) caused by water flow may be the main factors of degradation of the mechanical and hydraulic properties of the grout (and the rock mass indeed) (Tetel'min and Ulyashinskii 1992; Pedro, Mascarenhas, and Silva 1995; Carde and Françis 1999; Romanov, Gabrovšek, and Dreybrodt 2003).

Even though the cement grout does improve the shear strength of rock joints (Salimian et al. 2017), no studies combining the degradation of cement grout and the evolution of shear strength have been found in the literature. However, Nouailletas et al. (2017) reported a study on acidic degradation (HCL) of rock joints. They found no significant decrease of the shear strength. This research provides a new concept of rock joint degradation that adds erosion and dissolution with acid and water flow.

A comparison between the variation of shear strength of cement grouted joints, mortar joints (Sika 212) and injected rock joints (granite) is also presented. Based on the Mohr-Coulomb criterion (M-C), expressed by Eq. (1), a total of 38 shear tests were performed at normal stress of 100, 200 and 300 kPa.

$$\tau = \sigma \tan \phi + c \qquad [1]$$

where τ is the shear strength, σ is the normal stress, φ is the friction angle and C is the cohesion (0 in this study).

In order to present a different perspective, on each interface, the samples were scanned with 3D laser scanner before and after the degradation to assess the evolution on Barton's JRC where a decrease of JRC will signify a decrease of the shear strength (Barton 1973).

2 MATERIALS AND EXPERIMENTAL

To assess the proprieties of degraded samples, a fabrication method had to be designed. The initial purpose of the sample design was to resist a 100 kPa flow (neutral or acid) for 2 months or more (without stopping), to have a similar roughness than a standard granite rock joints and to be fabricated with similar materials that forms dam foundations in the Precambrian shield. Two degradation systems were designed to ease the deterioration processes, which includes 38 different samples separated in 5 series.

3.1 Samples fabrication and dimensions

Samples dimensions are 9 x 10 x 8 cm (width x length x height) where the height combines 2 layers of 3 cm of mortar (or rock) and one layer of 2 cm of grout. There is also a 1 mm gap between the bottom part of grout and the upper part of mortar (or rock). A gap between the materials was needed to allow a water flow inward the rock joints. This research considers that the gap occurs at the interface between rock (or concrete) and the cement injected grout. This served as a basis in the design and preparation of samples as each of them includes a joint with two different materials. Figure 1 shows the final result on a mortar sample of the fabrication process. In total, 9 steps spread out on a 20-days duration were needed to fabricate a set of 8 samples.

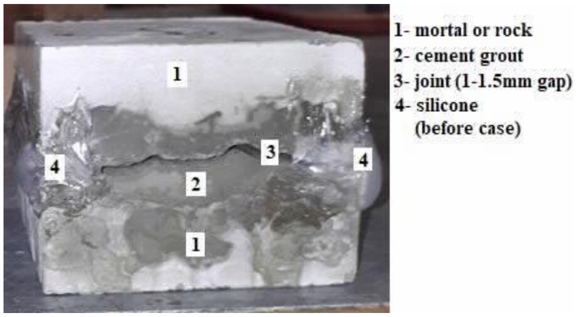

Figure 1. Different parts of the design samples

At the beginning, 8 molds and 8 silicon prints (same roughness) were made (JRC about 13). For the mortar samples, the first phase was to cast upper and lower parts. The lower part was cast on the rock joint silicon print. The upper part of mortar was directly cast after 24 hours on the lower part. After seven days of curing, the parts were detached, and the cement grout was injected in the gap. For the rock samples, replace this part of the process by the cutting of granite lower and upper part which had about the same roughness on the interface (JRC from 12 to 15). After another seven days of cement grout curing, the lower part (mortar or rock + cement) was detached from the upper part (only mortar or rock). To get the 1-1.5 mm gap, 4 plastic pieces were put at each corner of the sample. Finally, watertight enclosures were designed to seal the sides of samples during the degradation process while leaving an entrance and an exit allowing water flow. Figure 2 shows a sample prepared for the degradation installed in the test enclosure.

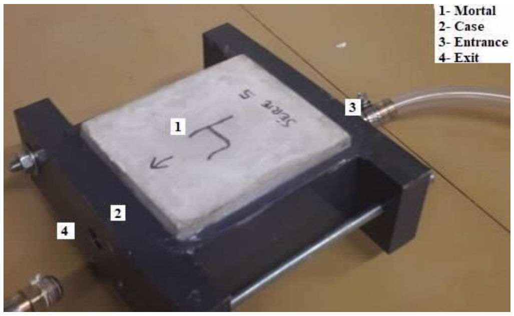

Figure 2. Sample in the degradation case

3.2 Degradation system

Once the samples are in the degradation enclosure, they can be plugged to the degradation system shown in Figure 3. The purpose of the system is to allow fluid circulation toward six different samples at the same time in a continuous process. A 3407 L/s pump induces a 33°C flow divided equally between the left and the right conduit of the system. With the pressure (about 20 kPa), the flow is once again divided in three parts (in each conduit) to pass through a sample joint. A tube is connected on the other side of the degradation enclosure to route the flow to the bucket of acidic solution or water (where the pump is located). For this study, two similar deterioration systems were designed, one for each fluid. The water system was considered stable when the pH of the water reached 8 (taps water started at 7.15). A solution of sodium phosphate and citric was chosen for the acidic flow (pH = 5) as this level of pH is assumed to produce a more global dissolution than localized attacks. Finally, the fluid pH was kept constant with hydrochloric acid (HCL) every day. The solution was changed every two weeks and analyze after each degradation set (2 months).

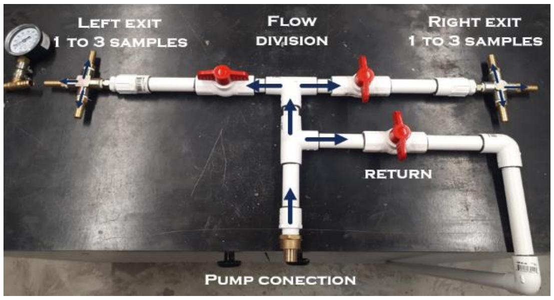

Figure 3. Deterioration system

3.3 Experimental protocol

The experimental program was divided in three phases: reproducibility of samples, degradation of mortar (Sika 212) samples and degradation of rock samples. Figure 4 shows the different test phases according to a timeline and also shows the five sets of degradation tests. The first phase included one set of mortar degradation by an acidic solution to accelerate the degradation process.

Its purpose was to ensure if there will be issues with the acid deterioration on the mortar joint and to know if all of the three samples will respond the same (shear strength and JRC variation) to a one-month degradation. The second and third phases were the mortar-grout degradation and the granite-grout degradation, respectively. They both include two sets of 8 samples, one for each solution (acid and water). Figure 4 shows how many samples were degraded for each time steps: 0, 14, 28, 42 and 56 days. Each day, for the complete test duration of two weeks or two months, the pH, the temperature and the pressure of the flows were monitored.

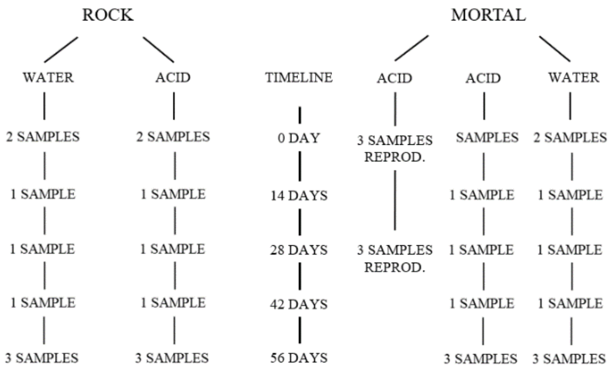

Figure 4. Experimental program

3.3.1 Roughness measurements

The evolution of the roughness parameter (JRC) under harsh flows conditions is one of the most important parameters to assess the degradation: it represents a direct link between the degradation and the shear strength. After the fabrication phase, both interfaces of each sample were scanned with a 3D laser scan (Kreon Zephyr© 25), right before the installation of the degradation case. Different studies have been made at the Université de Sherbrooke with this scanner (Moradian et al. 2010; Rousseau et al. 2012; Rullière et al. 2018). The device includes three essential parts: the articulated arm, a computer and a laser head, which is recording. The arm determines the coordinates (x, y) position when the head records the elevation (z) on the joint. The resolution (72 µm for the x and y axes, and 16 µm for z-axis) recorded a 3.5 million points per surface averaging 9000 of mm². Indeed, the scanning process was also repeated after the degradation to assess the evolution of joints for two months. After the scanning process, the data files were imported into Matlab to be meshed on a 0.5 mm interval (x, y) by an algorithm made by Rullière et al. 2018. This algorithm generates about 160 profiles in shear direction and quantified statistical parameters: A_i (average inclination of asperities), Z_2 (topographical slope), R_p (roughness index profile). The global roughness can be averaged by those profiles roughness parameters which gives a roughness coefficient for each surface. The equations used for the algorithm were found in Li and Zhang (2015) for a 0.5 mm mesh.

3.3.2 Shear tests

Once the surface had been scanned, shear tests were performed on each sample (mortar and rock) using a MTS hydraulic servo-controlled with a 3000 kN capacity with a special designed shear test box (details are found in Rousseau 2010). Constant Normal Load tests were conducted at a shear rate of 0.1mm/min until a displacement of 3 mm. In other to obtain peak values and friction angle for all the degradation process, every sample was tested for three runs at a normal load of 100, 200 and 300 kPa. Time, normal load, shear strength and displacement were recorded during the tests.

4 RESULTS

4.1 Samples reproducibility

A set of six samples was initially created to evaluate the variability of the results. Three of them were degraded for one month and the results of mass variation, JRC variation and maximum shear strength were collected and are presented in Table 1 and in Table 2.

Table 1. Reproducibility results of weight and JRC

#	Weight (g)	ΔJRC -
1	-11.8	-2.9
2	-12.6	-2.5
3	-13.4	-3.1
Average	12.6	-2.9
Std. Dev.	0.7	0.2

Table 2. Reproducibility results of direct shear tests

#	τ_{max} (kPa) $\sigma_n = 100$	τ_{max}(kPa) $\sigma_n = 200$	τ_{max} (kPa) $\sigma_n = 300$
1	145	230	360
2	105	190	290
3	120	200	280
Average	120	210	310
Std. Dev.	20	10	40

4.2 SEM investigation

A SEM study was carried out on the interface of cement grout to ensure that erosion and dissolution are the main factors of surface degradation. Figures 4 and 5, show a zoomed zone of degradation due to water and acid flow, respectively. The evolution of neutral degradation (Fig. 4) initially shows a layer of calcium oxide that begins to erode with time (T = 14). However, the growth of some calcium crystals was observed, which suggests that the dissolution of the grout is not significant. Therefore, it seems that degradation by water is primarily mechanical, expressed by erosion. Figure 5 shows the opposite. It is possible to see an overall dissolution (cracking) by the flow of acid on each sample, which seems to be similar to an increase in the porosity of the surface. In addition, the strong dissolution seems to prevent the precipitation of calcium oxide. According to this study, there was no evidence of further degradation during the process, such as a high presence of aluminum or sulphide, often associated with secondary ettringite.

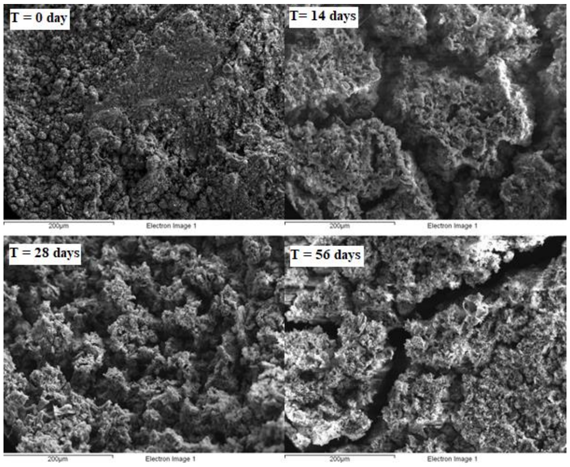

Figure 5. Neutral degradation SEM

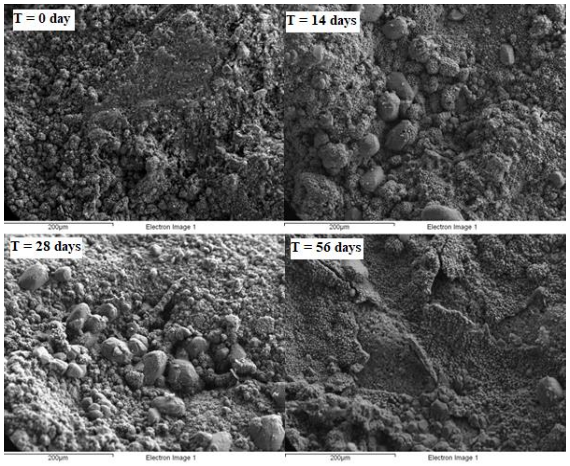

Figure 6.Acidic degradation SEM

4.3 Roughness coefficient results

Figures 7 and 8 show the variation of the roughness coefficient during the degradation process for 14, 28, 42 and 56 days. Figures 7 and 8 show the trend of variation of the JRC with regard to acid flow for cement and rock / mortar grout surfaces.

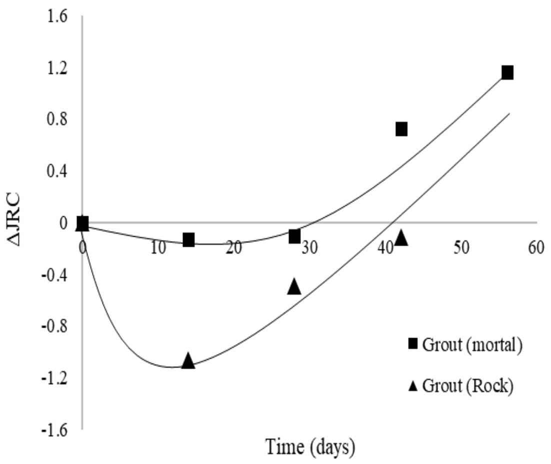

Figure 7. JRC variation of grout surface by acid flow

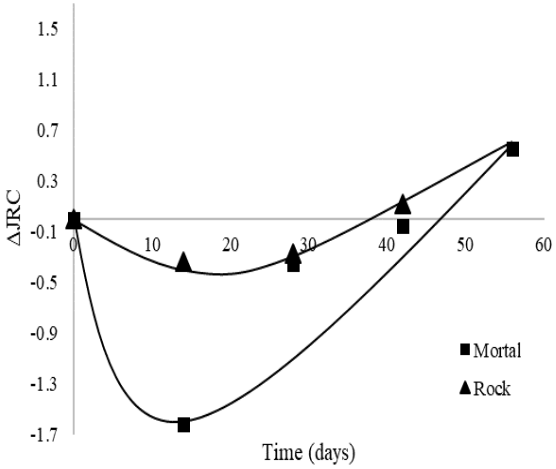

Figure 8. JRC variation of mortar and rock surface by acid flow

The graphs show a slight decrease of the JRC up to 14 days, which begin to increase after this point. Figures 9 and 10 show the results of a water flow for cement grout and rock / mortar interfaces. An overall decrease in the JRC occurred during the experiment for mortar and grout. However, the roughness of rock surfaces tends to be similar.

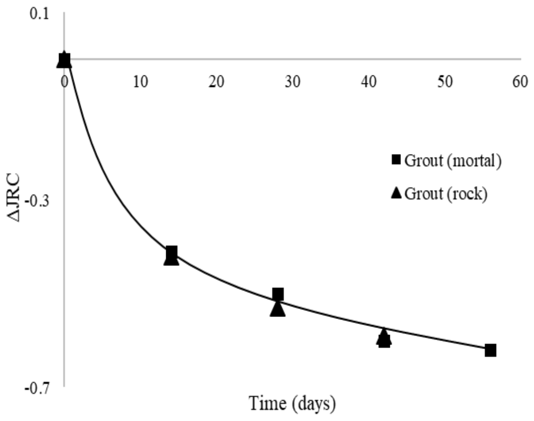

Figure 9. JRC variation of grout surface by water flow

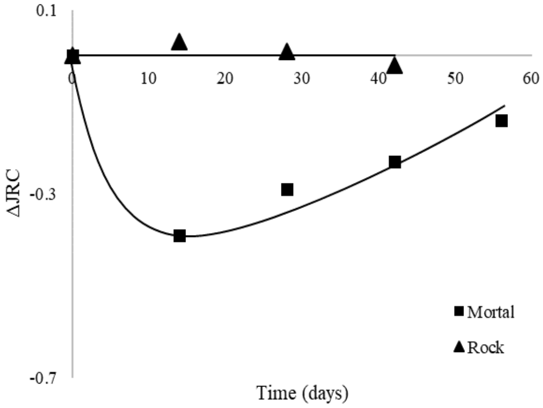

Figure 10. JRC variation of mortar and rock surface by water flow

4.4 Direct shear Test results

Figure 11 shows the maximum shear strength for 0, 28 and 56 days of degradation at normal stress levels of 100, 200 and 300 kPa. The trend is similar for each function as shown by the Mohr-Coulomb criterion. However, the apparent cohesion seems to decrease with degradation time (acid flow).

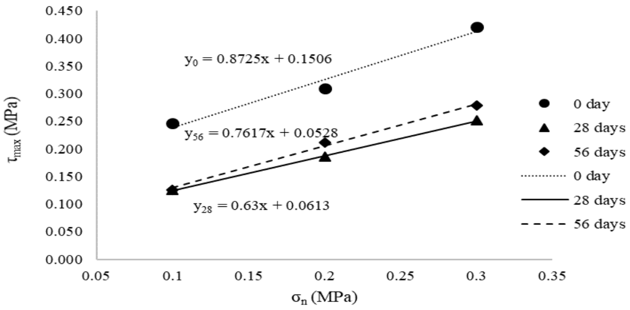

Figure 11. Example on M-C on acid flow degraded samples

Tables 3 and 4 show the angles of friction and cohesion results for all time steps and for all samples. It is important to know that the results T0 and T56 represent an average of 3 or more results. T56 shear strength results for grout / rock samples were not yet available. Finally, all results will be discussed in the following section.

Table 3. Friction angles and apparent cohesion results for T_0 and T_{14}

		T_0	T_{14}
Grout/Mortar	φ (°)	40	38
Acid flow	c_{app} (kPa)	150	50
Grout/Mortar	φ (°)	40	56
Water flow	c_{app} (kPa)	150	110
Grout/Rock	φ (°)	36	45
Acid flow	c_{app} (kPa)	190	10
Grout/Rock	φ (°)	36	20
Water flow	c_{app} (kPa)	190	240

Table 3. Friction angles and apparent cohesion results for T_{28}, T_{42} and T_{56}

		T_{28}	T_{42}	T_{56}
Grout/Mortar	φ (°)	40	38	32
Acid flow	c_{app} (kPa)	150	50	60
Grout/Mortar	φ (°)	40	56	40
Water flow	c_{app} (kPa)	150	110	260
Grout/Rock	φ (°)	36	45	45
Acid flow	c_{app} (kPa)	190	10	0
Grout/Rock	φ (°)	36	20	32
Water flow	c_{app} (kPa)	190	240	150

5 DISCUSSION

5.1 Roughness coefficient results

Figures 7 and 8 show the tendency of JRC variation on a sample exposed to acid flow for the three materials. The trend is similar, with a decrease in the JRC followed by a moderate decrease, then an increase in variation. According to these results in conjunction with the SEM investigation, it might be inferred that the initial decrease is related to the dissolution of the surface micro-roughness. The change in the trend after 14 days corresponds to a larger dissolution that increases the porosity and cracks start to appear (on cement grout and mortar surfaces), which means an increase in the JRC. These graphs also point out that the JRC variation of grout surfaces is greater on grout-rock samples than on grout-mortar samples. For the mortar surfaces, the results follow the same trend as grout surfaces, a positive evolution of the JRC from 0 to 56 days. A slight variation of the JRC was observed at the rock interfaces. However it can only be some grout degraded particles on the joint that can cause this variation.

Figures 9 and 10 show the trend of JRC variation on a sample exposed to a water flow for the three materials, which behave differently. First, there is no significant difference in the evolution of JRC between grout-rock and grout-mortar samples, which means that the only degradation factor is likely the erosion (same pressure /

same water). The tendency has always shown a change in the function direction (decrease followed by an increase in JRC variation), leading to the transition to a negative asymptote (maybe a maximal joint erosion JRC for this pressure). Thereafter, the rock surface does not seem to be affected by the water erosion of the flow. Finally, the mortar surfaces have the same tendency as seen in Figure 7 (acid flow), that is to say a decrease in the JRC followed by an uprising trend. However, this time, the variation seems to be about 3 to 4 times lower. The comparison between the JRC behavior on grout joint shows an initial drop on JRC followed by an increase, even larger than the initial JRC. It is too soon to claim whether the degradation by water flow would yielded an increase of the global roughness. However this process is a definitely slower than the acid flow. It is also possible to see a similar trend between acid degraded grout until 14 days and water flow grout until 56 days.

5.2 Direct shear tests results

The acid flow degradation results of the grout-mortar samples shown in Table 2 indicated an initial decrease in the friction angle followed by a change in trend (increase) similar to the JRC variation results. However, the degradation of the acid induced a reduction of the apparent cohesion, which may be related to a decrease in shear strength. The results of degradation by a water flow showed a nonlinear variation of the angle of friction and the apparent cohesion. Unlike acid deterioration, the friction angle increased, which can be caused by the soft crystallization of calcium oxide. It is too early to develop a model on the variation of cohesion since no correlation can be drawn from these results. For the grout-rock samples, the acidic degradation of the grout samples led to an overall increase in the friction angle and annihilation of the cohesion, which can be explained by the strong dissolution of the grout and the non-degradation of the rock surface (JRC evolution). For these samples, the results for water degradation showed a nonlinear decrease of the friction angle and an overall increase of the apparent cohesion, which suggest no dissolution.

6 CONCLUSION

The objective of this research was to evaluate the degradation of grouting material in rock and concrete fracture over the time. A test set-up had to be designed to simulate degradation by flowing liquids in a fracture, as well as an experimental protocol that considers accelerated testing. A degradation system and 38 artificial joints were made with silicone and have been degraded for two months. Then, the joints were scanned, and direct shear tests and SEM analysis were performed. The evolution of the roughness and the mechanical behavior of degraded cement grout joints (with mortar or rock) were measured to quantify the degradation. It was concluded that :

- Erosion and dissolution were the factors of degradation governing this experiment;
- Acid flows caused dissolution of micro-roughness leading to higher porosity;
- An overall increase in JRC (about 1) on surfaces was observed during the two-month acidic degradation process;
- A decrease in the angle of friction (5-10) and cohesion (50 kPa) was also observed.

The water flow mainly caused erosion over the crack surface, which induces a reduction of the JRC. However, the apparent cohesion seems to increase with the flow exposure. This experimental work indicated that a water or acid flow did affect the mechanical properties of cement grout, which are of general use in dam foundations for water tightening. It is important to notice that this study was made at the laboratory scale on small surfaces at relatively low pressures over a short period of time. Therefore the conclusions may be different at larger scale in field conditions.

7 ACKNOWLEDGMENT

The authors are grateful to the National Sciences and Engineering Research Council of Canada (NSERC) and Hydro-Québec for funding the project. We also thank Danick Charbonneau, Ghislaine Luc, Olivier Savary and Stéphane Gutierrez (Université de Sherbrooke) for their technical support during the experimental project.

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