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Freeze-Thaw Durability of Anchor Materials in Heritage Masonry Stones

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Abstract: Repair of heritage stone masonry structures sometimes involve anchoring the walls, to prevent from separation and to increase integrity of the walls. Performance of these anchors significantly depends on their ability to resist debonding forces induced from environmental freeze-thaw. Before choosing any anchoring materials for a heritage structure repair, capability of these materials in forming a sound bond with the existing masonry materials of that structure needs to be examined. A study was conducted at the University of Manitoba in collaboration with the Public Works and Government Services Canada (PWGSC), to test the behaviour of several anchors in stones. Conventional anchoring materials consist of steel, grout, and epoxy. On the other hand, suitability of Glass Fibre Reinforced Polymers (GFRP) to overcome the corrosion related problems of steel is well established. Keeping this aspect in mind, innovative anchors made from GFRP bars were also incorporated in this research program. Experimental program involved small scale replication of stone-anchor assemblies followed by monitoring of these assemblies for failures, while they were exposed to environmental chamber freeze-thaw cycles, in the W.R. McQuade Structures laboratory of the University of Manitoba. Varying rate of change of temperature and level of relative humidity were maintained in the environmental chamber during these exposures. At the end, monitoring data were analyzed to draw conclusions.

1 INTRODUCTION

Historic Canadian stone masonry structures are typically composed of two-wythe stone walls. Long-term exposure to harsh Canadian weather may cause these wythes of stones to separate. This separation can be prevented by anchoring these layers together, either with cross-stones (Tomasevic, 1999) or anchors. Such an intervention may have some impact on the stone masonry, and this research was conducted to monitor this impact.

The objective of this study was to conduct a compatibility analysis of both commercially available and GFRP anchors with the stones that are common in the walls of the Canadian heritage structures. The main objectives of this research work can be outlined as follows:

a) To examine the thermal compatibility of anchors in both unsaturated and saturated F/T cycles;
b) to determine the extent of environmental loads that initiate debonding in the stone-anchor assemblies; and
c) to measure the impact of different anchors on the permeability characteristics of masonry stones;

2 EXPERIMENTAL SETUP

2.1 Specimens

Two types of sandstone, i.e., Ohio and St. Canut, procured from Les Pierres St-Canut Ltee in Quebec, and one type of limestone, procured from Les Pierres Technoprofil Inc. in Quebec, were used as specimens. In order to get comparable results, all stone specimens tested were 300 mm x 300 mm x 150 mm. Both conventional and innovative anchors were tested. Conventional anchors tested were stainless steel threaded bars of both 10 mm and 6 mm diameter. In this study, Glass Fibre Reinforced Polymers (GFRP) anchors were also tested. Two types of commercially available GFRP rods, Aslan GFRP and V.Rod GFRP, were used to determine their suitability as anchoring materials in stones. Two types of cementitious grout, namely Presstec grout (CINTEC International Limited, 1996) and Sika cementitious grout (Sika Group, 2007), as well as one type of epoxy denoted Hilti epoxy (Hilti Corporation, 2001) were used as bond material between stones and anchors.

Seventy specimens were used in the study. Of these seventy, sixty four were stone-anchor assemblies and six were plain stones (two from each type of stone). Several stone-anchor specimens are presented in Figure 1. For each type of stone-anchor assembly, there was one control specimen that was not exposed to environmental loadings. Except for the control specimens, the specimens from each stone-anchor assembly were exposed to harsh environmental loadings before conducting permeability tests. These specimens are called conditioned samples in this report. Freeze-thaw cycles that were selected in this research are based on the actual climate data of the Western Canada region. The data were recorded and supplied by Public Works and Government Services Canada (PWGSC).

Figure 1: Completed stone-anchor specimens.

Figure 2: Stone-anchor assemblies with embedded sensors in the environmental chamber.

2.2 Instrumentation

Calibrated wood resistance-based embedded moisture sensors also known as Duff gauge sensors and thermistors were used to measure the moisture and temperature profiles inside the stone specimens during the freeze-thaw cycles. Calibration of these sensors was conducted at the Centre for Applied Research in Sustainable Infrastructure (CARSI) in Winnipeg, and at the University of Manitoba. These sensors were found to be adequate for monitoring moisture and temperature profiles in heritage stones. One sensor was installed in a predrilled hole in each stone specimen following the guidelines of the Structure Monitoring Technology Research Limited (SMT, 2008). The depth of each hole was such that the sensor was at the centre of that particular stone. While installing a sensor, the empty portion of the hole was filled with stone-dust from the same stone. The upper portion of each hole was sealed using permanent epoxy so that moisture could not infiltrate to the sensor through this opening. Selected stone-anchor specimens with embedded moisture sensor are presented in Figure 2.

2.3 Unsaturated Freeze-Thaw Tests

All of the conditioned stone-anchor assemblies were subjected to freeze-thaw cycles under unsaturated conditions (Figure 3), the environmental chamber being programmed to maintain 0% relative humidity. However, it was not possible to maintain 0% relative humidity during the whole test procedure, as shown in Figure 3. This can be partially explained by the fact that the amount of water required in the atmosphere to maintain a higher percentage of relative humidity at -25^{0}C is close to negligible. Specimens were exposed to 50 freeze-thaw cycles with the temperature changing from -25^{o}C to +40^{o}C at a rate of 1^{o}C every 4 minutes. Sharp jumps in the relative humidity profile (Figure 3) represent defrosting of the air-circulator in the environmental chamber.

The objective of these tests was to analyze the effect of harsh temperature cycles on the stone-anchor assemblies and to study the thermal compatibility of different foreign materials, i.e., anchors and anchoring adhesives in heritage stones. During the whole test procedure the stone-anchor assemblies were monitored carefully to determine the extent of the environmental loading that might initiate debonding in the stone-anchor assemblies.

2.4 Saturated Freeze-Thaw Tests

For the saturated freeze-thaw cycle tests of stones, the environmental chamber was programmed to maintain 100% relative humidity. All conditioned stone-anchor assemblies were exposed to temperature cycles similar to those in the unsaturated freeze-thaw tests, from -25^{o}C to +40^{o}C. Specimens were exposed to 50 freeze-thaw cycles with the temperature changing from -25^{o}C to +40^{o}C at a rate of 1^{o}C every 4 minutes. The test methodologies described in the American Society for Testing and Materials standard ASTM E1512-01 (ASTM, 2007) were followed, with some modification, in designing these tests.

All the stones were saturated before starting the freeze-thaw cycles by maintaining 38.1 mm of water on the top surface of the stones. This water level was maintained on the stone specimens throughout the test procedure. During the freezing part of the freeze-thaw cycles, absorbed water accelerated frost-induced damage in the stone specimens.

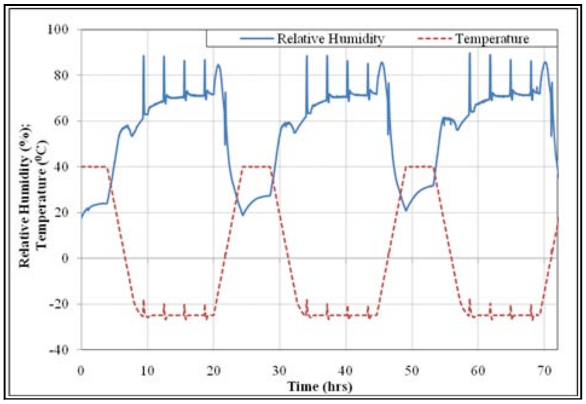

Figure 3: Environmental chamber air temperature and relative humidity profiles with time during unsaturated freeze-thaw cycles. (Uddin et al. 2010).

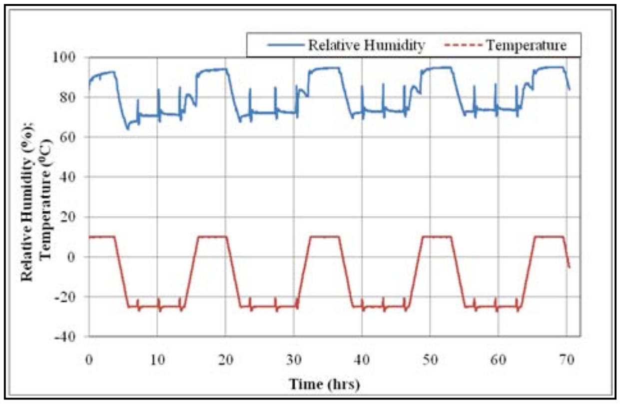

Figure 4: Environmental chamber air temperature and relative humidity profile with time during rapid freeze-thaw cycles. (Uddin et al. 2010).

2.5 Rapid Freeze-Thaw Tests

Heritage masonry structures in Canada need to sustain rapid freeze-thaw cycles involving sudden drops in temperature to below freezing level. This phenomenon was replicated in the rapid freeze-thaw tests. These are freeze-thaw cyclic tests under 100% relative humidity conditions in the environmental chamber. The environmental chamber was programmed to vary the temperature from +10^{o}C to -25^{o}C in 16 hours (Figure 4). Three cycles were completed within two days. The rate of change in temperature was set at 1^{o}C every 3 minutes and 26 seconds, the fastest capacity of the environmental chamber of the University of Manitoba.

ASTM C666/C 666M-03 test methodologies (ASTM, 2007) were followed, with some modification, in these tests. Before selecting the temperature range for these tests, several other combinations of temperatures were also tried in order to match the guidelines of the standard. Temperature ranges tried on stone-anchor assemblies included +15^{o}C to -25^{o}C, +15^{o}C to -20^{o}C, +6^{o}C to -25^{o}C, and +8^{o}C to -25^{o}C. Of these, the range from +10^{o}C to -25^{o}C was found to be the most appropriate based on the guidelines of the ASTM C666 standard (ASTM, 2007).

2.6 Permeability Tests

One of the most important characteristics of masonry walls is their ability to drain out moisture absorbed during precipitation events and also during freeze-thaw cycles. Most of the damage to masonry structures is related to the presence of moisture. Even a small quantity of moisture in masonry walls is sufficient for mould growth in the masonry materials (Black, 2006; Doll, 2002). Once mould has formed on masonry materials, it lowers the original aesthetic value of a heritage structure and also deteriorates the bonding between different masonry materials.

The objective of the permeability tests was to measure the impact of anchor installation on the permeability characteristics of the stones. The National Research Council Canada (NRC) bench top drying test methodology was followed with some modification in this regard (Trischuk & Mitchell, 2004).

Stone specimens, both with and without anchors, were first saturated by submerging them in water. The fully saturated condition was checked using the moisture sensors embedded in the stones. Once fully saturated, the stones were covered with silicone on all faces except the top surface. This silicone barrier forced the stone-anchor assemblies to lose water through one surface; i.e., upward movement through the top surface. Measurement of the amount of water loss provided a way of determining the temporal variation of moisture content within the stones. Analysis of these results should lead to a better understanding on how foreign materials, i.e., anchors, impact the permeability characteristics of the stone specimens.

3 RESULTS AND DISCUSSION

3.1 Freeze-Thaw Tests

All three types of conditioned stone specimens, with and without anchors, were exposed to three types of freeze-thaw cycle tests: unsaturated freeze-thaw, saturated freeze-thaw, and rapid freeze-thaw. While stone specimens were exposed to 150 freeze-thaw cycles, the moisture variation with time at the centre of the stones was monitored using Duff gauge sensors. These 150 freeze-thaw cycles represent approximately three years of environmental exposure for a heritage structure located in the Western Canada region (Private communication, February 12, 2008, PWGSC). Temperature profiles at the mid-depth of the stones were also monitored using thermistors attached with the Duff gauge sensors.

3.1.1 Unsaturated Freeze-Thaw Tests

The moisture profiles at the mid-depth of selected limestone specimens, both with and without anchors, during unsaturated freeze-thaw tests are presented in Figure 5. Moisture profile data recorded from the stone-anchor assemblies included: a limestone specimen with embedded Aslan GFRP anchor using Hilti epoxy (sample #3), a limestone specimen with embedded threaded steel anchor using Hilti epoxy (sample #11), a limestone specimen with embedded threaded steel anchor using Presstec grout (sample #13) and a limestone specimen without any embedded anchor (sample#65). During unsaturated freeze-thaw tests, conditioned limestone specimens both with and without anchors, exhibited similar moisture profiles. Similar behaviour was noted for the other stone types, so only results from limestone specimens are presented.

While exposed to unsaturated freeze-thaw cycles, stone-anchor assemblies were monitored for initiation of cracks and debonding and condition compared with the relevant control specimens. However, no such failures were detected while conditioned stone specimens were exposed to unsaturated freeze-thaw cycles.

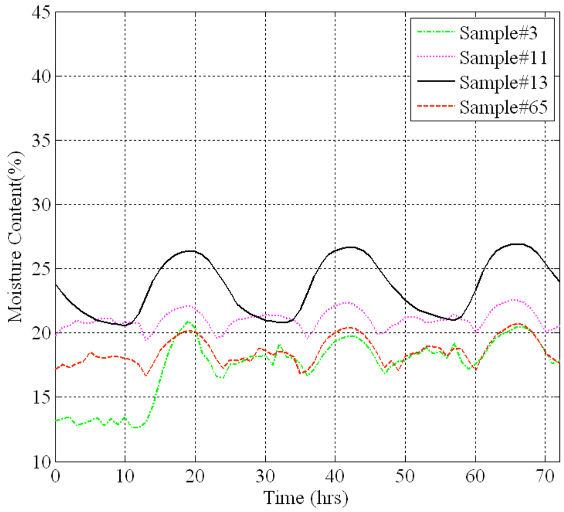

Figure 5: Moisture profiles in limestone specimens with and without anchors during unsaturated freeze-thaw cycles.

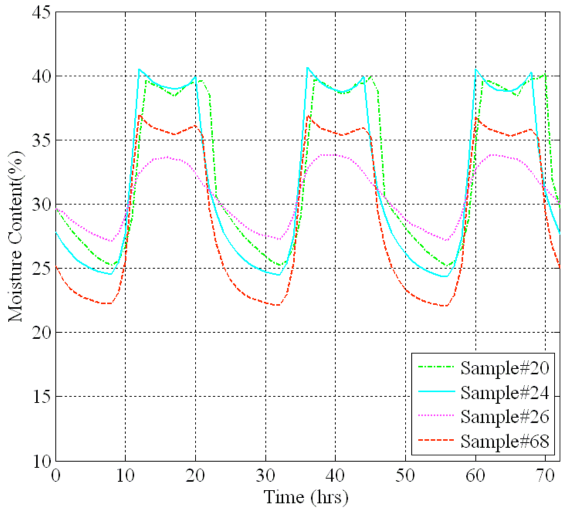

Figure 6: Moisture profiles in St. Canut sandstone specimens with and without anchors during saturated freeze-thaw cycles.

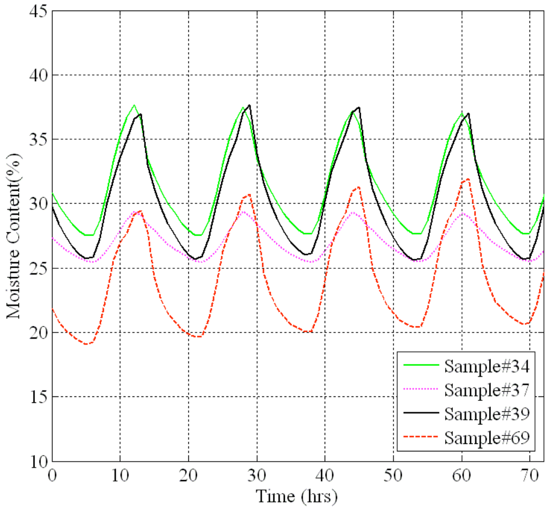

Figure 7: Moisture profiles in Ohio sandstone specimens with and without anchors during saturated rapid freeze-thaw cycles.

3.1.2 Saturated Freeze-Thaw Tests

Moisture profile monitoring results from saturated freeze-thaw cycles on selected St. Canut sandstone conditioned specimens are presented in Figure 6. Moisture profile data recorded from the St. Canut sandstone specimens included: one specimen with embedded Aslan GFRP anchor using Hilti epoxy (sample #20), one specimen with embedded V.Rod GFRP anchor using Hilti epoxy (sample #24), one specimen with embedded threaded steel anchor using Hilti epoxy (sample #26) and one specimen without any embedded anchor (sample#68). Similar to the unsaturated freeze-thaw test results, there was no notable impact of anchor installation on the moisture profiles in these stone specimens.

3.1.3 Rapid Freeze-Thaw Tests

Rapid freeze-thaw cycle tests were conducted on all conditioned stone specimens and moisture profile results from selected specimens are presented in Figure 7. Moisture profile data recorded from the Ohio sandstone specimens included: one specimen with embedded V.Rod GFRP anchor using Sika grout (sample #34), one specimen with embedded threaded steel anchor using Hilti epoxy (sample #37), one specimen with embedded threaded steel anchor using Presstec grout (sample#39) and one specimen without any embedded anchor (sample#69). Again, no major change was observed in the moisture profiles in the stone specimens due to anchor installation.

3.1.4 Temperature Profiles Measured during Freeze-Thaw Tests

While stone specimens were subjected to unsaturated freeze-thaw tests, temperature variations with time at the mid-depth of the stones were monitored using thermistors attached with the Duff gauge sensors. Temperature profiles at the mid-depth of different conditioned stone specimens, both with and without anchors, during unsaturated freeze-thaw tests are presented in Figures 8-10.

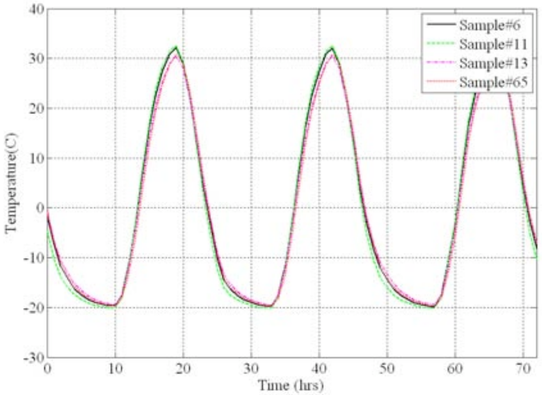

Figure 8: Temperature profiles in randomly selected limestone specimens with and without anchors

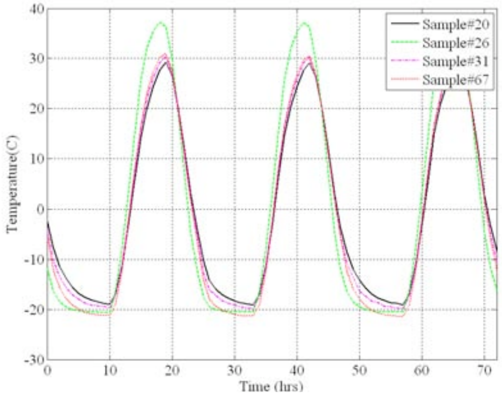

Figure 9: Temperature profiles in randomly selected St. Canut sandstone specimens with and without anchors during unsaturated freeze-thaw tests.

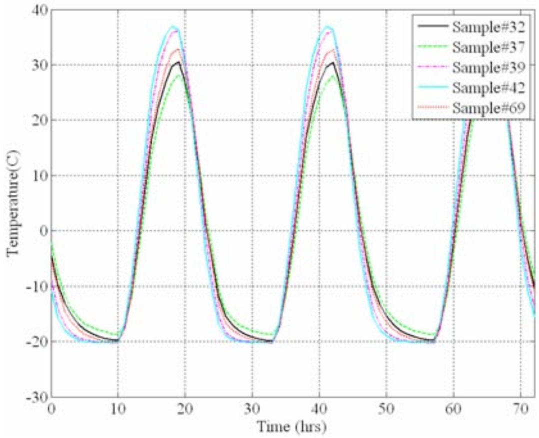

Figure 10: Temperature profiles in Ohio sandstone specimens with and without anchors during unsaturated freeze-thaw tests.

Temperature profiles from four limestone specimens are shown in Figure 8. Of these, three were stone-anchor specimens and one was a control specimen without an anchor (sample #65). Temperature data recorded from the stone-anchor assemblies included: a limestone specimen with embedded V.Rod GFRP anchor using Sika grout (sample #6), a limestone specimen with embedded threaded steel anchor using Hilti epoxy (sample #11) and a limestone specimen with embedded threaded steel anchor using Presstec grout (sample #13). As shown in Figure 8, the temperature profiles from the different limestone specimens were similar. Anchor installation appeared to have no effect on the temperature profiles in the limestone specimens.

Temperature profiles from St. Canut and Ohio sandstone specimens during unsaturated freeze-thaw tests, both with and without anchors, are shown in Figure 9 and Figure 10, respectively. Temperature profiles recorded from St. Canut sandstone specimens included: one specimen with embedded Aslan GFRP anchor using Hilti epoxy (sample #20), one specimen with embedded threaded steel anchor using Hilti epoxy (sample #26), one specimen with embedded threaded steel anchor using Presstec grout (sample #31) and one specimen without any anchor materials (sample#67). The trend of temperature profiles observed in all stone specimens was the same. On the other hand, temperature data recorded from Ohio sandstone specimens included: one specimen with embedded Aslan GFRP anchor using Sika grout (sample #32), one specimen with embedded threaded steel anchor using Hilti epoxy (sample #37), one specimen with embedded threaded steel anchor using Presstec grout (sample #39), one specimen with embedded threaded steel bars (6 mm diameter) using Restomix mortar (sample #42) and one specimen without any anchor materials (sample#69). Similar to the case of St. Canut specimens the trend of temperature profiles observed in all Ohio sandstone specimens was the same.

Because of the similarity to the unsaturated freeze-thaw test results, temperature results from saturated freeze-thaw tests and rapid freeze-thaw tests are not reported here.

3.2 Permeability Tests

The capacity of stones to dry from water absorbed during a precipitation event and during freeze-thaw cycles is a very important property for heritage masonry structures. Any strengthening or retrofitting measures that are undertaken to improve the life of a heritage stone masonry structure should not affect the hygrothermal properties of the walls. Permeability tests on stone specimens, both with and without anchors, were conducted to determine the effect of anchor installation on the permeability characteristics of stone specimens.

Four limestone specimens were used in the permeability tests. Of these, three were stones with embedded anchors and one was a control specimen without an anchor (sample #65). The limestone-anchor assemblies tested were an Aslan GFRP anchor with Sika grout (sample #1), a V.Rod GFRP anchor with Sika grout (sample #6) and a threaded steel anchor with Hilti epoxy (sample #11). The permeability characteristics of these assemblies were obtained and compared to the results from a permeability test on a limestone specimen of the same size and source. The results from these tests are shown in Figure 11. Moisture content readings were measured using embedded moisture measuring sensors. Permeability tests on limestone with steel anchor and Presstec grout combinations were discarded due to premature failure of these assemblies after freeze-thaw tests as discussed above.

As shown in Figure 11, limestone specimens with grouted anchors dried quickly compared to the control specimen. The drying curve of the limestone specimen with a steel anchor installed with Hilti epoxy anchor, on the other hand, matched that of the control specimen. It can be seen from Figure 11 that the maximum moisture content was not the same in all specimens. However, the maximum moisture content is not as important as the rate at which the stones dry. In this context, it can be said that grouted anchors appear to have changed the original permeability characteristics of limestone specimens.

Permeability test results from five Ohio sandstone specimens are presented in Figure 12. Of these five, four were stone-anchor specimens, and one was a control specimen (sample #70). Stone-anchor assemblies tested included: an Aslan GFRP anchor with Hilti epoxy (sample #33), a V.Rod GFRP anchor with Sika grout (sample #34), a threaded steel anchor with Presstec grout (sample #39) and a 6 mm diameter stainless steel pin set in Ohio sandstone with Restomix mortar (sample #42).

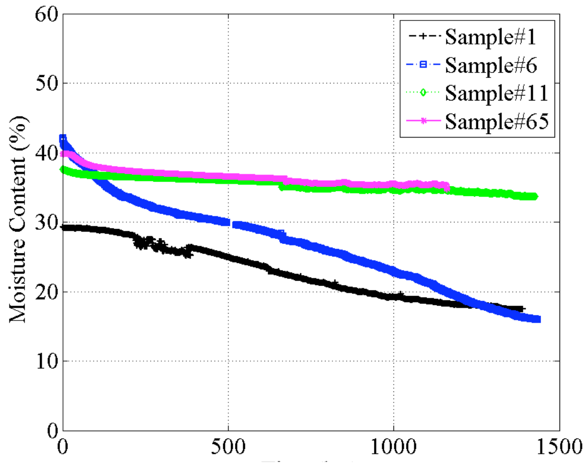

Figure 11: Drying curves of limestone specimens with and without anchors.

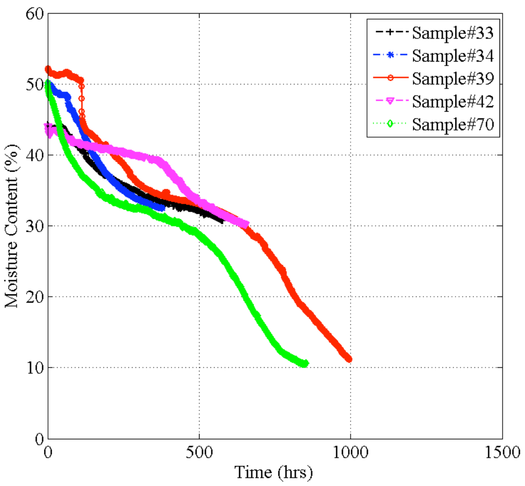

Figure 12: Drying curves of Ohio sandstone specimens with and without anchors.

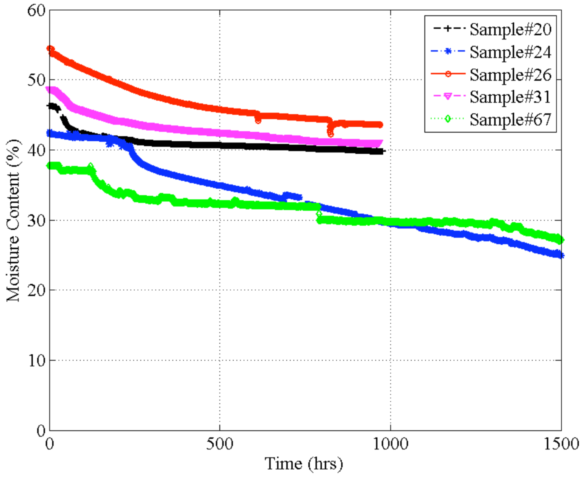

Figure 13: Drying curves of St. Canut sandstone specimens with and

As shown in Figure 12, the drying curves were somewhat similar for all specimens. In contrast to the limestone permeability test results, anchor installation appeared to have no effect on the permeability characteristics of the Ohio sandstone specimens.

Permeability test results from five St. Canut sandstone specimens are shown in Figure 13. Of these five, four were stone-anchor specimens, and one was a control specimen (sample #67). Stone-anchor assemblies tested included: an Aslan GFRP anchor with Hilti epoxy (sample #20), a V.Rod GFRP anchor with Hilti epoxy (sample #24), a threaded steel anchor with Hilti epoxy (sample#26) and a threaded steel bar with Presstec grout (sample #31). The rate of drying was similar in all the specimens tested. As with the permeability tests on Ohio sandstone specimens, anchor installation appeared to have no effect on the permeability behaviour of the St. Canut sandstone specimens.

4 CONCLUSIONS

Various stone-anchor assemblies were exposed to several tests so that the most compatible anchor and bonding agent could be selected for use in heritage buildings constructed from stones like those used in these tests. The stones used in the research program included St. Canut sandstone, Ohio sandstone, and limestone. Commercially available steel anchors along with GFRP anchors were also studied. The environmental compatibility study consisted of unsaturated and saturated freeze-thaw tests, rapid freeze-thaw tests, and permeability tests on stone-anchor assemblies.

Initially, all the conditioned stone specimens were subjected to 50 freeze-thaw cycles in each of three states: slow-unsaturated, slow-saturated, and rapid-saturated. During the freeze-thaw process, moisture and temperature profiles in the stones were recorded using embedded moisture sensors, also known as Duff gauge sensors. Stone-anchor specimens were also monitored to detect any debonding in stone-anchor assemblies due to exposure to freeze-thaw cycling.

Moisture profile data obtained from stone specimens, both with and without anchors, were analyzed to determine the impact of anchor installation on the moisture profiles in these heritage stones. Moisture content monitoring data showed that the moisture profiles in the stones exposed to freeze-thaw cycles were not altered by anchor installation. Temperature profiles in stone specimens, both with and without anchors, were also recorded during the freeze-thaw tests. Anchor installation had no effect on the temperature profiles in the stone specimens.

Permeability tests were conducted on several stone specimens, both with and without embedded anchors, after the freeze-thaw tests. The main objective of these tests was to investigate the impact of anchor installation on the rate of drying of absorbed moistures from the stone specimens. Except for some of the grouted anchors in limestone, anchor installation appeared to have no effect on the rate of drying in different stone specimens. Drying rates were found to be almost the same in stone specimens with and without anchors.

5 ACKNOWLEDGEMENTS

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