Critical Freeze/Thaw Saturation Measurement of In-Service Masonry

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ABSTRACT

When planning an insulation retrofit for an existing masonry building, it is important to analyze the freeze/thaw durability of the masonry units. The critical freeze/thaw saturation value is an important measure of durability, and frost dilatometry is an effective method of determining this value. This study reports developments in the field sampling of masonry units and critical saturation testing of in-service masonry.

The challenge when sampling masonry is to ensure that selected units are representative of the entire building or capture the range of material properties of units on the building. Two approaches to sampling are explored. Bulk sampling involves the removal of a large number of samples with the goal of randomly capturing the range of units of interest. Alternatively, field testing of a relevant material property can be performed to identify units that capture the range of material on the facade. A nondestructive field drying rate measurement technique is presented along with pilot study results suggesting it could completely replace the need for bulk sampling.

Significant variation in the permanent strain resulting from the frost dilatometry method has been found in previous testing. It is thought that this variation is due to lack of material homogeneity within the brick, resulting in variations between sample slices. It appears from the current study that use of the mean strain for as little as four samples at each saturation level will allow accurate determination of critical saturation. It further appears that use of a 95th percentile strain value for each saturation level could alternatively be used as a conservative method. Overall, the proposed new methodology was found to have a high level of reproducibility for critical saturation measurement.

INTRODUCTION

Older, load-bearing masonry buildings are common throughout North America. They are often in desirable urban locations, are aesthetically pleasing with architectural significance, and have solid structures and useful window areas and floor plans. Hence, they are good candidates for renovation and conversion. Given modern demands for low energy usage, thermal comfort, and carbon emission reductions, thermal insulation retrofits are a highly desirable part of renovation for this type of building stock.

From a building science point of view, adding insulation to the exterior of existing buildings is always the preferred approach for retrofits. This practically eliminates thermal bridging while simultaneously protecting the load-bearing structure from all exterior climatic elements. However, for aesthetic and historic reasons, the exterior of many load-bearing buildings must remain exposed, and interior retrofits must be considered. Unfortunately, the addition of interior insulation will change the thermal and moisture balance of any wall assembly and, in some cases, can initiate moisture problems such as freeze/thaw damage in masonry units by decreasing the drying capacity while simultaneously reducing the temperature of the inner wythes (Straube and Schumacher 2006). The increased risk of freeze/thaw damage has caused many designers and owners to avoid the addition of insulation altogether, thereby missing an opportunity that is rarely presented in many buildings.

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One method used to assess the risk of freeze/thaw degradation is frost dilatometry. The typical frost dilatometry process involves a site review and material sample collection, testing of project masonry units, hygrothermal analysis, and communication to inform project teams of the risks associated with various thermal insulation and other related retrofit measures. Case studies of such projects have been published (Ueno et al. 2013a) and the methodology described in detail in previous publications (Ueno et al. 2013b; Van Straaten 2014). A critical component of the methodology is to determine the performance threshold for the masonry at risk. Within the frost dilatometry methodology, a critical freeze/thaw saturation is determined and utilized in analysis. This paper describes critical saturation measurements along with recent developments in material sampling.

CRITICAL SATURATION BACKGROUND

Fagerlund (1977) found that porous, brittle materials below a certain moisture content level can be freeze/thaw cycled repeatedly without any measurable damage. Freeze/thaw damage can be quantified as irreversible growth in specimen volume, whose measurement is termed *dilatometry*. Freeze/thaw strain, Δ_{ft}, is calculated within the method from initial and post freeze/thaw length measurements, l_0 and l_{ft}, as follows:

$$\Delta_{ft} = \frac{l_{ft} - l_0}{l_0} \tag{1}$$

Fagerlund further found that freeze/thaw damage occurring at moisture levels above this critical saturation level is linearly proportional to the saturation level. This is illustrated in Figure 1, which shows a hypothetical critical saturation of 66% determined from the x-axis intercept of the strain of the damaged specimens (having strain greater than zero).

Freeze/thaw degradation of masonry is understood to be due to a number of mechanisms (Mensinga et al. 2010). A review of testing results from a number of projects did not reveal clear correlation of critical saturation with visible indicators (Van Straaten 2014). It was further shown that there can even be significant variation in sample lots where historical information and visible indicators suggest units were from the same manufactured lot. As a result of these factors, projects utilizing frost dilatometry to assess freeze/thaw degradation risk need to empirically determine the critical saturation of in-service masonry through lab testing. This study reports developments in field sampling and critical saturation testing of in-service masonry. Project brick testing results reported in the paper are all from testing completed by the authors.

FIELD SAMPLING OF MASONRY UNITS

Two general approaches to sampling are explored in this study. The challenge when sampling masonry is to ensure that selected units capture the range of material properties of units on the building. Bulk sampling involves removal of a large number of samples with the goal of randomly capturing the range of units. Alternatively, nondestructive field testing of a relevant material property can be performed to identify units that capture the range of material on the facade. Each method is presented separately in this section, examining current approaches, results of recent field applications, and a discussion of the practicality of each approach.

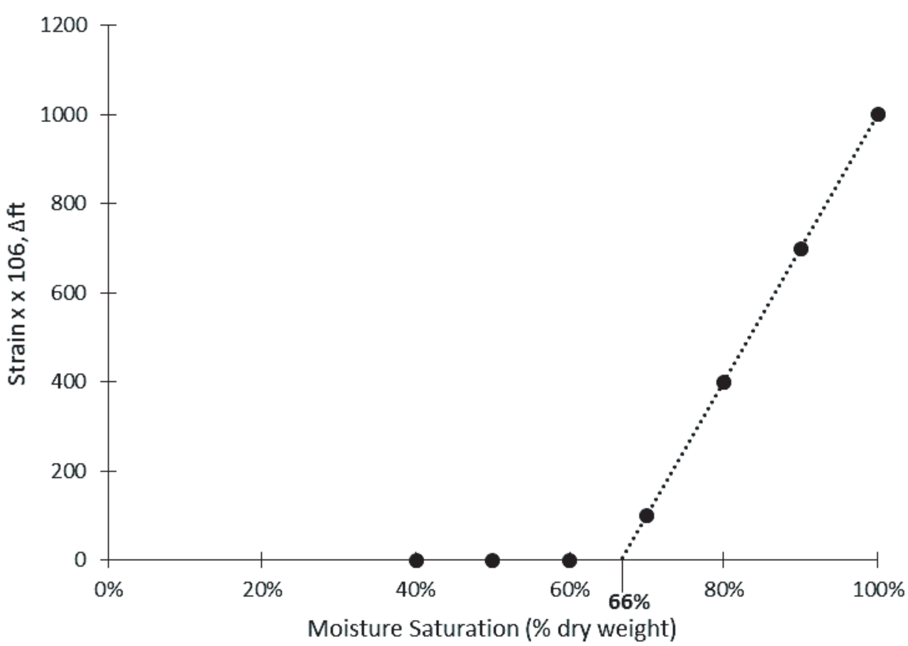

Figure 1 *Illustration of strain measurements after a number of freeze/thaw cycles.*

Bulk Sampling

Bulk sampling involves removal of a large number of masonry units from a building for testing. Assuming the bulk samples will be removed as part of a condition assessment for the building, the major limitation of this approach is the cost and timing required for full testing of a large sample set.

The sample size required for critical saturation testing has been reduced by characterizing and prescreening the population on the basis of water uptake testing. Water uptake testing is used for prescreening samples for three reasons: (1) it is used to derive liquid transport coefficients, which characterize capillary liquid transport (the dominant moisture transport mechanism in moist materials) (Wilson et. al. 1999); (2) the values reflect pore size distributions, which relate to a range of other properties; and (3) the measurements are done on whole sample units, avoiding the need for cutting and limiting the time required to obtain useful properties of the material.

Figure 2 shows water uptake results for a sample set of 47 bricks from an industrial to residential conversion project in Ottawa. The bricks are labeled in the plot with a number

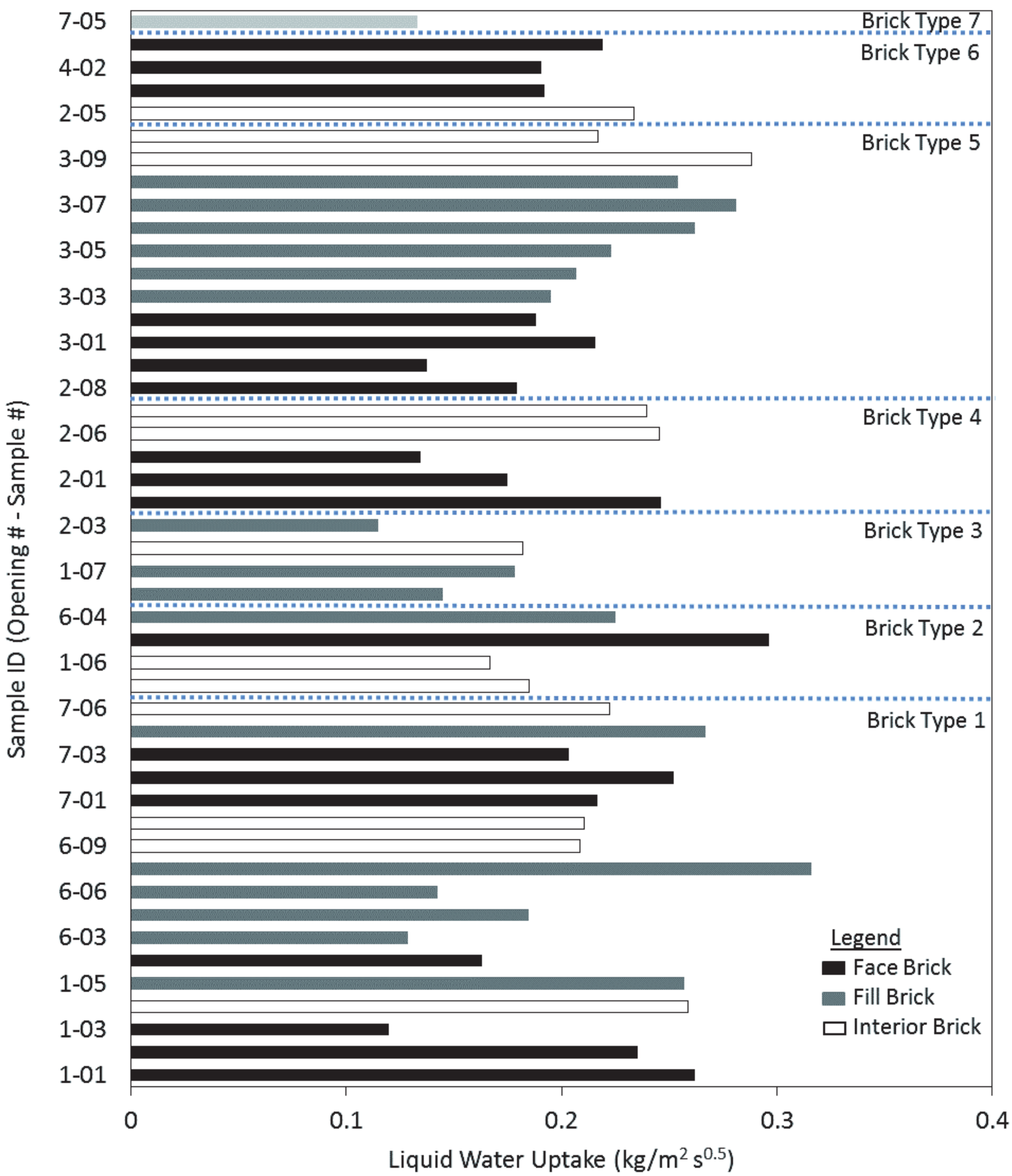

Figure 2 *Measured water uptake results for a large project sample set of 47 bricks.*

indicating their extraction location followed by a sample number (location#-sample#). The bars in the plot are black for exterior wythe bricks, gray for fill bricks, and white for interior wythe bricks. The bars are grouped into the seven brick types identified by different brick frog patterns. The variety of brick types was only revealed after they were removed from the building. The plot shows no correlations of visual characteristics with water uptake values; however, the water uptake values for this project were all similar. Within other projects, water uptake rates often vary by one or two orders of magnitude (Van Straaten 2014). For this project, the samples chosen for detailed testing primarily captured the different brick types and then secondarily the range of water uptake results.

The removal of a large number of bricks was feasible in this project due to the availability of samples from intrusive inspections performed to assess structural deterioration. A limitation to sampling using this approach is that the samples are not randomly selected. In many cases, openings will be targeted at areas of interest, typically with existing deterioration issues. Ideally the selection of intrusive inspection locations should be done in coordination with capturing masonry samples from areas showing the greatest vulnerability to freeze/thaw degradation.

In other projects, removal of a significant number of samples from a building can be both impractical and cost prohibitive. Challenges are most significant for projects with large stone masonry units or masonry units that are difficult to ship and replace. For these projects, nondestructive field tests are typically considered and will be discussed in the next subsection.

Nondestructive Field Testing

A common nondestructive field test for masonry is the RILEM tube test described by Driscoll and Gates (1993). The test results generally correlate well with water uptake. However, it is difficult to utilize RILEM tube testing to prescreen a large number of masonry samples due to the limited number of samples an operator can test in one day. It is also difficult, if not impossible, to test masonry with rough surfaces and/or significant cracks due to water leakage.

An alternative nondestructive screening test was developed by the authors using a Tramex Moisture Plus electrical impedance-based moisture content meter. This drying technique involves spraying 15 ml of water from a spray bottle held 20 cm from the target bricks at the start of the test. Moisture readings are taken before wetting and then two and ten minutes after wetting. The moisture content readings after wetting are expected to decrease (dry) as the water first redistributes to the interior of the brick and dries back towards the exterior. Drying (or drying/redistribution) rate is calculated as follows:

$$\dot{M} = \frac{M_{2min} - M_{10min}}{8min} \qquad (2)$$

The drying technique was piloted on a Chicago project. The various buildings were originally constructed in two phases, which is reflected by the cladding type (either red or beige bricks, see Figure 3). As a minimum, sampling from both brick types for the project was required and the drying technique was further applied to capture the range of material properties for both brick types.

Figure 3 *Photos showing the red brick and beige brick facades on the test building.*

Three locations were evaluated on the buildings with red bricks and five locations on the buildings with beige bricks. Eighty bricks were tested in approximately four hours. The operator only needed a step ladder, a spray bottle, the Tramex meter, and an audio recorder for recording results.

The initial moisture meter readings and drying rates are plotted in Figure 4 for these bricks. The red bricks tested at Location 3 were initially damp and had a low drying rate. However, the beige bricks at Locations 4 and 5 were also initially somewhat damp but had a wide range of drying rates. The remainder of the bricks had a range of drying rates and were all initially dry. The one exception was one of the beige bricks at Location 3, which was damp. This brick had a high drying rate but other dry bricks at the same location showed a similar drying rate. Based on these measurements, six red and six beige sample bricks were selected on the basis of capturing the range of drying rates and different initial moisture contents within the same wall areas.

A comparison of the lab water uptake measurements and field drying rates for sample bricks from the Chicago project selected for full testing is shown in Figure 5. A clear linear correlation was found for the red bricks. A nonlinear correlation is apparent for the beige bricks but is less clear.

The initial moisture content may vary based on material properties of the brick but will also vary based on exposure and assembly. It may be possible in future projects to conduct hygrothermal analysis for these specific locations using recent weather data to estimate masonry material properties and/or local exposure factors based on such initial moisture readings. It may also be possible to conduct the analysis immediately after the collection of the reading and use the result to assist with sample selection.

The correlation between the dry/redistribution rates suggests the technique could completely replace the need for bulk sampling. This would be quicker, allow evaluation of more samples, and impose less restrictions on sampling locations.

CRITICAL FREEZE/THAW SATURATION MEASUREMENT

Modern critical saturation measurement of bricks is described in detail by Van Straaten (2014). The process basically involves the following steps:

1. cut masonry into slices (typically 12 × 20 × 100 mm);
2. dry in oven, then cool to room temperature;
3. measure dry weights;
4. saturate with water by vacuum saturation;
5. measure saturated weights;
6. dry slices to a range of saturation levels;
7. measure initial lengths;
8. seal slices in plastic wrap;
9. freeze/thaw slices in chilled bath;
10. allow slices to warm to room temperature; and then
11. measure final lengths to determine strain.

Van Straaten (2014) also provided suggestions for a number of improvements aimed at reducing the time and cost requirements, including the following:

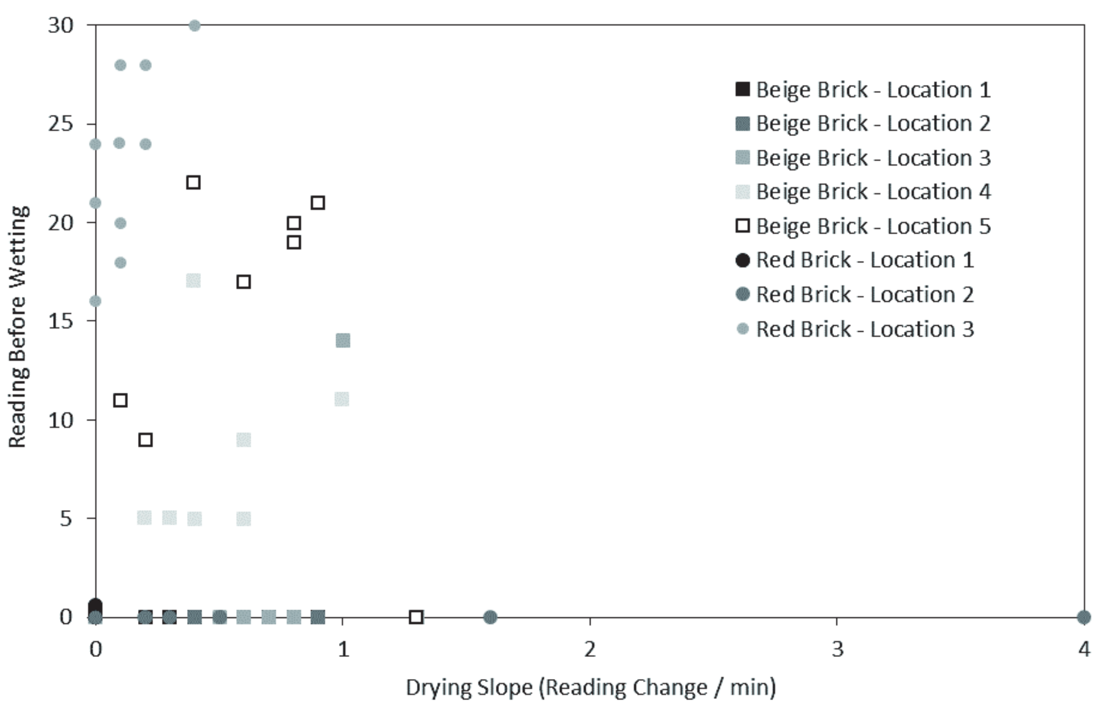

Figure 4 *Initial moisture meter readings and drying slope measured on project wall locations.*

1. direct measurement of the slice surfaces in lieu of set pins,
2. freeze/thaw cycle routine optimized to minimize runtimes, and
3. simplification of plastic sealing method.

A concern with the methodology is that for some materials it was found that length measurements were not repeatable. This issue was explored through a repeatability study of the slice length measurement and is reported in this section. Furthermore, high strain variance has been found for highly saturated samples in some cases after freeze/thaw cycling. A further study is also reported investigating this issue and evaluating the within-lab reproducibility of critical saturation measurements.

Sample Slice Length Measurements Repeatability

Limestone sample slices were cut from a single block on a table wet saw with guiding brackets to achieve square cuts. Limestone was used because it has a hard cut surface to limit mechanical wear from repeat testing. Three operators used a micrometer mounted within a measurement jig (see Ueno et al. 2013b) within the same lab to measure the length of limestone slices. The results of eight consecutive measurements of individual samples are shown in Figure 6 for six sample slices. Note that these measurements have all been done prior to freeze/thaw cycling in the lab.

A slight decline in the lengths of some samples can be seen and was suspected to be due to mechanical wear. The rate of wear, *m*, was calculated using a method of least-squares linear curve fit to each consecutive length measurement for individual samples with resultant values given in Figure 6.

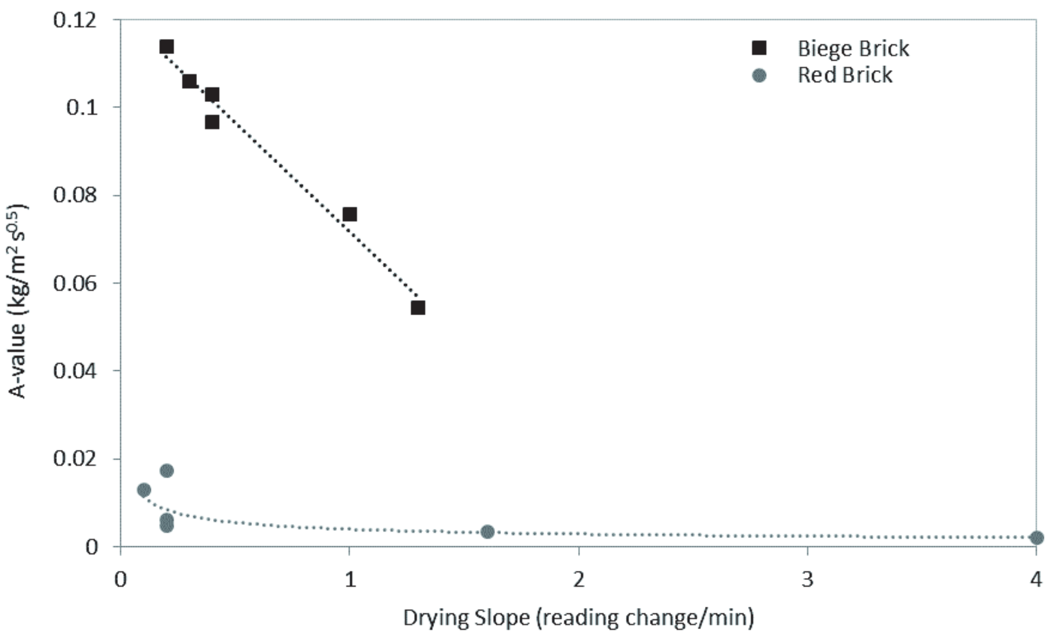

Figure 5 *Comparison of water uptake and drying measurement results for selected bricks.*

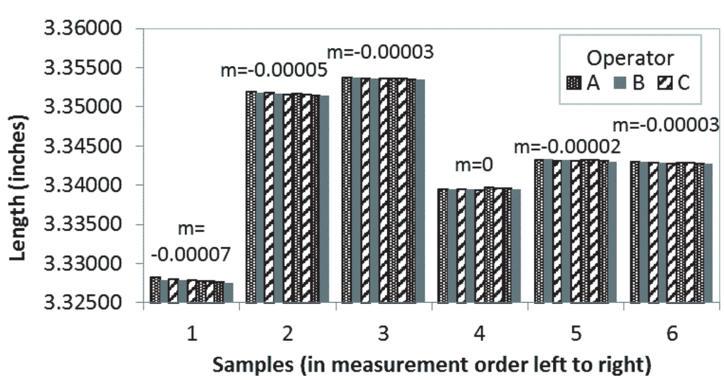

Figure 6 *Mean repeated length measurements of six sample limestone slices.*

To estimate the repeatability of length measurements, it was assumed that mechanical wear could be resolved in the future by repeating sample measurements until a consistent measurement was found. Equivalent strain values were adjusted for this rate of wear and calculated as follows:

$$\Delta'_{eq} = \frac{l_n - m(n-1) - l_1}{l_1} \quad (3)$$

The results of this calculation are shown in Figure 7 and suggest a repeatability of ±100 equivalent μstrain.

To account for potential mechanical wear effects, the testing methodology was modified as follows:

1. initial micrometer length measurements are repeated until consistent within ± 0.00005 in. (0.001 mm) to remove or set loose and/or soft surface materials, and
2. post freeze/thaw cycling slice length is only measured once to limit mechanical wear on the material surfaces by the micrometer.

The precision of critical saturation measurements including these modification were evaluated through a further within-lab critical saturation measurement reproducibility study presented in the next subsection.

Within-Lab Critical Saturation Measurement Reproducibility

Two operators measured critical saturation for slices from the same clay brick. For one operator, 12 slices were saturated to 80%, 90%, and 100%, for a total of 36 slices. The other operator used four slices at the same saturation levels. Testing of four slices at a number of saturation levels is more feasible for most projects, as collection of 12 slices would be expensive and may not be physically possible for some brick types. However, a larger number of samples was included in this study to explore variations in measurements.

Dilation measurements are given in Figure 8 for the slices after 12 cycles. Significant strain and variance were found for the 90% and 100% saturated samples. The 80% saturated samples show strain just above the length measurement repeatability and less variance. The graph includes an approximate plot of the Student T Test distribution (similar to Gaussian but adjusted for small sample lot sizes) based on the data set's mean strain, $\bar{\Delta}$, standard deviation, Δ, and number of samples. This variation in strain is thought to be due to lack of material homogeneity. The 95th percentile values, Δ, were calculated in an attempt to capture the materials within the brick that were sensitive to freeze/thaw degradation. The samples were subjected to a further 12 freeze/thaw cycles (24 in total). The results shown in Figure 9 show increased strain and variance.

The mean and 95th percentile strains are plotted relative to water saturation in Figure 10. Applying a method of least-squares fit resulted in a similar zero-strain intercept as for linear curve fits. The resulting critical saturation values are summarized in Table 1 within the "All Data" row. The same critical saturation value of 77.4% was found using the mean data while slightly lower critical values of 76.3% and 77.2% were found when the 95th percentile was used.

The results were further split between the two operators with results given in Table 1. Using the 77.4% critical saturation mean value measured from the whole dataset as a reference, the largest variation was 0.9% saturation. For the 95th percentile values and same reference, the largest variation was 2.6%.

CONCLUSIONS

This study reports developments in field sampling and critical saturation testing of in-service masonry. Two general approaches to sampling are explored. A method for prescreening samples from bulk sampling by water uptake testing is demonstrated. Within a case study of this approach, a number of issues are raised revolving around the low likelihood that actual random sampling will be applied in such sampling. A new alternative field testing approach for sample selection is presented. This nondestructive field drying rate measurement technique shows good correlation between measurements and water uptake. The technique used has an opportunity for further optimization, which should be explored in future stud-

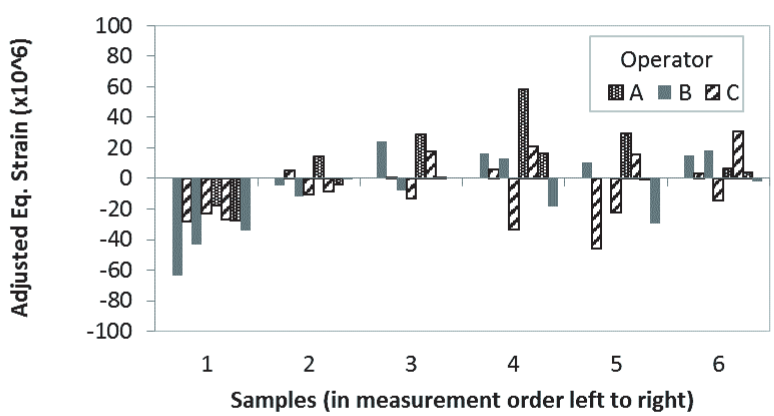

Figure 7 *Adjusted equivalent strain relative to first Operator A measurement.*

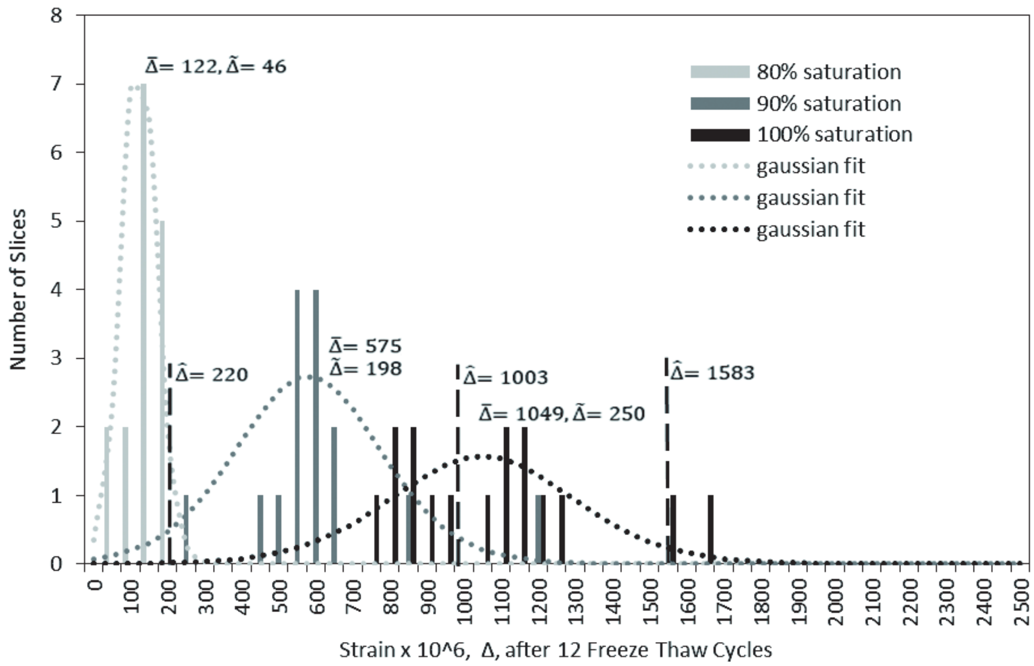

Figure 8 *Histogram of slice dilation measurements after 12 cycles.*

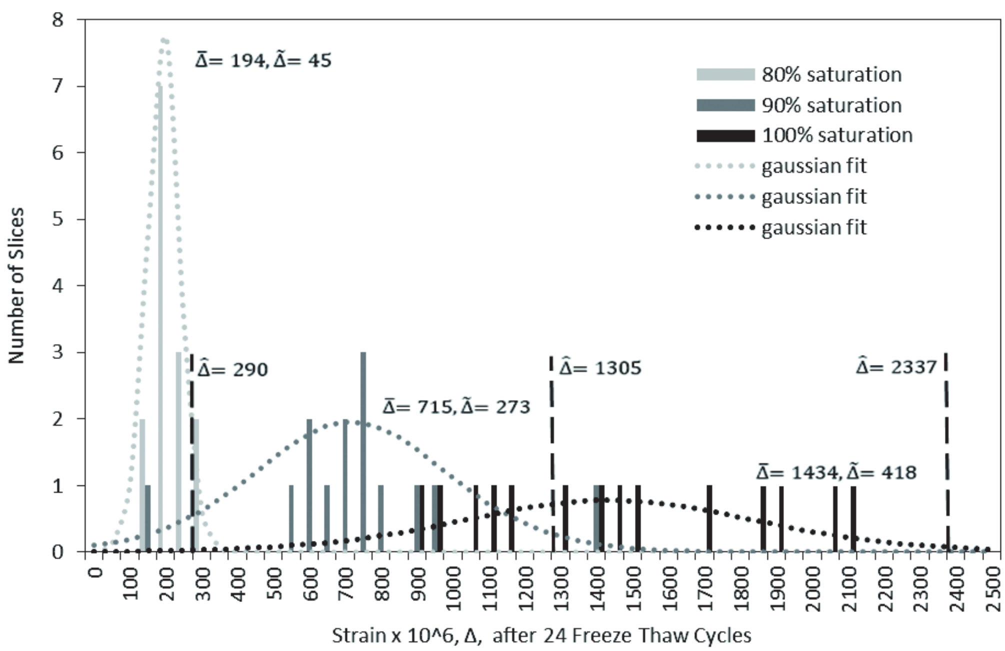

Figure 9 *Histogram of slice dilation measurements after 24 cycles.*

ies. It also presents an opportunity to provide initial moisture measurements, which may prove useful in sample selection and hygrothermal model calibration.

Significant variation in strain was found for freeze/thaw cycle slices at similar moisture saturation levels above critical saturation. It is thought that this variation is due to lack of material homogeneity within the brick resulting in variations between sample slices. The results suggest that use of a 95th percentile strain value for each saturation level will result in a slightly lower (more conservative) estimate of critical saturation.

It appears from the study that use of the mean strain for as little as four samples at each saturation level will allow repeatable determination of critical saturation. Overall, the study showed a high level of critical saturation measurement repro-

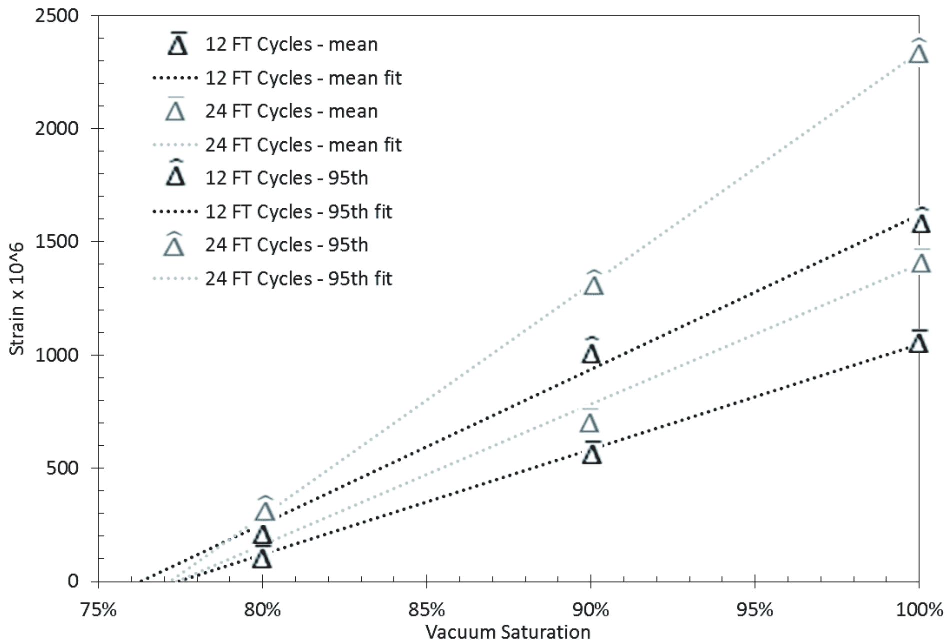

Figure 10 *Mean and 95th percentile strain after 12 and 24 freeze/thaw cycles.*

Table 1. Critical Freeze/Thaw Saturation Measurements

Operator	12 Freeze/Thaw Cycles			24 Freeze Thaw Cycles		
	# of Saturation Samples	Mean	95th Percentile	# of Saturation Samples	Mean	95th Percentile
All Data	16	77.4%	76.3%	14	77.4%	77.2%
A	4	76.5%	74.8%	2	77.0%	76.3%
B	12	77.4%	76.5%	12	77.6%	77.3%

ducibility using the new methodology described in the paper. This study should be repeated for a number of different masonry materials to allow greater confidence in the methodology.

ACKNOWLEDGMENTS

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NOMENCLATURE

m = rate of mechanical wear, in./measurement
M = moisture meter measurement value, dimensionless
$\dot{M}$ = drying rate, dimensionless/min.
n = total number of consecutive measurements
Δ = strain, in./in.
Δ' = adjusted strain, in./in.
$\underset{\sim}{\bar{\Delta}}$ = mean of strain measurements, in./in.
$\underset{\wedge}{\Delta}$ = standard deviation of strain measurements, in./in.
Δ = 95th percentile of strain measurements using Student T distribution, in./in.

Subscripts

eq = equivalent
ft = post freeze/thaw cycling

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