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Testing and Freeze-Thaw Durability Prediction for Clay Bricks

A Review of North American and European Developments

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***Abstract*—Prediction of freezing and thawing durability or frost resistance of clay bricks for masonry structures in North America and Europe has evolved into three philosophies since 1964. Qualification for severe weather exposure in North America is based on property based criteria or on omnidirectional freezing tests. In Europe, qualification is based on unidirectional freezing tests. Recently, investigators employ measurement of residual expansion after freezing in durability predictions.**

Keywords-frost resistance; durability; clay brick; testing; masonry; structures.

I. INTRODUCTION

The freeze-thaw durability of porous building materials to include clay bricks, concrete, and stone is reviewed by Litvan [1]. He discussed the mechanism of frost failures in materials with damage occurring when entrapped water solidifies. Litvan states, "This mechanism if not indigenous to any single type of solid, thus it is applicable to cement paste, stone, and bricks, and could be used for increasing the durability of porous materials and for improving test procedures".

There have been efforts to improve durability testing of clay bricks and thereby improve the prediction of durability performance in structures for over 80 years (TABLE 1). Three schools of thought developed over time with one "school" favoring the prediction of durability performance based on physical property assessments and with another "school" favoring performance testing. A third "school" developed recently with researchers measuring the effect of freeze thaw cycles on saturated brick by observing expansion phenomena. In some cases, national standards allow both as in the USA's ASTM C 216 – a brick can qualify for Severe Weathering (Grade SW) rating by meeting physical property criteria or alternately (and stated as equally) by performance testing in a laboratory freezer test [2].

The key idea is *qualify* as Grade SW. To quote paragraph 4.1.1. of C 216, "Brick (Grade SW) intended for use where high resistance to damage caused by cyclic freezing is desired". Note that the Standard does not say, "Where there will be *no damage* from cyclic freezing and thawing". In other words, there is always a chance of durability failures even with Grade SW bricks in severe exposure situations – as given in the Standard's Appendix X4.4 to include "horizontal and sloped surfaces, free-standing walls, parapets, chimneys, wing walls, and brick in contact with the ground".

Reflecting an architect's viewpoint, Koroth and co-workers [3] state, "The current American and Canadian standards for the evaluation of brick durability have, in certain cases, been criticized by researchers as time consuming, unrealistic, and inadequate". They continue, "These standards cannot be used for comparing the performance level of bricks." Koroth and associates conclude that there is a need for a new durability index.

Other researchers are more direct, "The primary shortcoming of predicting durability of a material based on the ASTM and CSA (Canadian) acceptance criteria is that they are based on an incomplete understanding of the physics of freeze-thaw damage, an oversimplification of field exposure conditions, and testing that focuses on unit, not material, response to freeze-thaw cycling" [4]. One reason for such criticism may be tests in standards are usually differentiated from scientific tests, in that the tests in standards are intended as practical and adaptive as quality control procedures in manufacturing.

II. EARLY EFFORTS OF THE U.S. NATIONAL BUREAU OF STANDARDS

In Europe prior to formation of the European Union, each country had a government-supported laboratory for each industrial sector such as bricks. In the United States the National Bureau of Standards (NBS) functioned in this capacity. J. W. McBurney of the NBS apparently published the original paper relating freezing and thawing resistance to physical properties of clay bricks [5]. Since the bricks tested in these early publications were made before vacuum de-airing, McBurney subsequently tested de-aired bricks for physical properties and with ambient exposure testing, reporting results in 1956 [6]. McBurney and Johnson concluded that "the current specifications apply to both de-aired and non-deaired brick".

Initial Developments

McBurney, 1933,
Absorption and Strength in Criteria
for Durable Brick (Non-deaired)

McBurney, 1956, Confirms Values for De-aired Bricks and Provides Field Exposures

Butterworth, 1964, Questions Property Based Durability Predictions

Property Prediction Approach	**Test Qualification Approach**	**Freezing Expansion Approach**
Robinson, Holman, and Edwards, 1977 Grade SW and the C67 Freezer Test	Peake and Ford, 1988 (U.K.) Correlation of Field Exposure and the British Freezer Cabinet Test (Omnidirectional Freezing)	Kung, 1985 Limit on Residual Expansion for Durable Brick
Maage, 1990 Prediction Based on Pore Sizes	Arnot, 1990; Dutch Freezer Cabinet (Omnidirectional Freezing)	Nakamura, 1988; Unidirectional Freezing and Expansion
Robinson, Butler, and Smalley, 1995; Use of Combined Indices Based on Properties	Vickers, 1993; Comparison of C67 Freezer Test with a Face Freeze-Thaw Procedure	Seaverson, 2003, Unidirectional Freezing by Cryogenic Dilatometry
Koroth, 1998; Combined Indices	Cobbledick, 1994; Unidirectional Freezing with Ultrasonic Defect Detection	Straube, 2010; Delineation of a Threshold Saturation for Freezing Expansion
Borchelt and Trimble, 2011; Grade Qualification and Field Exposures	Sanders, Brosnan, and Cobbledick, Rapid Face Freeze Thaw Procedure, 2003 & 2008	
	CSA A82-06 (2006); Altered Freezer Test Procedure for Canadian Exposures	

Figure 1: Time Line In Developments In Understanding Of Freeze-Thaw Durability Testing

A closer look at the results is warranted:

- Slightly over one percent of brick tested that met the boiling water absorption limit of 8% exhibited durability failures in exposure tests.
- With respect to saturation coefficient averages (exhibiting wide variations by plant or source), the data predicted failures correctly as observed field tests in 98.1% of 1438 bricks tested. Saturation coefficient is the quotient of cold water absorption and boiling water absorption.
- Many researchers consider an exposure tested of bricks partially buried in the ground in a frost prone climate as "severe".

McBurney concluded, "The current specifications apply to both deaired and non-deaired bricks". He further comments that Grade SW bricks "not exceeding 8% in boiling water absorption, irrespective of saturation coefficient, reasonably predict the (good observed) durability of … bricks considered in this investigation".

III. A Detractor and a New Path: Butterworth

In 1964, Butterworth considered property based durability and concluded that they were not sufficiently predictive of observed durability of bricks in structures [7]. It is important to note that Butterworth was a part of the British Research Establishment. Edgell reflects Butterworth's findings by saying, "There are many cases of frost resistant bricks, so defined (by properties in Standards), which fail to live up to expectation and conversely, many bricks that fail to conform to the standard but perform satisfactorily in severe exposure conditions" [8].

The significant problem for the British was that property based prediction of service performance with respect to freezing and thawing simply was not sufficiently accurate or precise. This is justified, in part, by Edgell who notes the very strong influence of firing temperature and duration (aka "heat work" or degree of sintering) on durability, meaning small variations in kilns or changes in sintering temperature to achieve certain colors *can or may* affect durability strongly. The result was a divergence of opinion in global standards that persists until today.

IV. ROBINSON, HOLMAN, AND EDWARDS INFLUENCE AMERICAN STANDARDS

Robinson, Holman, and Edwards created a specimen set of 5,217 "commercially acceptable" bricks, determined absorption and strength properties, and tested them in the freezing and thawing method in 1977 [9]. They say, "despite criticism leveled at this work (with work referring to McBurney and prediction of durability based on physical properties), it continues to serve as the basis for the present day specifications in the U.S". The criticism was from Butterworth [7].

They found that 5.6% of bricks meeting the physical prope*rty requirements for Grade SW in ASTM C 216 subsequently* failed in the freeze thaw tests given in ASTM C 67; i.e., the overall assurance of a brick as being durable as defined by the freezer test was 94.4%. For the specific properties tested the percentage passing the freezer test were according to the author's Table V:

1. Boiling Water Absorption <8% - 57.8% (3016 passed the freezer test /5217 total tested).

2. Saturation coefficient <0.78, - 66.0% (3441 passed the freezer test/5217 total tested).\

The conclusion reached by the authors is that a combination of properties would better predict durability in service. The combinations suggested would be specific saturation coefficient maximums (or initial rate of absorption ranges) for boiling water absorption being above or below a specific value.

Further analysis of the author's data provides the following conclusions:

- McBurney found 98.1% of "modern" bricks meeting 1960's Standards passed exposure tests in Maryland, and Robinson found 94.6% of commercially acceptable bricks essentially meeting USA specifications to also pass the freeze-thaw test described in ASTM C 67.

- Reliance on a single property, such as saturation coefficient, may qualify a brick for Grade SW, but it gives a prediction of performance with less than 66% confidence; assuming that the C67 test is correlated with field performance (a topic to be addressed below).

In 2011, Borchelt and Trimble reported on results of a 10-year study of field exposure panels with correlation with brick properties [10]. The results are presented in Table 1, and the results define expectations for exposures in climates similar to those in the test panel sites of Manassas, VA, Saginaw, MI, and Lantz, Nova Scotia (all "extreme" weathering sites).

The overall results for modern bricks, as presented by Borchelt and Trimble, show that a confidence level of bricks qualifying as Grade SW by physical properties and/or the C 67 freezer test in severe weather exposure is on the order of 50-65% for successful service. This is a considerably lower value that found by McBurney in 1955, although it is significant that McBurney tested bricks with boiling water absorption less than 8%.

Having these observations, it is important to put the results in *perspective*. It is obvious that bricks qualifying as Grade SW do not fail in 35 – 50% of structures. In fact, Grimm cites his experience that insufficient materials are implicated in only 15% of masonry failures [11], and that estimate is from a very large population of masonry buildings with no significant failures. The perspective emerges that the Grade SW qualification for bricks in the USA, while sufficient as a general goal for products, is not a confident *predictive tool* for performance in severe weathering conditions.

TABLE 1: RESULTS OF FIELD EXPOSURE TESTS FOR BRICKS MEETING GRADE SW BY PROPERTY AND/OR FREEZER TESTS

Brick Types	**Qualification for Grade SW**	**Percent With No Degradation in Field Panels**
All – molded and extruded	Properties	64.1
Extruded	Properties	48.1
All – molded and extruded	Freezer Test (C 67)	61.1
Extruded	Freezer Test (C 67)	48.1
All – molded and extruded	Properties and Freezer Test (C 67)	66.7
Extruded	Properties and Freezer Test (C 67)	53.3

V. MAAGE'S DURABILITY PREDICTION INDEX

Magne Maage developed a calculated frost resistance or index in 1990 based on mercury porosimetry measurement of pore sizes in bricks [12]. His index was based on total pore volume and the proportion of pores above three microns in diameter, i.e. those pores that were sufficiently large to not experience excessive saturation and undue forces to the expansion of water on freezing. In 2008, the Maage index was found to produce similar ratings of brick durability as obtained by absorption measurements [13]. Edgell says, "The reliability of these techniques (mercury porosimetry) is not sufficient to gain widespread acceptance by brick manufacturers or others" ([8], p. 34).

VI. UNIDIRECTIONAL TESTING

With the perspective of Butterworth [7] that the property specifications and freezer test (ASTM C 67) were insufficiently predictive of service performance, efforts in the United Kingdom were focused on a test simulating the way that freezing occurs in a typical wall, i.e. freezing from one direction starting with the exposed brick face inward toward the insulation on a heated building. The perspective is that a typical freezer test (as in C 67) causes freezing of water within bricks simultaneously from all faces – a situation called "omni-directional" freezing resulting in many failures by major cracks developing in manufacturing defects like laminations or firing cracks. Developing a freezing test with freezing from one direction, i.e. "unidirectional freezing", became the chosen course of direction, and it was found that such tests produce failures in non-durable bricks of the same types seen in walls (importantly as mortared assemblies).

Edgell describes the details of test development and correlation with field exposure panels in Scotland [8]. The key correlation of the test to exposure panels reported by Peake and Ford are the basis of the method's ultimate acceptance [14]. Edgell further chronicles that European Union's efforts through CEN Technical Committee 125 to choose a standard test from among those including German, Dutch, and France. The end result is that the "British Freezer test" was found as the most accurate qualifying test method when correlated with exposure panels (prEN 772-22 or BS 3921). This test uses a cured 10-course mortared panel of three stretcher brick width that is preconditioned by water immersion for seven days and exposed sequentially to 100 cycles of freezing, thawing, and re-wetting. Bricks without damage after the test are regarded as fully frost resistant or Grade F.

Realizing that the apparatus for the British Freezer test was expensive and the time to qualify bricks as frost resistant was considerable, Vickers developed a freezer test to simulate unidirectional freezing [15]. In this test, bricks at 5-hour boiling water saturation were frozen and one face was allowed to temporarily "defrost" over a hot plate prior to refreezing of the complete unit in the test. Thus, the freezing and thawing was from one face or unidirectional even though a conventional chest freezer was used. Vickers found that 10% of the Grade SW samples qualified by absorptions subsequently failed the standard freezer test per ASTM C67, but when he increased the saturation in the standard freezer test to 5-hour boiling water he observed 62% of the specimens to fail – with a predominance through defects such as pre-existing cracks. In his face freeze-thaw procedure at 5-hour boiling water saturation, he found 33% of Grade SW bricks to fail.

Cobbledick [16] also developed a unidirectional freeze-thaw test after finding a paper by Nakamura [17]. Nakamura used a Peltier cooling plate to accomplish freezing and monitored residual expansion of 5-hour boiling saturated specimens and their weight loss in cyclic freezing and thawing. While his data did not correlate with other methods, he produced cracking failures in his unidirectional method parallel to the exposed freezing face. Cobbledick used larger brick specimens monitoring the depth of cracks using ultrasonic finding cracking parallel to the exposed freezing face.

Cobbledick's ideas influenced Sanders and Brosnan [18] to develop a "rapid freeze thaw test" that placed saturated bricks in a freezer cabinet in pans of water over silicone heating pads providing for sequential partial defrosting of the brick face while contained in the freezing environment. This technique allowed accumulation of 50-cycles of freezing and thawing in less than two weeks as compared to about 12.5 weeks to complete the freezer test in ASTM C 67. In another paper, Sanders, Brosnan, and Cobbledick used the method to compare results to C 67 and Canadian test methods [19].

VII. THE CANADIAN EVOLUTION IN STANDARDS

John Storer-Folt of Canada Brick (now Hanson Brick) made significant contributions to the understanding of freeze-thaw durability. He recognized limitations on the ASTM C 67 method and the fact that many Canadian Brick of known durability failed to qualify as Grade SW under C 216. Storer-Folt, Cobbbledick, and others initiated a research program through the Clay Brick Association of Canada and conducted at the National Research Council (Ottawa). In this program the so-call Dutch Freezer Cabinet (unidirectional freezing) was employed in frost-resistance testing. The results were published by Arnot and Maurenbacher [20].

Storer-Folt made the key observation that the average saturation of bricks declined in the C 67 freezer cabinet method the five day test procedure when bricks were stored in the drying room over the weekend during the course of 50-cycle testing. That meant the C 67 test became progressively less severe during the course of the test.

The C 67 test was altered to include storing bricks in the freezer over the weekend to maintain constant saturation during the 50-cycle sequence, and the revised test was found to provide similar results as those of the Dutch freezer cabinet. For this reason, the revised procedure was incorporated in the Canadian Standard A82-06. The consensus was that this revised test was more severe than the method in C 67 and better predictive of durability in Canadian environment since it maintained a constant level of saturation in bricks being tested for the duration of cyclic exposures.

VIII. ROBINSON AND COMBINED PROPERTY INDICES

Robinson published two articles in 1995 regarding the prediction of frost resistance [21]. While he acknowledged a publication by Butterworth and Baldwin [22], he confirmed that his pursuit of the property qualification approach as due to reducing time for qualification from 50-70 days (freezer method) to two days (property method). In the first paper, the authors employed a number of physical tests to include capillary suction ("capillarity" as similar to extended IRA tests), air permeability, mercury porosimetry, and strength tests. The authors concluded that combinations of properties such as absorption and capillary suction or absorption and an index of strength where more predictive of bricks passing the C 67 freezer test than use of the saturation coefficient. There was no correlation to field performance.

In a second article, Robinson and associates employed additional freezing test methods to include the C 67 test, the C 67 test at boiling water saturation, the "Vickers test" [15], a unidirectional freezing panel test, a freezer test where the brick were saturated on one face only (called the "gradient test"), and a sulfate crystallization test. Robinson concluded that each test produced a different failure process in the bricks. For example, the sulfate crystallization test results reflected the "fired bond" developed in bricks due to vitrification. In the freezer test a boiling water saturation, the test was adept at revealing manufacturing flaws such as cooling cracks, bridge strains, and uneven density. Robinson's novel moisture gradient freeze that test provided results at least similar in crack development to the Vickers unidirectional freezing test, and this approach merits the attention of future researchers. In general, the Vickers and gradient tests produced more failures than the ASTM or unidirectional freezing panel tests.

IX. A THIRD DIRECTION – FREEZING EXPANSION AND DURABILITY

To this point, the estimation of durability was either through property qualification or through testing in either unidirectional or omnidirectional freezer cabinet testing. In 1985, Kung concluded that freeze-thaw durability is so dependent on absorption characteristics and heat work (in kilns) that another type of evaluation of potential durability was required [23]. After conducting tests measuring expansion of saturated bricks on freezing and residual expansion after defrosting, Kung proposed 0.15% residual expansion after freezing and defrosting as a discrimination point defining non-durable bricks. He estimated the accuracy of this prediction as 93% and found that his criteria would reject only about two percent of durable bricks.

Kung thusly measured the *consequence* of freezing as an index of durability. This was followed by Seaverson who used cryogenic dilatometry to measure freezing expansion and residual expansion of bricks at 5-hour boiling water saturation [24]. In turn, this was followed by the work of Straube [4] defining a threshold in absorption when residual expansion is observed. Straube and co-authors concluded that moisture content in walls should be held below the threshold saturation, but he did no damage assessment in the laboratory or through field exposure panels to prove his theory. Note that Fagerland also used a "critical saturation" in assessing the freeze-thaw resistance of concrete [25]. Further, Nakamura also suggested that observation of freezing expansion with bricks has "several technological advantages" over the conventional freezer test in terms of "facilities, data processing procedures, and saving time" [17].

X. REVIEWS OF TEST METHODS AND NEW DIRECTIONS

Borchelt, Edgell, and Frederic compared a modified C67 freeze-thaw test to the British panel test in 2003 [26]. This test modified the C 67 procedure to include storage of bricks submerged in the thawing tank over the weekend, so the results were not a straightforward comparison using the C67 test (due to higher average saturation, and may be considered as similar to the Canadian test). The authors conclude, "The property requirements classification under ASTM (C 216) appears to be conservative, but not entirely accurate. Two brick classified by properties as SW under the North American System failed one of the C 67 freeze-thaw test". A further examination of the data shows "delamination" and face cracks of all U.S.A. Grade SW bricks in the British test (BS 3921 or prEN 772), yet they retained a "frost resistant" grade in the European test.

Koroth and others used pore size distribution, as by Maage, and combined the results with either water absorption or capillarity to arrive as a "combined predictive index" for durability [3]. They found a good correlation with a rapid freeze-thaw test but offered no correlation to a standard test or to exposure panels. In effect, they reached a similar conclusion as Robinson [21] that use of combined physical properties provided better results than use of a single property for durability prediction.

XI. CONCLUSIONS

From 1933 to 2014 (80+ years), excellent research has been published providing insights into freezing and thawing resistance in clay bricks. Relative tendencies of bricks in certain environments are known by experience and through correlations with field exposure panels. Reliance on physical properties to predict durability, as in existing USA Standards, apparently provides only moderate confidence in successful performance in frost prone areas. In his final advice to the US brick industry, Robinson suggested scrapping the saturation coefficient criterion in ASTM C 216 in favor of a combination of properties depending on a threshold of 6% boiling water absorption [21]. This allows manufacturers to exceed the 6% boiling water absorption if a minimum index of "fired bond" is achieved, a conclusion essentially reached 50 years earlier by McBurney [5]. Reliance on a performance test, such as in prEN 772-22, remains a choice for qualifying bricks as durable in Europe.

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