Characterization of armour stone breakwater through a freeze-thaw resistance approach

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ABSTRACT
A study was performed on the prematurely degraded breakwater stone on the bay at Rivière-au-Renard and from the quarries in which they originate. The objective of the study was to highlight, through observation and laboratory testing, the probable causes of deterioration and to further propose new criteria to include in the specifications in order to minimize the number of problematic stones implemented in future coastal structures. The test for resistance to freezing and thawing cycles was carried out on slices of rock in order to recreate with more accuracy the observed degradation phenomena on the structures in place.

RÉSUMÉ
Une expertise a été réalisée sur des pierres s'étant dégradées prématurément sur des brises-lames de l'anse de Rivière-au-Renard ainsi que sur les carrières d'où elles proviennent. L'objectif de cette expertise était de faire ressortir, grâce à des essais en laboratoire et d'observations, les causes probables de leur détérioration ainsi que de proposer des nouveaux critères à inclure aux devis afin de pouvoir limiter au maximum le nombre de pierres problématiques mises en place dans les ouvrages côtiers futurs. C'est un essai de résistance aux cycles de gel/dégel réalisé sur des tranches de roches qui a permis de recréer avec le plus de fidélité les phénomènes de dégradation ayant pu être observés sur les ouvrages en place.

1 INTRODUCTION

With consideration of the context and Gaspesie's geological history, finding quality stones for use as part of maritime and coastal works is difficult and represents a challenge that the parties involved frequently meet. Through observation and experience in marine structures, it was noticed that the stones put in place, having initially met laboratory tests standards, have degraded faster than they should have with time.

Among these problematic structures, we find the main breakwater and wharf in Rivière-au-Renard, both located on the inlet of the Renard River in an open bay on the St. Lawrence Gulf. These two structures were subjected to remedial work carried out in 2004 by *Public Works and Government Services Canada* (PWGSC).

A study was therefore carried out on the stones of interest of these structures as well as the quarries from which they originate in order to highlight, through laboratory tests and observations, the probable causes of their deterioration, and to propose new criteria to add into the next specifications in order to ensure to exclude the problematic stones into future coastal structures.

2 METHODOLOGY

2.1 Field Visits

Field visits were first performed at the breakwater and wharf of Rivière-au-Renard in order to target and sample the prematurely deteriorated stones on the structures. During these visits, the problematic rocks were cored *in situ* using a portable core drill powered by a generator. Manual sampling was also performed using masses.

The main breakwater at Rivière-au-Renard is about 750 m long and is located north of the inlet of the Renard River. Damaged stones were observed on the last 300 m southeast of the latter end. The majority of stones in bad condition that were cored and sampled on the breakwater site mainly corresponded to altered sandstone, fractured, crumbly and with a low hardness at the surface.

Located east of the same bay as the main breakwater, the main wharf, roughly 275 m in length, is protected in part by a riprap. The area in which the problematic blocks were inspected and sampled corresponds to the slope of the rockfill on the side of the wharf. The cored stones in poor condition along the wharf correspond to a calcareous dolomite containing 10% to 40 % fossils depending on the sample. Boulders containing bedded and altered crystalline limestone were sampled as well.

Photographs of each of these observed stone types are presented in Figure 1 in which we find from top to bottom, (1) the altered and crumbly sandstone, (2) the fossiliferous and calcareous dolomite (3) the bedded crystalline limestone.

Furthermore, since the remedial work was primarily conducted in the 2000s, the quarries from which the different materials used originate as well as the zones from which they had been established in the structures of interest were well known and documented. Mass sampling was performed at the three quarries used as sources of production. These samples were either taken in bulk near the production areas or in the form of roughly 25 cm blocks.

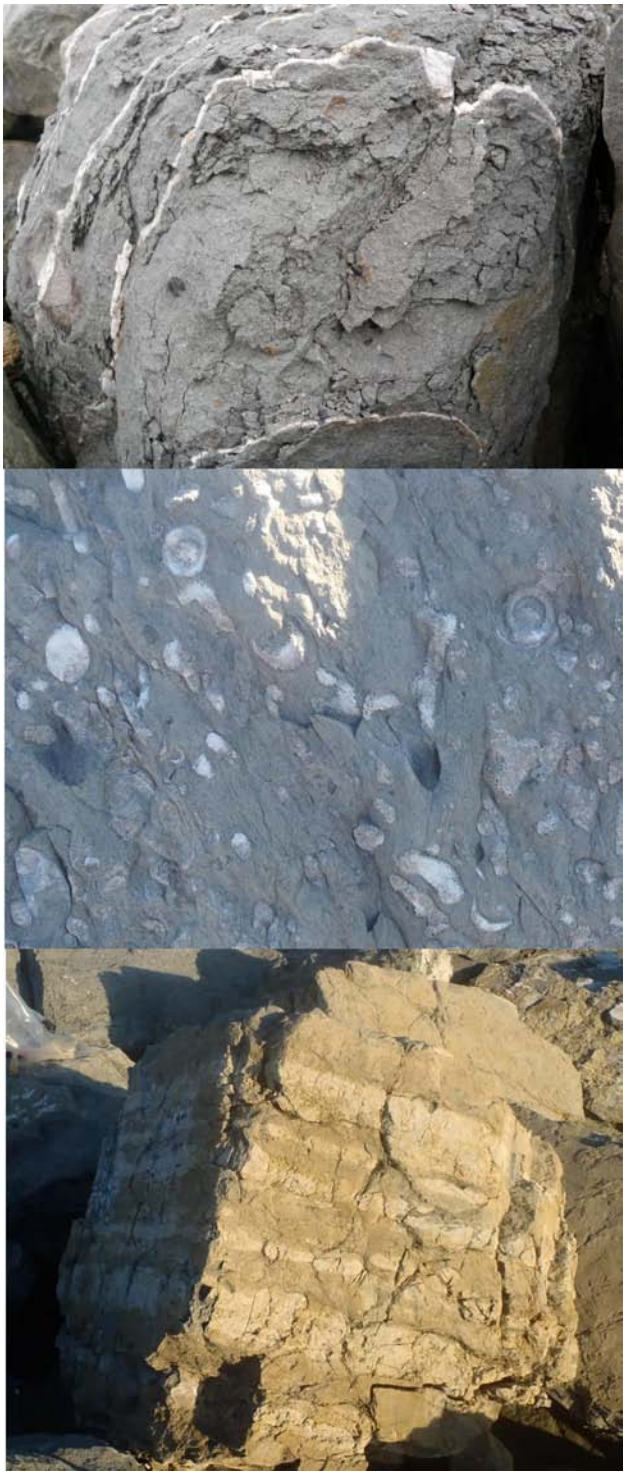

Figure 1. Photographs of the 3 problematic lithologies

The sandstone described above is a grey-beige to greenish-grey medium to very coarse-grained rock (0.3 mm to 1.5 mm in diameter) and mainly consists of quartz (70%) of plagioclase feldspars (23%) , calcite (4%) and other accessory minerals. At the quarry, the sandstone banks observed have thicknesses varying from 0.15 m to 2 m interspersed with fissile siltstone beds from 0.1 m to 0.45 m thick. These banks have an orientation of approximately N130º and a 40º to 50º dip. Moreover, calcite veins and veinlets were observed and sometimes appear to leave carbonate plating on the rock surfaces.

The dolostones are composed of a grey-beige very fine grained (<0.1 mm) calcareous dolomite. The rock observed at the quarry contains relatively large amounts of fossils varying from 5% to nearly 50% in proportion and appear to be predominantly tubular shaped (possibly crinoids). These fossils were observed to be grouped with a variety of different organisms. The matrix is predominantly dolomitic with a percentage of calcite that largely depends on the proportion of fossils and calcite veins and veinlets. Secondary minerals such as quartz, biotite and plagioclase feldspars were observed as well. The dolomite banks of the quarry have an approximately orientated N115º / 65º and are from 0.2 m to 1.5 m thick.

The limestone blocks previously described are composed of a gray fine to very fine grained (≤ 0.2 mm) crystalline dolomitic limestone. The matrix is mainly calcareous and contains a small percentage of dolomite. These blocks also contain calcite veins and veinlets varying from 1 mm to 45 mm in thickness. Secondary minerals such as quartz, plagioclase feldspars, biotite and opaque minerals were observed in trace amounts. The limestone banks are oriented at N95º and dip from 30º to 45º with thicknesses mainly varying from 0.15 m to 1.00 m and can reach up to 2.0 m thick.

2.2 Laboratory Tests

The following laboratory tests were conducted on samples taken from the problematic blocks of the structures or at the quarry during field visits:

- Resistance to compressive strength – ASTM D4543-07 and ASTM D7012-07;
- Resistance to degradation by abrasion in the Micro-Deval apparatus – ASTM D6928 06;
- Relative density (specific gravity) – ASTM C127-07;
- Absorption – ASTM C127-07;
- Soundness by use of magnesium sulfate – ASTM C88-05;
- Durability of rock slices under freezing and thawing cycles– ASTM D5312-04;
- Durability of rock slices under wetting and drying cycles – ASTM D5312-04;
- Resistance of unconfined coarse aggregate to freezing and thawing – CSA A23.2-24A.

3 RESULTS

The mean test results on the samples from the structures and quarries are shown on Table 1 below. In order to lighten the text, the terms sandstone, dolomite and limestone were used to describe the three studied lithologies.

Table 1. Mean lab results for each rock type sampled

Laboratory Test	Sandstone	Dolomite	Limestone
Specific gravity Min : 2.65 ; Max : 2.85	2.69 (2.65) [1]	2.71 (2.70)	2.68 (2.68)
Absorption (%) Max : 0.5 %	0.37 (0.61)	0.41 (0.63)	0.11 (0.42)
Micro-Deval (%) Max : 15 %	23.1 (29.6)	30.2 (27.5)	4.5 (6.1)
$MgSO_4$ (%) Max : 1.5 %	2,07 (1.67)	3.20 (0.95)	1.23 (0.74)
Resist. compression (MPa) Min : 100 MPa	66.3 (85.3)	51.8 (61.5)	89.9
Wetting/drying (%) Allowable value : N/A	0.47	0.35	0.05
Freeze/thaw (%) Allowable value : N/A	0.90	5.11	0.15
Freeze/thaw (aggregates)(%) Allowable value : N/A	15.40	12.90	1.80

[1]The results outside the parentheses were performed on rocks sampled in different quarries and those within were performed on sampled rocks on the breakwater or the wharf at Rivière-au-Renard, when applicable.
[2]The minimum and maximum allowable values included in this table are the ones generally accepted by PWGSC for maritime and coastal works.

3.1 Specific Gravity and Absorption

Five specific gravity and absorption determinations were performed for each quarry studied. Fifteen tests for specific gravity and absorption were performed on blocks from the breakwater or wharf at Rivière-au-Renard.

The mean specific gravities obtained for the samples from limestone, sandstone and dolomite quarries are 2.677, 2.688 and 2.710, respectively. The blocks sampled on the structures returned mean specific gravity values of 2.652 for sandstone, 2.678 for limestone and 2.703 for dolomite.

The results obtained for the absorption tests revealed mean values, all below a maximum value of 0.5%. Thus, the mean absorption percentages obtained are 0.11%, 0.37 % and 0.41 % for the limestone, sandstone and dolomite quarries, respectively.

The absorption tests on the structures' sampled blocks returned mean values of 0.61 % for sandstone, 0.42% for limestone and 0.63 % for dolomite.

3.2 Micro-Deval

A total of fifteen Micro-Deval tests were performed on samples from the three quarries and fifteen on Rivière-au-Renard's wharf or breakwater blocks.

For the limestone samples, a mean score of 4.46% was obtained. The tests performed on the sandstone revealed a mean score of 23.08%, while those on the dolomite reached a value of 30.16%, being the highest of the three quarries.

The Micro-Deval tests performed on the sampled blocks of the structures returned mean values of 6.08% for limestone, 29.60% for sandstone and 27.50% for dolomite.

3.3 Magnesium Sulfate Test ($MgSO_4$)

The MgSO4 tests performed on representative samples of the three quarries revealed relatively variable results, even for samples from the same quarry. The results obtained are as follows.

For the limestone samples, the two results obtained revealed a loss of 0.75% and 1.7%, while 0.84% and 3.3% of loss for sandstone. Only one sample of dolomite was analyzed and showed a loss of 3.2%.

For the structures, a total of seven samples of sandstone, four of limestone and four of dolomite were subjected to the MgSO4 test. These tests returned mean results of 1.67%, 0.74% and 0.95% for sandstone, limestone and dolomite, respectively.

3.4 Resistance to Compressive Strength

Compressive strength tests were carried out on quality cores from the studied structures and on blocks from the quarries.

Since the blocks were selected due to their significant deterioration, the collected cores were not of good quality. Thus, only four compression tests were carried out on samples from the breakwater and wharf.

The compressive strength for two sandstone cores returned values of 52.5 MPa and 118.2 MPa, while those consisting of dolomite returned results of 53.1 MPa and 69.9 MPa. However, none of the limestone cores were of good enough quality to be subjected to a compressive strength test.

To address this lack of data, it was decided to perform compressive strength tests on seven additional samples from the quarries and cored in the laboratory.

The compressive strength of the limestone, sandstone and dolomite blocks returned mean results of 89.9 MPa, 66.3 MPa and 51.8 MPa, respectively.

3.5 Resistance to Wetting/drying and Freeze/thaw Cycles on Slices of Rock

Tests for resistance to freeze/thaw cycles (ASTM D5312) and wetting/drying (ASTM D5313) are rarely used for evaluating the quality of rockfill stone, due to their significant time requirements.

For each test made according to these standards, five slices of rock had to be analyzed within the same test. Thus, a total of 50 slices were produced in our laboratories in order to perform these tests. Of these slices, ten were produced from the sandstone blocks, ten from limestone blocks and thirty from dolomite blocks.

Since both tests are performed according to both ASTM standards, photographs of the rock slices' initial and final state were taken before and after being subjected to the number of cycles required for each test.

It was decided to submit each sample to 56 cycles for the freeze/thaw test. Since the standard did not specify any number of cycles for Canada, the number of cycles chosen was to reflect (on a relative basis) the representative temperature conditions of the Gaspé region, where the breakwater and Rivière-au-Renard's wharf are built. In order to compare, the recommended standard on the U.S standard is a maximum value of 45 to 50 cycles on the East and 55 on the North-Western part of the country.

With respect to the wetting/drying test, a total of eighty cycles was carried out as specified in the stated standard.

Table 2. Mean results of freeze/thaw and wetting/drying tests

Resistance to freeze/thaw		Resistance to wetting/drying	
Sample group	Average loss (%)	Sample group	Average loss (%)
G1 (sandstone)	0.90	S1 (sandstone)	0.47
G2 (dolomite)	3.83	S2 (dolomite)	0.39
G3 (dolomite)	7.14	S3 (dolomite)	0.11
G4 (dolomite)	4.35	S4 (dolomite)	0.54
G5 (limestone)	0.76	S5 (limestone)	0.05

Sample groups G1 (for the "freeze /thaw" test) and S1 (for the "wetting/drying" samples) refer to the quarry containing the sandstone outcrops. Since a total of three pairs of freeze/thaw and wetting/drying tests were planned at the dolomite quarry, slice samples were divided according to their proportions in calcareous fossil. Thus, sample groups G2 and S2 contain few fossils, S3 and G3 groups contain moderate amounts, while G4 and S4 groups contain large amounts. Meanwhile, G5 and S5 sample groups refer to the limestone rocks. A summary of the results for these tests are presented in Table 2.

The results show that the dolomite samples are far less resistant to the freeze/thaw cycles as opposed to the other two quarries.

As for the resistance to wetting/drying cycles, the differences are less noticeable between quarries. However, the limestone stones seem to withstand better the cycles relative to the other two.

The before and after photographs of the rock slices are inherently quite eloquent for stone degradation; the test for resistance to freeze/thaw cycles appears to be more representative of the conditions observed on the deteriorated stones along the main wharf and the breakwater, particularly on stones made of sandstone and dolomite.

The photographs reveal noticeable damage along the edges of the sandstone rocks. Although the percentage of loss does not appear as significant, the degradation of the sandstone with respect to the freeze/thaw cycles is visually noticeable on some of the observed slices. Figures 2 and 3 illustrate examples of degraded stones observed and sampled on the structures compared to samples from their respective quarry having been subjected to the freeze/thaw test.

Figure 2. Photographs of disaggregated sandstone from the breakwater (left) and after the freeze/thaw test (right)


Figure 3. Photographs of disaggregated dolomite located on the wharf (left) and after the freeze/thaw test (right)

Concerning the dolomite rock slices, the percentage of loss at the end of different cycles does not seem to depend on the amount of fossils they contain since samples having a larger percentage loss were not necessarily those with a significant amount of fossils. Considering the dolomitic nature of the rock's matrix, it would appear more relevant to associate dolomite or one of its components to the low resistance of these slices of rock. This fact can easily be verified when observing Figure 4 which represents the state of the rock after 56 freeze/thaw cycles. It shows that mainly the dolomitic matrix was disaggregated and not the calcareous fossil compounds, which show a positive relief.


Figure 4. Photograph of a fossil rich dolomite sample after the freeze/thaw test.

3.6 Resistance to Freeze/thaw on Unconfined Aggregates

The test for resistance to freeze/thaw cycles performed on the rock slices (ASTM 5312-04) provided interesting visual and quantitative results on the degradation of the samples subjected to the test. Therefore, it was decided to submit samples from the same quarry to test for resistance to freeze\thaw for coarse unconfined aggregates, according to CSA A23.2-24A.

The standard used to perform this test specifies to submit the samples to five freeze/thaw cycles. In order to increase the chances for correlation between the tests performed, it was decided to submit the same samples to a second series of five freeze/thaw cycles.

A total of eight tests were performed on samples obtained from the three quarries. For the sandstone and limestone quarries, one sample from each was submitted to the freeze/thaw test; however, six samples from the dolomite quarry were tested since most previous freeze/thaw tests following the ASTM D5312-04 standard were performed.

In addition, the number of samples remaining in our laboratories had also limited the amount of sandstone and limestone samples tested. The results obtained are presented in Table 3.

Table 3. Results for resistance test to freeze/thaw for coarse unconfined aggregates (CSA A23.2-24A)

Resistance to freeze/thaw for coarse unconfined aggregates			
Sample no	Rock type	Loss after 5 cycles (%)	Loss after 10 cycles (%)
1	Limestone	1.8	2.9
2	Sandstone	15.4	39.2
3	Dolomite	11.4	30.4
4	Dolomite	15.5	54.3
5	Dolomite	10.9	35.4
6	Dolomite	7.1	22.6
7	Dolomite	13.8	37.9
8	Dolomite	18.7	40.6

Similar to the freeze/thaw results following ASTM D5312-04, the limestone sample showed the highest resistance to the freeze/thaw cycles. As for the sandstone and dolomite sample, the percentages of loss are relatively similar and much greater than the ones originating from the limestone quarry.

4 DISCUSSION

The analysis of the laboratory results performed in this study on collected samples of the three quarries has finally revealed that they did not meet several of the criteria currently used for the acceptance of armour stones by PWGSC.

The Micro-Deval tests revealed that only the stones consisting of limestone respected the maximum value of 15% loss. The resistances to Micro-Deval obtained on sandstone (23.08%) and dolomite (30.16 %) samples exceeded the allowable maximum value of 15%.

In terms of all the compressive strengths from quarry blocks obtained within the context of the study, none of the results reached the minimum value of 100 MPa. For the Micro-Deval test, the limestone obtained the best results, followed by sandstone and ending with dolomite.

The $MgSO_4$ test did not show any convincing results as for the resistance of the analyzed stones. For the sandstone and limestone, one of two trials was greater than the permitted limit of 1.5%. The only test performed on the dolomite revealed a loss of 3.2%, which is also greater than the permitted limit. Regarding the relative density and absorption, the results meet the requirements, which are between 2.65 and 2,85 for the relative gravity and below a maximum value of 0.5% for the absorption. It is, however, interesting to note that in terms of absorption percentage, the dolomite has the worst result (0.41%), and is closely followed by sandstone (0.37%).

Since the resistance to freeze/thaw and wetting/drying cycles are not required by PWGSC, and that no limiting value has been determined, the analysis of the results is mainly based on the comparative analysis of photographs of rocks before and after the cycles, as well as the comparison of percentage loss for the different quarries studied.

The freeze/thaw resistance test (ASTM D5312) proved very useful for the analysis of stones originating from the quarries. Thus, the deterioration phenomena observed during our visits to the various structures have successfully been recreated in the laboratory. Photographs for several slices of rock originating from the dolomite quarry that were put in place on the Rivière-au-Renard's wharf showed an accelerated deterioration following the 56 cycles of freeze/thaw.

The sandstone rock slices, despite representing a relatively small percentage loss (0.90 on average) were also visually more altered at the end.

The test for resistance to wetting/drying cycles revealed, like the majority of laboratory tests performed in the framework of this study, that the limestone rocks are more resistant than those from the other quarries. Photographs taken during the test were, however, less revealing of a deterioration caused by exposure to 80 cycles of wetting/drying.

Finally, the test for resistance to freeze/thaw of coarse unconfined aggregate (CSA A23.2-24A) revealed, similar to the freeze/thaw test on rock slices (ASTM D 5312-04), that the limestone samples have by far best resisted to the cycles, whether it was after five or ten cycles. The sample from the sandstone quarry revealed greater differences in percentages of loss than for the trial conducted according to ASTM, nearing closer to the results of dolomite samples. It is to note that, for this test, the percentages lost between five and ten cycles have, in general, more than doubled.

5 CONCLUSION

According to the laboratory tests on samples from the dolomite quarry, it appears that these stones produced should not have been put in place on Rivière-au-Renard's wharf. The test for resistance to freeze/thaw cycles clearly revealed that the dolomite did not resist well enough to freeze/thaw cycles. Even crystalline fossils consisting of calcite, despite generally a mineral known not to be of a high resistance and that dissolves faster than its host rock, resisted better than dolomitic matrix. Moreover, even if the fossils present in the rock resist better to freeze/thaw, the presence of the latter also causes additional plans of weaknesses in the rock.

Regarding altered and crumbly sandstone observed on the breakwater, the test of resistance to freeze/thaw cycles conducted on its quarry samples was able to partially reproduce in the laboratory the alteration that could be observed on the breakwater armour stones.

As for the observed wharf's stones originating from the limestone quarry, we believe that they are the result of a gap in the quality control for stones when selected from the quarry and during implementation. As observed at the quarries, the stones produced often contain bedding that, when too pronounced, greatly diminishes the integrity of the stone. A more rigorous selection of stones should have been done at the quarry.

In order to avoid including poor quality stones in upcoming structures, and based on the results of this study, the recommendations being found in subsequent paragraphs were given.

A higher number of tests should be required in the qualification of quarries in order to have a global view of the stone originating from the same place. Nevertheless, we believe that the limits of acceptability located in the PWGSC specifications are acceptable since that according to the laboratory test results performed during this study, the sandstone and dolomite quarries studied within the framework of this assessment would normally have been rejected on the basis of current requirements.

Since the test for resistance to freezing and thawing cycles of coarse unconfined aggregate could raise a noticeable difference in the loss of the limestone quarry samples and the other two quarries, it would be pertinent to include this test in the PWGSC specifications. The limited number of samples tested in this study makes it difficult, however, in determining a limit for acceptable loss. A maximum loss of 6% after five cycles could be set as a reasonable criterion for acceptability. All sandstone or dolomite samples tested had higher loss percentages than 6%. Moreover, it is this limit that was set by the Canadian Association for Standardization to determine whether coarse aggregates can be added to the production of concrete subjected to freeze-thaw. A further study including a sample pool much larger with variable lithologies should be conducted in order to determine the maximum loss to not exceed as well as the number of freeze/thaw cycles suitable for the use of stones for riprap works.

We believe that dolomite rock should be further analyzed in depth in order to verify if the phenomenon observed on the stones of this study could be reproduced for dolomite from other quarries. A study should be conducted on structures built using dolomitic stones to see if cases similar to that of Rivière-au-Renard exist.

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