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Monitoring moisture levels in stone masonry using Duff gauge sensors

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Monitoring the moisture and temperature levels inside building envelopes of masonry structures is important to ensure their safe and long lasting performance. The presence of moisture within cavities can lead to frost damage and mould growth. Eventually, moisture in the envelope degrades the strength and integrity of a masonry structure. Monitoring moisture and temperature in masonry structures is greatly hampered by the lack of a simple and cost effective technique. Moreover, preservation guidelines for heritage masonry structures do not permit alteration of the original exterior appearance and texture. Thus, monitoring such structures is a complex task. One option for monitoring moisture and temperature is to use Duff gauge sensors with incorporated thermistors. Duff gauge sensors have been found to be reliable in monitoring moisture and temperature levels in brick masonry. These sensors were installed in masonry stones and moisture and temperature monitored while the stones were exposed to freeze-thaw cycles in both dry and wet conditions. Various types of anchors and anchor systems were installed in the stones in order to study their impact on the properties of the stones. Conventional Canadian masonry stones (e.g. St. Canut and Ohio sandstone, and limestone) were included in this study. A wireless data acquisition system facilitated real-time remote health monitoring of the test specimens. The data obtained will enhance our understanding of the impact of the various anchors on the performance of stone masonry.

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ABSTRACT: Monitoring the moisture and temperature levels inside building envelopes of masonry structures is important to ensure their safe and long lasting performance. The presence of moisture within cavities can lead to frost damage and mould growth. Eventually, moisture in the envelope degrades the strength and integrity of a masonry structure. Monitoring moisture and temperature in masonry structures is greatly hampered by the lack of a simple and cost effective technique. Moreover, preservation guidelines for heritage masonry structures do not permit alteration of the original exterior appearance and texture. Thus, monitoring such structures is a complex task. One option for monitoring moisture and temperature is to use Duff gauge sensors with incorporated thermistors. Duff gauge sensors have been found to be reliable in monitoring moisture and temperature levels in brick masonry. These sensors were installed in masonry stones and moisture and temperature monitored while the stones were exposed to freeze-thaw cycles in both dry and wet conditions. Various types of anchors and anchor systems were installed in the stones in order to study their impact on the properties of the stones. Conventional Canadian masonry stones (e.g. St. Canut and Ohio sandstone, and limestone) were included in this study. A wireless data acquisition system facilitated real-time remote health monitoring of the test specimens. The data obtained will enhance our understanding of the impact of the various anchors on the performance of stone masonry.

1 INTRODUCTION

The protection of heritage structures is important for future generations. In Canada, a significant portion of heritage structures is of stone masonry and the potential for the safe and enduring existence of these structures can be enhanced by adopting compatible strengthening techniques. For structures where the walls consist of inner and outer wythes of stone separated by a rubble core, anchoring the wythes together across the width of the wall can be a feasible option in this regard. Certainly this sort of “stitching” has been implemented in the past (Ellis, 1990; Lizzi, 1981). However, the anchors in such a strengthening technique are foreign materials with respect to the masonry and should be chosen so that they have no detrimental impact on the parent masonry materials. Zambas (1992) for example, reports on the use of lead to prevent water reaching steel reinforcement in elements of the Parthenon and on the use of titanium anchors to prevent the stone from splitting. Compatibility between foreign materials such as anchoring and parent masonry materials can be assessed by health monitoring of such masonry structures. Health monitoring of masonry structures can also serve to ensure continuous and satisfactory performance of masonry structures.

In order to test the compatibility between anchoring materials and certain Canadian masonry stones, stone-anchor assemblies were exposed to slow freeze-thaw cycles in both dry and saturated conditions, and then subjected to rapid freeze-thaw cycles. During the exposure to the freeze-thaw cycles, the moisture level and temperature profiles inside the stones were monitored. Understanding how the moisture content and temperature change over time under such conditions and which combinations of moisture, temperature and temperature gradient cause failure is necessary to improve our ability to attain good durability when using such anchors in heritage stone masonry enclosures.

Monitoring the moisture level and temperature within stones is a complex task. Moisture content-based wood electric resistance sensors incorporated with thermistors were used for this purpose. Duff gauge sensors were selected following their reliable performance in both laboratory and field applications for many researchers (e.g., Straube & Burnett, 2005; Ueno, 2008; and Wilkinson et al., 2007). In our work, the sensors were manufactured and installed by Structure Monitoring Technology Research Limited (SMT).

1.1 Background of sensors

1.1.1 Uncorrected moisture content of wood

One of the useful properties of wood is that its moisture content can be related to its electrical resistance (Garrahan, 1989). The relationship between the electrical resistance and moisture content of many North American wood species is shown in Figure 1. 90% of the test values for different wood species are represented by the shaded area in Figure 1.

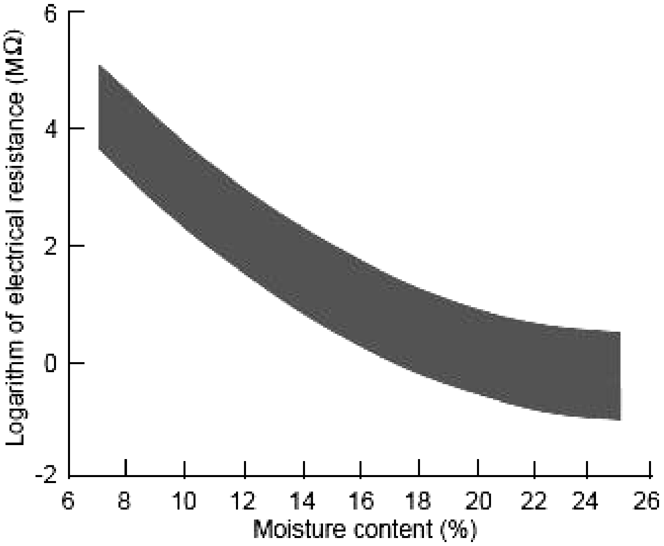

Figure 1. Approximate realtionship between mositure content and electrical resistance (measured along the grain at 27^0C) for many North American wood species (Simpson & TenWolde, 1999).

Straube et al. (2002) developed a realtionship between the uncorrected moisture content and the electrical resistance of wood (Douglas Fir) as follows:

$$log_{10}(M) = 2.99 - 2.113\left(log_{10}\left(log_{10}(R)\right)\right) \tag{1}$$

where M is the uncorrected moisture content of wood in mass % and R is the electrical resistance in Ω.

Most moisture content-based wood sensors are calibrated using Douglus Fir at room temperature. Corrections are then applied for other species and temperatures (Straube et al., 2002). For this project, sensors were manufactured from Western Hemlock by SMT. For this species moisture content was calculated using the following formula (SMT Research Ltd., 2008):

$$R = 5 \times 10^9 M^{-7.1449} \tag{2}$$

where R is the probe resistance in MΩ, and M is the uncorrected moisture content in the wood in mass %.

1.1.2 Corrected moisture content of wood

The electrical properties of wood vary from species to species and also from source to source. Wood moisture content also varies with temperature. To account for these variations, the moisture content obtained from Equation (2) should be modified according to the following formula (Garrahan, 1989):

$$MC = \left[\frac{M + (0.567 - 0.026T + 0.000051T^2)}{0.881(1.0056^T)} - b\right] \div a \tag{3}$$

where *MC* is the moisture content of the wood at 23^0C; *M* is the uncorrected moisture content obtained from Equation (2); *T* is the temperature of the wood in ^{0}C and *a, b* are species correction regression coefficients obtained from the drying curve for each sensor (Table 1).

1.1.3 Sorption isotherm

There is a relationship between the relative humidity in the sorrounding environment and the corresponding moisture content in wood. This relationship between the equilibrium moisture content of a porous medium and the environmental relative humidity is known as the sorption isotherm. The sorption isotherms for wood at different temperatures are shown in Figure 2. Based on these relations, Duff gauge sensors were built and installed in stone specimens of interest. It is noticeable that at low humidity levels, the slope is low and a small error in the moisture measurement will lead to larger errors in the estimate of moisture level within the specimen.

1.2 Calibration of Duff gauge sensors

1.2.1 Preparation of the dowel assemblies

Dowels for Duff gauge sensors were prepared from Western Hemlock which has a high absorbance capacity. Pine can also be used. Each dowel is 12 mm in diameter and 38 mm long. After removing any rough edges, each dowel was secured in a 12 mm diameter jig with a screw on each end. A channel was made in the dowel so that a 22 AWG (American wire gauge) wire could sit flush in the channel connecting the electric probes on both ends of the dowel. A notch was made on one end of the dowel with a 12 mm chisel to house a thermistor bead so that temperature could also be measured. A 9 mm deep, 3 mm diameter hole was drilled in each end of the dowel to allow stainless steel screws to be installed without cracking or damaging the dowel. The final wire harnesses is sealed with heatshrink (Figure 3).

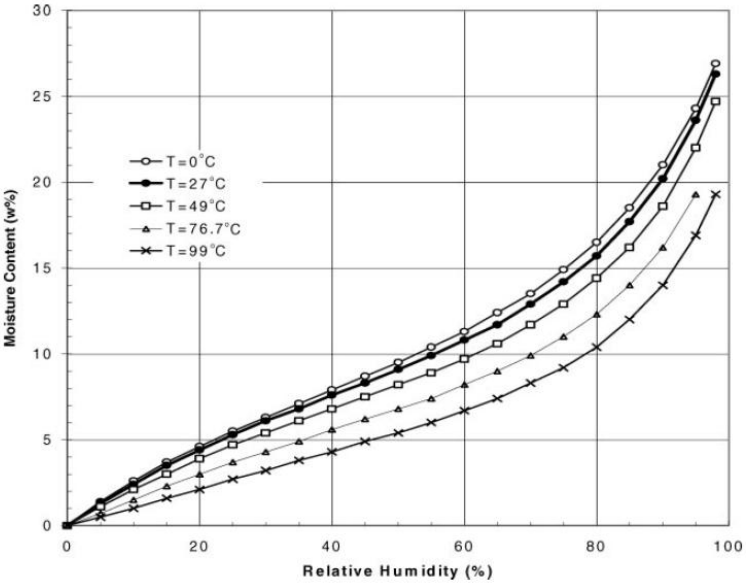

Figure 2. Average sorption isotherms for wood as a function of temperature (Straube el al., 2002).

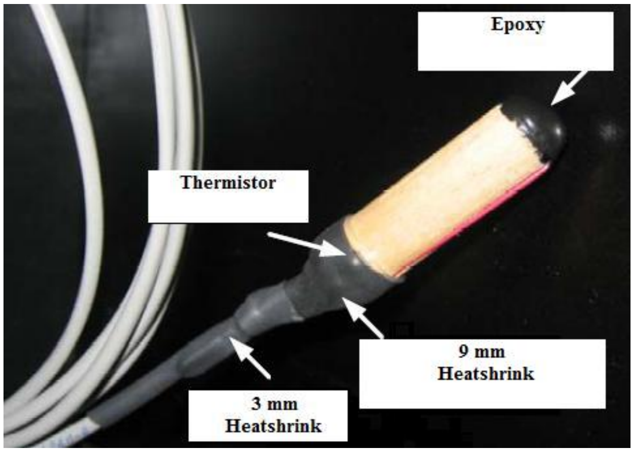

Figure 3. Duff gauge sensor with embedded thermistor (SMT Research Ltd., 2008).

1.2.2 Constant dry sample weight

The methodology described in ASTM D 2216-05 (ASTM, 2007) was followed to obtain the dry weight. The dry weight of the dowel assembly was measured. The dowel assembly was placed in an oven at 104^0C for 24 hours. The weight of the oven dried dowel was measured with a 0.0001 resolution calibrated scale and recorded as *W1*, and the dowel assembly placed back in the oven for a further 2 hours. The weight was measured again and recorded as *W2*. The process involved 2 hours of baking followed by measuring the weight. This was repeated until the difference between sequential measurements was within 1%. Once this condition was achieved the final weight was taken as the constant dry sample weight of that individual dowel assembly.

1.2.3 Dry curve formation

All dowel assemblies were soaked by immersion in water for 12 hours. After soaking, the dowel assemblies were removed from the container and excess water wiped off using paper towel. The assemblies were then placed in a controlled room at 21.5^0C and 50-55% relative humidity for 2 hours. After this holding period, samples were weighed and the weight recorded as *W3*. Using the wireless data acquisition system manufactured by SMT Research Ltd. (SMT-WiDAQ), the resistances of the dowel assemblies were measured and recorded. Once the resistance was measured, the assemblies were placed in the controlled room for a further 2 hours, after which they were sealed in an air tight container and placed in the controlled room for a minimum of 12 hours to reach equilibrium moisture conditions. The whole process of measuring W3 to attainment of equilibrium moisture conditions was repeated for 4 days. Example of a drying curve obtained from these tests is shown in Figure 4.

The equipment used to perform the resistance measurement on the calibrated wood is designed to measure a wide resistance range with high resolution. Also, the method of measurement has been optimized for measuring moisture content in building materials. In the area of moisture content consideration for building materials, i.e. between 10% to 30%, has a respective change of electrical resistance between 1GΩ to 100 KΩ. The features of the data acquisition unit (WiDAQ) designed by SMT Research is such that it uses 24-bit precision A/D converter capable of measuring accurately from 100 Ω to 1GΩ. The polarization effect or "diode effect" of wood over time is handled by having the WiDAQ take an averaged dual polarity measurement. The Center for Applied Research in Sustainable Infrastructure (CARSI) in Winnipeg did the calibration of the Duff gauge sensors.

1.2.4 Species correction regression coefficients

Species correction regression coefficients for each sensor were calculated based on its drying curve and Equation 3. Thirty-one sensors were used in this research work. The correction values for 10 sensors are shown in Table 1.

Table 1. Sensors species correction regression coefficients.

Duff gauge sensor no.	Species correction regression coefficients	
	a	b
1	1.0965	3.0958
2	1.0186	3.6952
3	0.6051	7.7982
4	1.5537	-2.9165
5	0.9832	4.8156
6	1.3778	-1.0052
7	1.1574	1.9929
8	1.5376	-2.9688
9	0.9816	2.6271
10	1.5150	-1.2554

2 TEST SETUP

2.1 Stone-anchor assembly preparation

Three types of stones those are common in the Canadian stone masonry heritage structures were tested - Ohio sandstone, St. Canut sandstone and limestone. Different types of commercially available anchors and Glass Fibre Reinforced Polymer (GFRP) bars were installed in each type of stone with cementitious grout and epoxy resin. Duff gauge sensors were installed in each stone-anchor assembly to measure and monitor the moisture and temperature profile at the centre of the assemblies while they were exposed to freeze-thaw cycles in the environmental chamber. The objective of using Duff gauge sensors was to examine which anchor-adhesive combination alters the original temperature and moisture profile in the masonry stones significantly, during exposure to freeze-thaw.

2.2 Duff gauge sensor installation

The sensors were installed in predrilled holes in the stone-anchor assemblies. The depth of each hole was such that the sensor was at the centre of that particular stone. While installing the sensors, the empty portion of the holes was filled with powder from the original stone (Figure 5). The upper portion of each hole was sealed using permanent epoxy so that moisture could not infiltrate to the sensors through these openings.

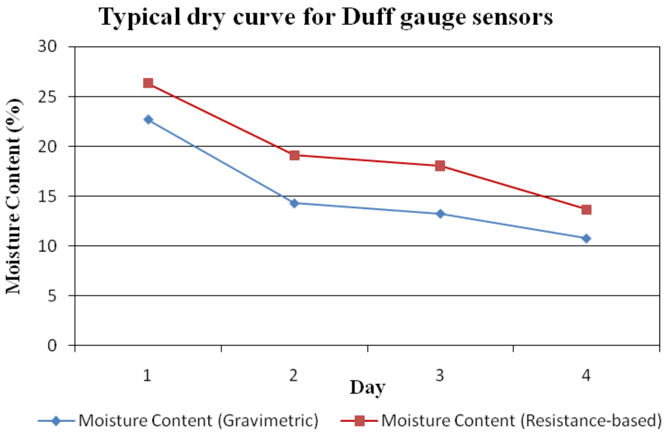

Figure 4. Dry curve for Duff gauge sensor number 1.

2.3 Freeze-thaw cycles

Each of the stone-anchor assemblies was exposed to 50 cycles of each of the three different freeze-thaw regimes - dry freeze-thaw, saturated freeze-thaw, and flash freeze-thaw cycles. During dry freeze-thaw cycles the environmental chamber (Figure 6) was programmed to maintain 0% humidity conditions while temperature was varied between -25^{0}C and +40^{0}C. During saturated and flash freeze-thaw cycles, the environmental chamber was programmed to maintain 100% relative humidity. The temperature variation was between -25^{0}C and +40^{0}C in the saturated freeze-thaw cycles, but only between -25^{0}C and +10^{0}C in flash freeze-thaw cycles. The dry and saturated freeze-thaw cycle temperature range was selected based on actual temperature data from the Ottawa region. The temperature cycles for the flash freeze-thaw test were selected based on the ASTM C666/C 666M-03 (ASTM, 2007) standard.

Figure 5. Duff gauge sensor installation; original stone dust used to fill the hole.

Figure 6. Stone-anchor assemblies with embedded sensors in the environmental chamber.

2.4 *Permeability test*

The permeability of a masonry wall reflects its capacity to drain out moisture after a precipitation event and is thus an important characteristic. Damage to masonry structures is sometimes related to the presence of moisture, because even a small quantity of moisture in a wall can be sufficient for mould growth (Black, 2006; Doll, 2002). The Institute for Research in Construction bench top drying test methodology was followed (Trischuk & Mitchell, 2004). The test procedure involves measuring the amount of water loss over time from saturated stone-anchor assemblies through the top surface of the stones. The Duff gauge sensors were used to provide additional data. The objective was to measure the impact of anchor installation on the permeability behaviour of the stones.

2.5 *Data collection*

Resistance and temperature readings from Duff gauge sensors were recorded using the SMT-WiDAQ. The readings were forwarded to the SMT monitoring laboratory via the internet. A predefined computer program converted the resistance readings into equivalent relative humidity readings. Real-time remote monitoring of the temperature and moisture conditions inside and also outside stones was thus facilitated via the SMT website.

2.6 *Conclusions*

The experimental program described here was designed to determine the compatibility of anchors in stones used in masonry structures in Canada. Different types of commercially available anchors were assessed. GFRP bars were also installed in stones to check the feasibility of using GFRP as an anchoring material. The stone-anchor assemblies were exposed to different freeze-thaw cycles and monitored using Duff gauge sensors with integrated thermistors. These sensors were also used to examine the impact of the anchoring materials on the permeability behaviour of the original masonry stones. Analysis of monitoring data from Duff gauge sensors would assist in adopting efficient preservation techniques with minimal impact on the original stones in masonry heritage structures. This research program is still in progress and the results will be published once the study is complete.

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