Mechanical and environmental characterization of new and reclaimed brick for use in Canadian masonry construction

by

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Abstract

The number of freeze-thaw cycles is expected to grow with climate change in northern latitudes, prompting a growing emphasis on mitigation strategies in the masonry construction industry in Canada. While also addressing the stricter energy requirements in recent decades, masonry construction has seen a shift from traditional thick and solid masonry walls to energy-efficient ventilated cavity-walls, meant to promote drying and also improve the building's energy efficiency. Despite these advancements, the growing environmental awareness movement of the 1970s has caused the rise in popularity of reclaimed brick used in modern construction, yet these bricks are more susceptible to freeze-thaw damage. Additionally, faulty construction of cavity-walls can still cause them to be vulnerable against freezing and thawing. Bricks used in modern Canadian construction must conform to the requirements of CSA A82:14 *Fired masonry brick made from clay or shale*, which includes several mandatory environmental and mechanical tests. However, past studies suggest that the performance of bricks in the field are inconsistent with laboratory test results. The CSA A82:14 durability requirements are unreliable, as bricks that have failed the laboratory tests have performed well in service and others that have passed have proven to be not durable. Also, it is unclear whether CSA A82:14 is applicable to reclaimed brick due to a conflicting clause in the NBCC Part 9. In this paper, the mechanical and environmental properties of eleven different bricks – both new and reclaimed – will be compared. These properties include freeze-thaw resistance, 24-h cold water absorption, 5-h boiling absorption, saturation coefficient, and compressive strength. Their compliance with CSA A82:14 will also be verified.

Résumé

Le nombre de cycles de gel-dégel devrait augmenter avec le changement climatique dans les latitudes nordiques, ce qui met l'accent sur l'importance des stratégies d'atténuation dans l'industrie de la construction en maçonnerie au Canada. Tout en répondant également aux exigences énergétiques plus strictes des dernières décennies, la construction en maçonnerie a connu une évolution des murs de maçonnerie traditionnels épais et solides vers des murs à cavité ventilés écoénergétiques destinés à favoriser le séchage et à améliorer l'efficacité énergétique du bâtiment. Malgré ces avancées, le mouvement croissant de sensibilisation à l'environnement des années 70s a entraîné une augmentation de la popularité des briques récupérées dans la construction moderne, bien que ces briques soient plus sensibles aux dommages causés par le gel-dégel. De plus, une construction défectueuse des murs à cavité peut encore les rendre vulnérables au gel et au dégel. Les briques utilisées dans la construction canadienne moderne doivent être conformes aux exigences de la norme CSA A82:14 *Brique de maçonnerie cuite en argile ou en schiste*, qui comprend plusieurs tests environnementaux et mécaniques obligatoires. Cependant, des études antérieures suggèrent que la performance des briques sur le terrain est incohérente avec les résultats des tests en laboratoire. Les exigences de durabilité de la norme CSA A82:14 sont ne sont pas fiables, car les briques qui ont échoué aux tests en laboratoire ont bien performé en service et d'autres qui ont réussi se sont révélées non durables en service. De plus, il n'est pas clair si la norme CSA A82:14 s'applicable aux briques récupérées en raison d'une clause contradictoire dans la partie 9 du CNB. Dans cet article, les propriétés mécaniques et environnementales de onze briques différentes – neuves et récupérées – seront comparées. Ces propriétés comprennent la résistance au gel-dégel, l'absorption d'eau froide pendant 24 heures, l'absorption de l'ébullition pendant 5 heures, le coefficient de saturation et la résistance à la compression. Leur conformité à la norme CSA A82:14 sera également vérifiée.

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1 Introduction

1.1 Climate change trends in Canada and its influence on masonry infrastructure

Unprecedented changes in climate patterns have been observed worldwide since the mid-18th century. The excessive burning of fossil fuels during the First Industrial Revolution caused drastic rises in greenhouse gas emissions, which has been the primary cause of global warming. The annual global mean surface temperature (GMST) has risen by over 1˚C between this era and the years 2015–2017. Remarkably, just between 1948 and 2016, the annual GMST has increased by 0.8˚C. Within this same time frame, Canada has experienced an increase of 1.7˚C in annual mean surface temperature (MST). Hence, surface temperatures in Canada rise at over double the rate compared to global values. Both current data and future projections support this data. In Northern Canada, the annual MST has increased by 2.3˚C, nearly triple the global mean. Different regions of the world are subjected to different levels of global warming. High northern latitudes have been observed to experience the highest degree of global warming due to ideal geographic conditions for climate feedback mechanisms. Such mechanisms include the snow/ice albedo feedback, which is when snow and ice melt, the surface reflectivity diminishes due to its darker colour and warming is accelerated. As such, climate change is especially concerning for Canada (Bush & Lemmen, 2019). As for future projections, the annual MST in Canada is expected to rise acutely. Between 2016 and 2035, surface temperatures are predicted to increase by 0.9–1.7˚C for a low-emissions scenario (RCP2.6) or by 1.1–1.9˚C for a high-emissions scenario (RCP8.5) relative to the 1986–2005 average recorded temperature (Figure 1.1) (Government of Canada, 2019).

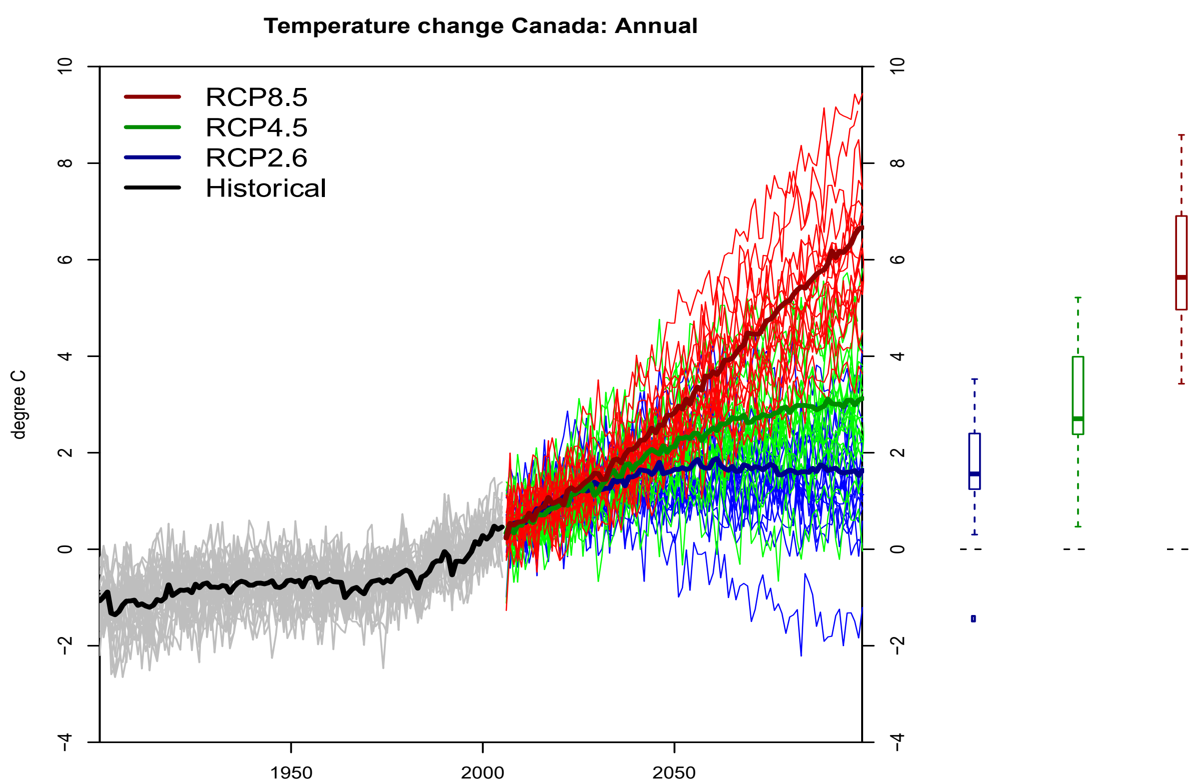


Figure 1.1. Prediction of temperature change in Canada based on three emissions scenarios (Gov. of Canada, 2019)

Temperature extremes are also changing due to climate change. Warm days are defined as days where the highest temperature is above the daily 90th percentile whereas cold nights are defined as days where the lowest temperature is below the daily 10th percentile. Based on data from the majority of monitoring stations, the number of warm days has increased and the number of cold nights has decreased annually between 1950 and 2010 (Warren & Lemmen, 2014).

Atmospheric humidity has increased as a consequence of global warming since warm air can retain more moisture than cool air. With every additional 1˚C the atmosphere warms, the atmosphere can hold 7% more water. Thus, higher levels of precipitation are expected across Canada. However, robust data is scarce due to the variability of precipitation patterns, complexity of collecting data, and lack of longstanding monitoring stations. Normalized precipitation, which is precipitation divided by its prolonged mean, is alternatively used to determine trends. Between 1948 and 2012, there has been a 20% rise in average normalized precipitation in Canada. In Northern Canada, the average normalized precipitation has increased by 30%, although the reliability of this value is questionable (Bush & Lemmen, 2019). Future projections for 2016–2035 suggest that precipitation will change by -1.6–10.4% for RCP2.6 or -0.8–11.4% for RCP8.5 relative to the 1986–2005 average recorded precipitation (Figure 1.2) (Government of Canada, 2019).

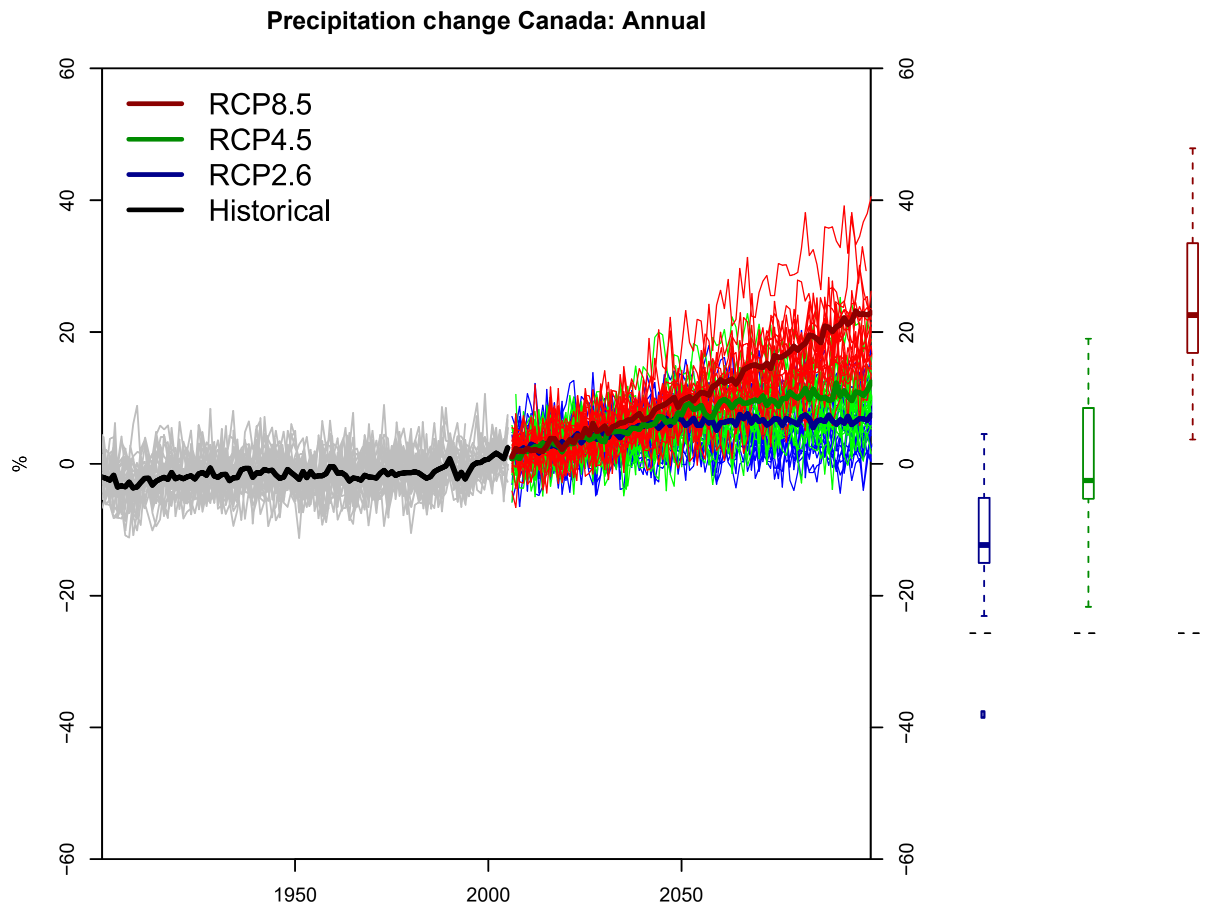


Figure 1.2. Prediction of precipitation change in Canada based on three emissions scenarios (Gov. of Canada, 2019)

Between 1950 and 2010, Canada's annual precipitation (snowfall and rainfall) has increased by 16%. The precipitation observed in spring and fall has increased; however, winter precipitation has decreased. Snowfall has been steadily declining but winter rainfall has remained constant, which explains this trend. Exceptionally in certain regions of Southern Canada, precipitation is expected to decrease during the spring and fall. Between 1950 and 2009, the increase in annual rainfall was about 13% (Warren & Lemmen, 2014). In Southern Canada, the proportion of precipitation representing snowfall is gradually decreasing (Bush & Lemmen, 2019). Between 2016 and 2035, annual snow depth is predicted to decrease by 0.02–1.99 cm for RCP2.6 or by 0.02–2.09 cm for RCP8.5 measured relative to the 1986–2005 average snow depth (Government of Canada, 2019).

Extreme rainfall events are also expected to become significant in the future. Short-term extreme rainfall, precipitation that lasts for a maximum of one day, is alarming as it can cause severe flooding and consequently major damage to infrastructure. Once again, there are few stations in Canada from which data is collected and precipitation patterns cannot be extracted for such events. Station data does suggest an overall increase in extreme precipitation; however, it is plausible that these observations are random. Therefore, Canadian precipitation changes cannot be validated. However, the increase in extreme precipitation globally can be observed with more certainty. For every 1˚C increase in GMST, the median increase in these events is approximately 7%. This rate corresponds to the same value as the atmosphere's ability to retain water. Extreme precipitation events are anticipated to become more frequent during the 21st century (Bush & Lemmen, 2019). The frequency of these events is expected to double by 2050 (Warren & Lemmen, 2014).

Damage to infrastructure from intense weather events include costly repairs, service disruptions, human injuries and fatalities, and adverse socioeconomic consequences to all levels of government (Cannon et al., 2020). Canada's buildings and public infrastructure systems are designed using codes and standards that fail to consider future climate projections as they are solely based on historical climate data (Government of Canada, 2022). Since most infrastructure in Canada is designed for a long service life ranging from 50 to 100 years, it is necessary to consider changing climatic loads in design (Cannon et al., 2020). The Council of Canadian Academies (CCA) assembled an Expert Panel on Climate Change Risks and Adaptation Potential who established 12 major risks that Canada faces due to climate change. Physical infrastructure was listed among the top 6 major risks. Codes and standards will need to be updated using data from climate projections for the design of new infrastructure. Modifications to existing infrastructure will also be necessary based on condition assessments. Such modifications may include maintenance repairs, upgrades, and the inclusion of life-cycle management. Evaluating existing infrastructure is very important in Canada as the majority of buildings are relatively old. Although initial costs may be high, there will be huge savings in terms of life-cycle costs (Council of Canadian Academies, 2019). CSA Group revisited all of their standards included in the 2015 National Model Codes and found that 81 standards needed to be revised in order to incorporate climate change adaptation guidelines. In total, 3 masonry standards were included in this selection (Sparling et al., 2021b).

Masonry is of particular interest to Canada since this material is commonly used for residential, commercial, and institutional buildings. It can be used for both structural and non-structural elements. This material is advantageous due to its strength, durability, fire resistance and heat resistance, as well as its thermal mass and thermal regulation properties (Sparling et al., 2021b).

Moreover, at the end of its service life, masonry can be completely reused and/or recycled. The embodied energy of a masonry structure can be between 30-40% smaller compared to a reinforced concrete structure (Ismaiel et al., 2022). With a changing Canadian climate, which includes higher temperatures and higher levels of precipitation, the durability of masonry structures will be greatly impacted. Freeze-thaw is most likely the most dangerous deterioration mechanism for exposed porous building materials (Litvan, 1975). Freezing and thawing can cause cracking and eventually premature deterioration of the structure (Sparling et al., 2021b). The number of freeze-thaw cycles is expected to rise with increasing temperatures in northern latitudes with traditionally colder winters such as Canada (Auld et al., 2007), although more research is necessary to study these trends (Sparling et al., 2021b). Since at least 1980, the number of freeze-thaw cycles has risen in most regions of Canada (Auld et al., 2007). It may seem counterintuitive that the number of freeze-thaw cycles is expected to increase with rising temperatures. However, this only applies to regions with extreme cold climates. In regions with warmer winters, the number of freeze-thaw cycles is expected to decrease. During harsh and cold winters, temperatures do not go above the freezing point often. With global warming, these regions may experience more temperature fluctuations around the freezing point. Finally, freeze-thaw damage will only occur if the masonry is saturated, and higher levels of precipitation suggest that the presence of moisture will increase in exposed masonry, increasing its vulnerability to damage.

1.2 Impact of freezing and thawing on masonry walls

1.2.1 Influence of the brick microstructure on its freeze-thaw resistance

After a heavy rainfall, masonry is exposed to moisture and the pores of the bricks fill with water. When outside temperatures drop below the freezing point, for example at nightfall, the water in the pores expands upon freezing. Frozen water occupies 9% more volume than liquid water, so if there is not enough empty pore space to accommodate this expansion, internal stresses are developed within the bricks. These stresses can cause irreversible strains, leading to cracking and spalling. Once temperatures rise again, these cracks can allow even more moisture to enter, continuing and worsening the cycle. The freeze-thaw cycle of masonry is illustrated in Figure 1.3.

Blachere and Young (1974) made important observations regarding capillary-shaped pores, suggesting that freezing occurs in two phases in a clay medium. At 0°C, water freezes in large pores and between –2°C and –8°C, water freezes in capillaries. As the temperature gradually decreases, freezing occurs in the smaller and finer capillaries which can be seen in Figure 1.4. This can build a large hydraulic pressure inside the medium, making the brick more susceptible to damage. They suggest that bricks with a less dispersed pore distribution will thus perform better against freezing and thawing. They also conclude that bricks with a lower pore volume and larger average pore diameter are more resistant against frost action.

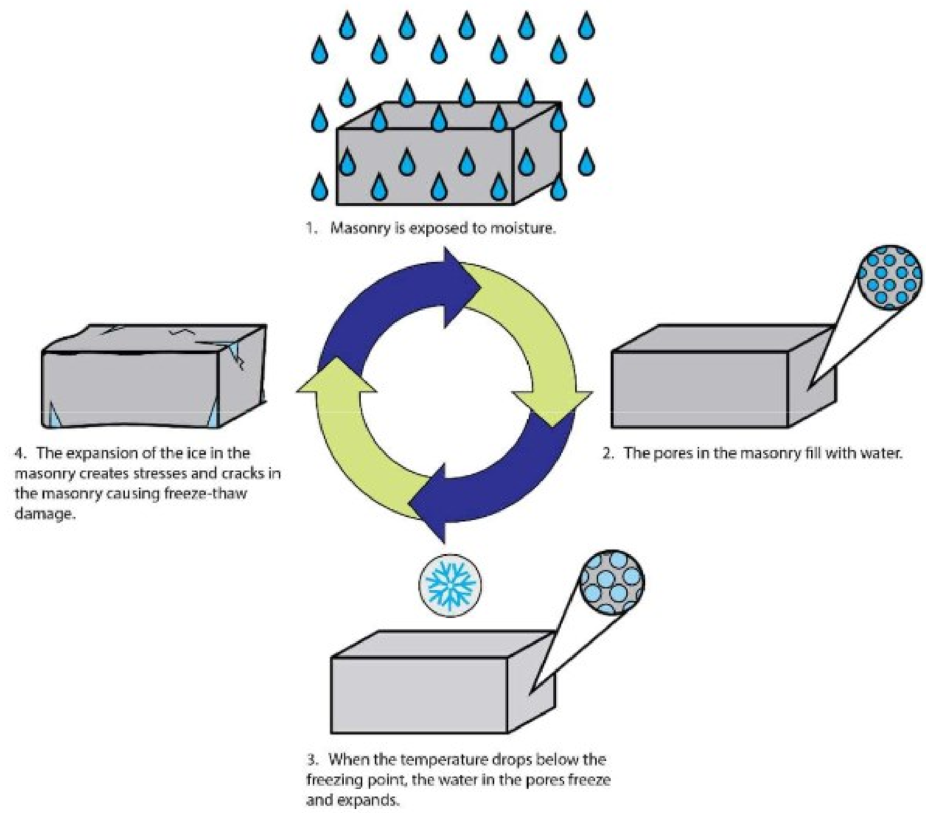


Figure 1.3. The freeze-thaw cycle in masonry (Moore et al., 2022)

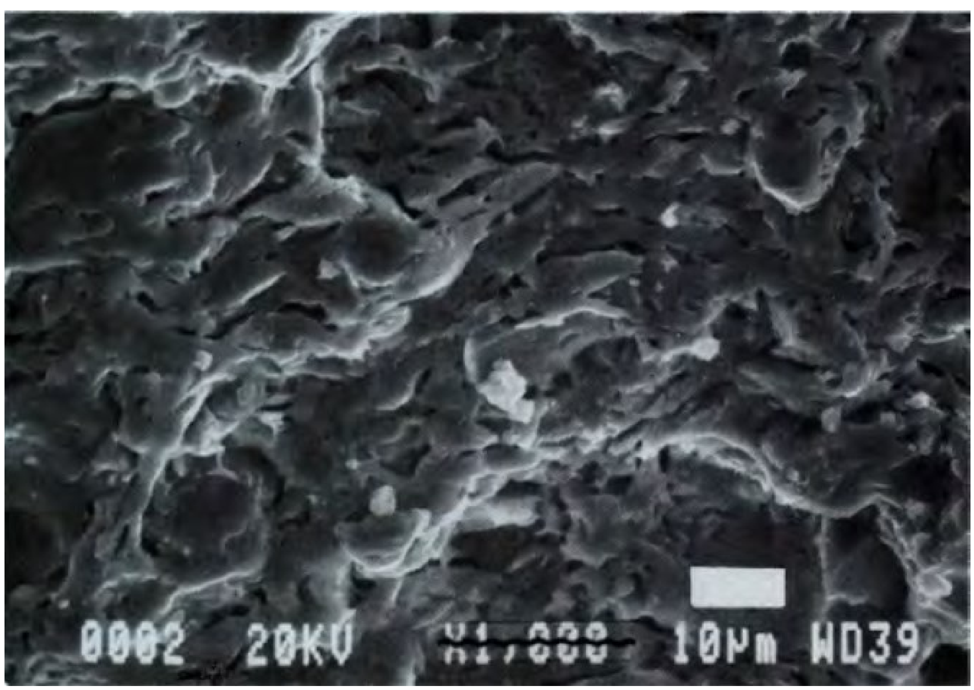


Figure 1.4. Long and narrow capillaries seen in the microstructure of a clay brick (Marusin, 1990)

1.2.2 Failures of masonry walls in service due to freeze-thaw

Although freezing and thawing occurs at the microstructure level, it can still have catastrophic consequences for masonry structures. Damage to infrastructure due to freezing and thawing is not immediately evident and can take months or years for it to become noticeable (Auld et al., 2007). By eliminating either temperature cycles about the freezing point or moisture accumulation, damage from freeze-thaw can be minimized. As it is not possible to control the weather, moisture control is a primary focus in freeze-thaw mitigation strategies. There are several ways that can help prevent moisture from entering the façade such as mortar repointing, localized crack repairs, replacement of damaged bricks, or installing roof overhangs to divert water away from the masonry surface (Moore et al., 2022). Severe freeze-thaw damage is often observed in the form of brick spalling, as shown in Figure 1.5a (Maurenbrecher & Suter, 1989). Without early intervention, Figure 1.5b demonstrates how inadequate water diversion, such as poorly designed gutters, can allow moisture to accumulate and result in life-threatening damage.

(a) (b)

Figure 1.5. (a) Brick spalling caused by freezing and thawing (Maurenbrecher & Suter, 1989)*; (b) Severe freeze-thaw damage caused by local moisture accumulation* (Trainor, 2019)

1.3 Adapting masonry cavity-wall construction to changing climatic loads

1.3.1 Evolution of the masonry cavity-wall in response to modern energy requirements

Mass masonry construction was common up until the early twentieth century (Scott & Erik, 2013), where masonry buildings were typically comprised of solid loadbearing masonry walls with multiple wythes of brick or stone (Artigas & O'Brien, 2019). As mitigating the effects of climate change became urgent in recent decades and more stringent energy codes were developed (Ismaiel et al., 2022), designers were required to improve the energy efficiency of buildings. One approach to reducing the operational energy consumption is to improve the thermal resistance of masonry walls. In modern construction, there has been a shift from traditional thick and solid masonry walls to thinner and more energy-efficient assemblies, such as cavity-walls (Ismaiel et al., 2022). Cavity-wall construction is a type of masonry wall construction where an outer and inner wall are separated by an air gap but connected by a tie system (Figure 1.6). The outer veneer wall (clay bricks) is a non-structural component that acts as a barrier against the environment, i.e. a rain screen, and transmits out-of-plane loads to the inner wall. The infill masonry wall (concrete blocks) is the loadbearing component of the structure (Martins et al., 2017). Other components of a cavity-wall include mortar, grout, thermal insulation, vertical/horizontal/joint reinforcement, metal ties and shelf angles (Ismaiel et al., 2022).

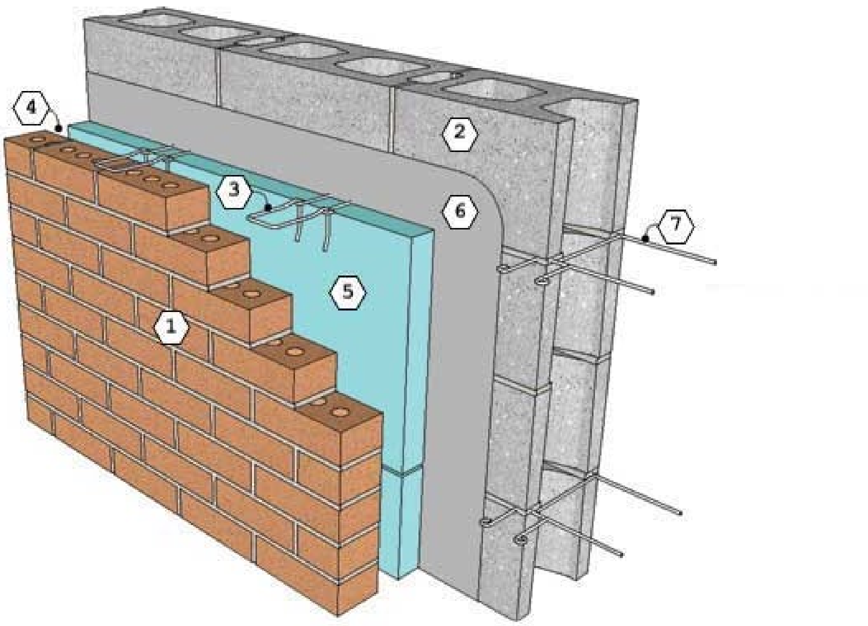


Figure 1.6. Cavity-wall details. (1) clay brick veneer; (2) concrete block backup; (3) wall ties; (4) air gap; (5) insulation; (6) vapour barrier; (7) horizontal joint reinforcement; (8) shelf angle (Construction Canada, 2022)

The purpose of the air cavity is to promote drying of the brick veneer. Aside from the addition of a thermal insulation layer, some research suggests that the air cavity itself contributes to the thermal resistance of the cavity-wall assembly (Stovall & Karagiozis, 2004). Under different cavity-wall configuration and weather patterns, Stovall and Karagiozis (2004) observed temperature variations between the external air and the cavity air, suggesting that the brick veneer and air gap contribute to the insulating effect. Moreover, an even higher thermal performance can be achieved by enlarging the air cavity separating the inner and outer wythes. Unfortunately, there is a lack of research on this topic. Data from the ISO 6949:2017 (International Organization for Standardization, 2017) indicates that the thermal resistance of a ventilated masonry cavity-wall was 0.11 m^2K/W with an air cavity thickness of 5 mm and 0.17 m^2K/W with an air cavity thickness 15 mm, indicative of a correlation between thermal performance and air cavity size. It is noteworthy to mention that the thermal resistance stabilized at 0.18 m^2K/W for air cavity thicknesses between 25 and 100 mm, suggesting a possible upper bound (Ismaiel et al., 2022).

1.3.2 Durability challenges encountered with cavity-wall construction

Older masonry buildings, although improperly insulated and less energy efficient, did perform well amidst freeze-thaw action. Redundancy in design, such as multi-wythe walls, protected the structure from rainwater intrusion (Charron & Van Straaten, 2021). Also, indoor heating warmed the interior wythes and prevented freezing from occurring (Artigas & O'Brien, 2019). As mentioned earlier, modern cavity-walls are energy-efficient as the air cavity and thermal insulation layer both improve the thermal performance of the building. However, this introduces a new problem: the building's indoor heating does not reach the brick veneer and freezing is likely to occur, especially in harsh northern climates such as Canada. The clay veneer itself is susceptible to moisture damage as masonry is a porous material and can allow water to penetrate even when uncracked (Sparling et al., 2021b). By the late 1900s, modern brick veneers were optimized to provide ventilation which promoted drying, and included "weep holes" at the base of the veneer to allow water to drain out (Figure 1.7). Without weep holes, water that has passed through the outermost layer of the veneer would simply travel down the inner side of the wall and accumulate at the bottom of the cavity (Ismaiel et al., 2022). Still, poor construction practices can cause excess mortar to fall within the cavity and block the weep holes, although some devices have been designed to mitigate this issue (Schulenburg, 2000). Improper detailing and improper ventilation can also cause excess moisture accumulation, although drying may not even be possible altogether with certain weather conditions (Sparling et al., 2021a). It is worth noting that although the ventilated cavity-wall has been optimized from earlier cavity-wall designs to reduce moisture accumulation, air flow within the cavity may affect the insulating performance of the wall (Ismaiel et al., 2022).

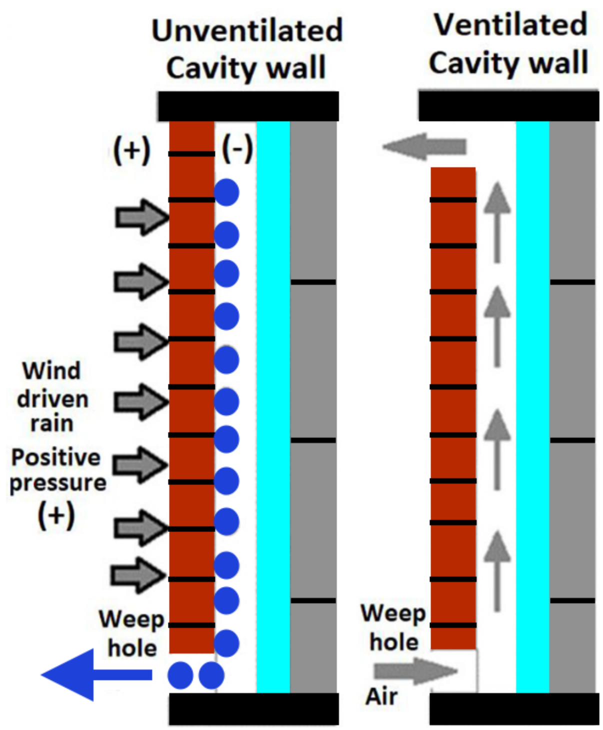


Figure 1.7. Ventilated cavity-wall design with weep holes (Ismaiel et al., 2022)

This issue becomes more severe when reclaimed brick is used for the veneer construction. The use of reclaimed brick in new construction has been common practice in Canada since the 1970s, whether it be for aesthetic purposes or economic reasons (Ritchie, 1971), but also to reflect the growing environmental awareness and conservation movement (Lanz & Pendlebury, 2022). Reclaimed bricks utilized in interior applications such as fireplaces and interior walls do not usually present structural concerns since they are protected from the outside environment. However, challenges arise with bricks that are exposed to weathering (Ritchie, 1971), particularly those used in veneer applications. Existing bricks have likely undergone numerous freeze-thaw cycles during their service life and are consequently more damaged and more porous compared to new bricks. It is also difficult to estimate how much of their service life remains. Also, mortar and dust residue may prevent proper bonding between the brick and mortar, leading to higher levels of moisture penetration into the veneer (Malhotra, 1997). With climate change, these deterioration mechanisms can accelerate and cause premature failure.

In essence, although proper ventilation can significantly reduce moisture accumulation for brick veneers, several factors such as faulty construction, the use of reclaimed brick, and the impacts of climate change can still cause modern brick veneers to be vulnerable to freezing and thawing.

1.4 Current Canadian standards on the selection of brick for modern veneer construction

Bricks used in modern masonry construction in Canada must meet the criteria outlined in CSA A82:14 (R2018) *Fired masonry brick made from clay or shale* (Canadian Standards Association, 2018). Bricks are classified as either Interior Grade (IG) or Exterior Grade (EG). Grade EG bricks can be used for both interior and exterior applications whereas Grade IG bricks can only be used for interior applications. Bricks used for veneer applications in a harsh Canadian climate are always classified as Grade EG (Mensinga et al., 2010).

The acceptance criteria for Grade EG bricks is presented in Table 1. The 24-h cold water absorption is meant to be an estimation of the water content of a brick after a severe rainfall during its service life (Mensinga et al., 2010). In other words, it provides an estimate of the water content that is easily absorbed by the brick. The procedure to obtain this value according to CSA A82:14 involves placing a sample of five half-brick specimens in a bath of distilled water between 15°C and 30°C for twenty-four hours and using Equation 1 to calculate the 24-h cold water absorption:

$$\text{24-h cold water absorption [\%]} = \frac{M_2 - M_1}{M_1} \times 100 \qquad \textit{Equation 1}$$

where:

M_1 = *oven-dry mass of specimen*

$M_2 = \textit{saturated mass of specimen after twenty-four hours in cold water}$

The 5-h boiling absorption, calculated using Equation 2, is a measure of the total pore space of the brick, which provides an indication of its freeze-thaw resistance. It is analogous to the vacuum saturation of the brick. The 5-h boiling test immediately follows the 24-h cold water absorption test. The five half-bricks are boiled in distilled water for 5 hours. 5-h boiling absorption values are always higher than 24-h water absorption values because the higher water vapour pressure is able to drive out air in the pores, allowing more space in the voids for water to occupy (Lovatt, 1993).

$$\text{5-h boiling absorption [\%]} = \frac{M_3 - M_1}{M_1} \times 100 \qquad \textit{Equation 2}$$

where:

M_1 = *oven-dry mass of specimen*

$M_3 = \textit{saturated mass of specimen after five hours in boiling water}$

The saturation coefficient, defined as the ratio between the 24-h cold water absorption and the 5-h boiling absorption (see Equation 3), represents the proportion of the total pore volume that can be easily filled with water (Lovatt, 1993). In theory, the remaining pore space should be able to accommodate water expansion due to freezing if only a portion of the total pore volume is filled. For instance, a saturation coefficient of 0.88 can accommodate 12% expansion without causing damage, which is greater than the 9% expansion that occurs when water freezes (Davison, 1975). The lower the saturation coefficient, the less likely the brick is to be damaged due to freeze-thaw expansion (Lovatt, 1993).

$$\text{Saturation coefficient} = \frac{M_2 - M_1}{M_3 - M_1} \qquad \textit{Equation 3}$$

To be classified as a Grade EG brick, the bricks must satisfy: (1) the 5-h boiling criteria, and (2) either the 24-h cold water criteria or the saturation coefficient criteria displayed in Table 1. The freeze-thaw test must be performed should the bricks exceed the acceptance criteria in Table 1, and must pass the test to qualify as a Grade EG brick. The freeze-thaw test consists of 50 cycles of freezing and thawing. The mass loss cannot exceed 0.5% upon completion of the test, nor form a crack that is at least as long as the minimum dimension of the brick.

Table 1. Acceptance criteria for Grade EG bricks in CSA A82:14

Compressive strength		***24-h cold water absorption***	***5-h boiling absorption***	***Saturation coefficient***
Average of 5 samples	**Individual sample**			
20.7 MPa	17.2 MPa	8%	17%	0.78

Regarding reclaimed brick, it is unclear whether or not CSA A82:14 is applicable to them. Clause 1.5 states that:

> **1.5**
> Testing of brick removed from in-situ masonry construction is not within the scope of this Standard.

This seems to clearly suggest that CSA A82:14 is not applicable to reclaimed brick. However, Clauses 9.20.2.1. and 9.20.2.2. of the National Building Code of Canada Part 9 (Canadian Commission on Building and Fire Codes, 2018) suggest otherwise:

> **9.20.2.1.   Masonry Unit Standards**
>
> **1)** Masonry units shall comply with
> a) ASTM C 73, "Calcium Silicate Brick (Sand-Lime Brick),"
> b) ASTM C 126, "Ceramic Glazed Structural Clay Facing Tile, Facing Brick, and Solid Masonry Units,"
> c) ASTM C 212, "Structural Clay Facing Tile,"
> d) CAN/CSA-A82, "Fired Masonry Brick Made from Clay or Shale,"
> e) CSA A165.1, "Concrete Block Masonry Units,"
> f) CSA A165.2, "Concrete Brick Masonry Units," or
> g) CSA A165.3, "Prefaced Concrete Masonry Units."
>
> **9.20.2.2.   Used Brick**
>
> **1)** Used bricks shall be free of old mortar, soot or other surface coating and shall conform to Article 9.20.2.1.

Here, the code says that reclaimed bricks should comply to CSA A82:14 as long as existing mortar and other debris or coatings are removed from their surfaces. The ambiguity and contradiction in modern Canadian codes and standards makes it unclear how to assess the suitability of reclaimed brick in new construction.

1.5 Knowledge gaps and innovative research directions

Numerous publications suggest that bricks that have met the durability requirements in CSA A82:14 have failed in service, and others that have been durable over a long period of time did not meet these requirements (Butterworth & Baldwin, 1964; Davison, 1975; Marusin, 1990). A plausible explanation is that the laboratory tests detailed in CSA A82:14 are severe and not representative of real-life service conditions. For instance, freezing occurs unidirectionally in service as only one face of the brick is exposed. For the 50-cycle test, freezing occurs omnidirectionally which can cause a large hydraulic pressure build-up in the middle of the brick (Mensinga et al., 2010). Another drawback is that the pass/fail criterion does not allow different brick types to be compared (Koroth et al., 1998). Furthermore, the brick samples that are submerged in a water tank for four hours does not agree with partially saturated conditions in the field (Davison, 1975). CSA A82:14 attempts to provide a standardized test that determines resistance against frost action; however, it only determines the freeze-thaw resistance under a set of imposed conditions (Litvan, 1975). Another issue with the acceptance criteria is that they are based on outdated laboratory test data from the 1930s (McBurney & Lovewell, 1933). Sparling et al. (2021b) suggest that the test methods need to be re-evaluated and that alternative methods such as frost dilatometry, which determines the saturation level at which permanent freeze-thaw damage may occur at, could more accurately predict the resistance of bricks against freezing and thawing.

In 2018, the Canadian Standards Association (CSA) published a report that identified research topics in need of further attention regarding masonry cavity-walls. Particular needs include the creation of an up-to-date database on physical and mechanical properties, as well as other design factors such as durability, of masonry units and other components of the masonry structure (Sparling et al., 2021b). In this paper, the mechanical and environmental properties of eleven different bricks will be compared, which includes freeze-thaw performance, 24-h cold water absorption, 5-h boiling absorption, saturation coefficient, and compressive strength. These bricks are classified into three groups: new, used (mid-20th century), and old (late 19th century/early 20th century). Their compliance to CSA A82:14 will also be evaluated.

2 Experimental work

2.1 Selection of bricks representative of modern and historic Canadian infrastructure

Eleven Canadian bricks were selected and categorized into three groups: (1) “new” bricks; (2) “used” bricks (from the mid-20th century); and (3) “old” bricks (from the late 19th/early 20th century). By collaborating with the Canada Masonry Design Centre, the new bricks were selected based on commonly used bricks in modern Canadian masonry construction. The used and old bricks are considered reclaimed as they were extracted from existing buildings that were demolished. The old bricks, sourced from buildings in Montreal, are representative of Canada’s historic building stock. The Lachine Canal was a prime location for industrialization due to its access to hydro-electric power and its ideal location for shipping across North America (Davis & Malomo, 2023). Bricks manufactured in Montreal could therefore be easily transported to other regions in Canada. All relevant information on the eleven brick types are presented in Table 2, with photos in Figure 2.1 to Figure 2.3.

Table 2. Eleven Canadian brick types used for the experimental work

Group	*Type*	*Date*	*Solid, cored, or hollow*	*Description*
New	GREY	modern	cored	• Extruded clay brick • Velour texture
	SHALE	modern	cored	• Extruded shale brick • Sand texture
	GEO	modern	solid	• Moulded clay brick • Sand texture
	BROWN	modern	cored	• Extruded shale brick
Used	MILTON	~1950	solid + frogged	• Extracted from residential building in Quebec City, QC
	CORED	~1950	cored	• Extracted from residential building in Quebec City, QC
	ORANGE	~1950	solid	• Extracted from residential building in Quebec City, QC
Old	BERRI-S	1912	solid	• Extracted from the structural backup of a residential building on Berri street in Montreal, QC
	BERRI-NS	1912	solid	• Extracted from the veneer of a residential building on Berri Street in Montreal, QC • Layer of red paint on exposed surface (see Figure 2.4)
	CRAIG	1887	solid	• Extracted from industrial building in Montreal, QC (the Craig pumping stations)
	ROSEMONT	unknown	solid	• Extracted from a residential building in the Rosemont neighbourhood in Montreal, QC

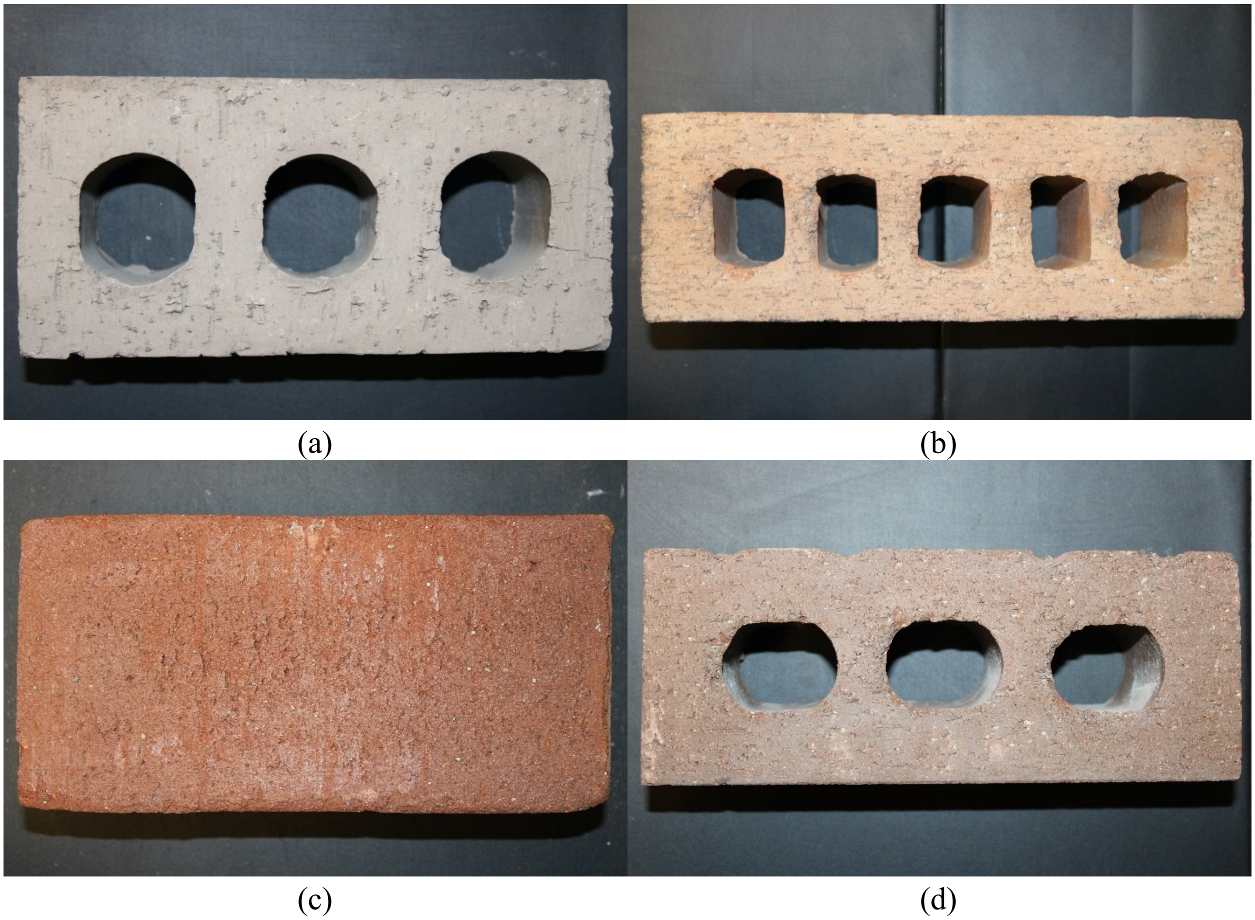
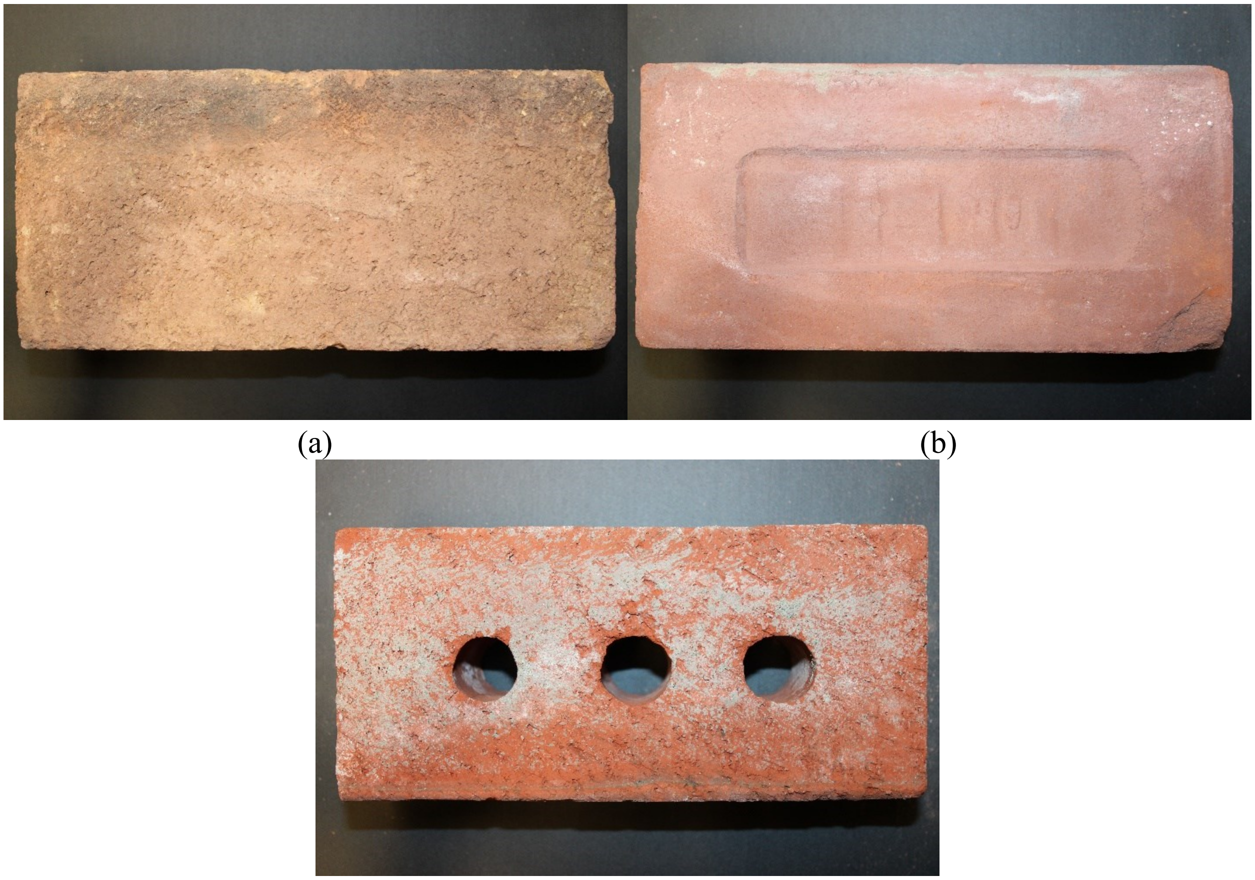


Figure 2.1. New bricks. (a) GREY; (b) SHALE; (c) GEO; (d) BROWN.



(a) (b) (c)

Figure 2.2. Used bricks. (a) MILTON; (b) ORANGE; (c) CORED.

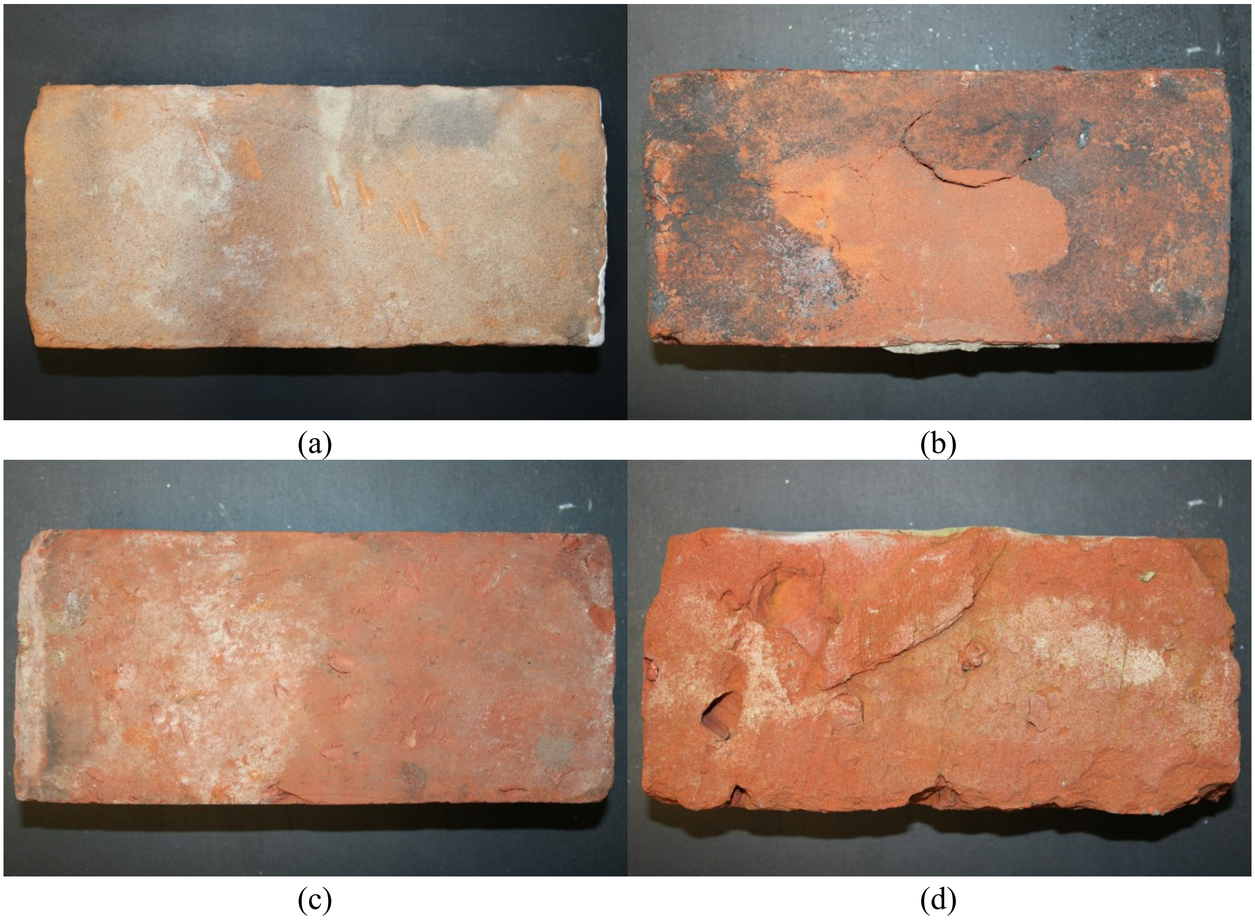


Figure 2.3. Old bricks. (a) BERRI-S; (b) BERRI-NS; (c) ROSEMONT; (d) CRAIG.

Figure 2.4. Red paint on exposed face of BERRI-NS

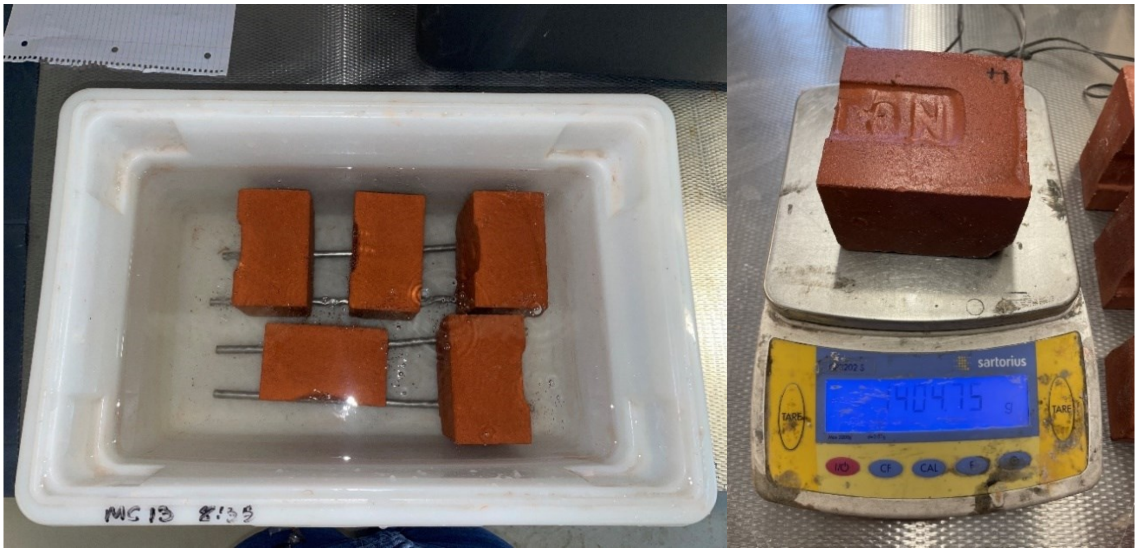
2.2 Environmental characterization of typical Canadian bricks

The environmental tests performed on all eleven bricks include: (1) the 24-h cold water absorption test; (2) the 5-h boiling absorption test; and (3) the freeze-thaw test, according to the CSA A82:14 standard. For each test, 5 half-brick specimens were sampled and prepared according to Clause 12. Each half-brick was obtained from a different full-size brick. The specimens were dusted with a straw brush and any loose fragments were removed from their surfaces. For the BERRI-NS specimens only, a 1-2 mm thick slice was cut off of the bricks in order to remove the layer of red paint seen in Figure 2.4. The half-bricks were labelled with a china marker to prevent the labels from being removed by water. Next, the specimens were dried and cooled according to Clause 12.5 and 12.6. The samples were weighed after being placed in an oven at 115°C for 24 hours (see Figure 2.5a), and then weighed every subsequent two hours until the difference in mass did not exceed 0.05%. Finally, the samples were cooled on metal racks in a room with an average temperature of 22.8°C and relative humidity of 53% (see Figure 2.5b).

(a) (b)

Figure 2.5. (a) Half-bricks drying in the oven at 115°C; (b) half-bricks cooling on a metal rack

Once the samples cooled down, the 24-h absorption test could begin according to Clause 14. The half-brick specimens were placed on 8 mm-diameter stainless steel rods inside a flat plastic container. The rods were slightly bent in order to prevent them from rolling and potentially shifting the bricks. Enough distilled water was poured inside the container such that the specimens were completely submerged, as shown in Figure 2.6a. Saran wrap was used to cover the container and the bricks were left overnight. After 24 ± 0.5 hours, the specimens were removed from the container and wiped down with damp paper towel to remove any excess water from the surface. They were weighed one at a time (Figure 2.6b) and quickly placed back in the container of water to maintain the same level of saturation for the start of the 5-h boiling test. Once the weighing was complete, the 5-h boiling test started immediately according to Clause 14.



(a) (b)

Figure 2.6. (a) 24-h cold water absorption test; (b) weighing of specimens following the test

The boiling pot was placed on a hot plate set to 400°C and turned on 30 minutes before the start of the test. The half-bricks were placed on 8 mm-diameter stainless steel rods inside the pot and distilled water was poured over the specimens until they were fully submerged. Temperature readings were taken at 15-minute intervals for the duration of the test. The water started to boil at approximately 1 h ± 15 min and the bricks were boiled continuously for an additional 5 hours. When the water level dropped below the bricks, boiling water from a kettle was added to the pot. At the end of the test, the hot plate was turned off and the bricks were allowed to cool overnight. After at least 12 hours, the bricks were wiped with damp paper towel and they were weighed.

Figure 2.7. 5-h boiling absorption test

Using Equation 1 and Equation 2, the 24-h cold water and 5-h boiling absorption values were calculated. The saturation coefficient was calculated using Equation 3. The average of five specimens for each brick type along with the coefficient of variation (COV = standard deviation/mean) are presented in Table 3. The values highlighted in green are those that have passed the acceptance criteria in Table 1 and the values highlighted in red are those that have failed the acceptance criteria in Table 1. The values highlighted in yellow are those that were close to meeting the acceptance criteria, which are considered a "marginal pass".

Table 3. 24-h cold water absorption and 5-h boiling absorption values for new, used, and old bricks

Type	Name	Trial #	24-h cold water absorption	5-h boiling absorption	Saturation coefficient	Pass/Fail
New	GREY	1	**5.9%** (2.0%)	**8.3%** (1.6%)	**0.71** (1.8%)	**Pass**
	SHALE	1	**9.8%** (5.7%)	**14.3%** (3.0%)	**0.68** (2.8%)	**Pass**
	GEO	1	**5.5%** (17.7%)	**10.3%** (11.0%)	**0.53** (8.2%)	**Pass**
	BROWN	1	**2.2%** (4.6%)	**4.4%** (2.5%)	**0.51** (5.1%)	**Pass**
Used	MILTON	1	**12.9%** (7.0%)	**16.1%** (7.3%)	**0.80** (0.7%)	**Pass**
		2	**12.2%** (6.6%)	**15.3%** (6.0%)	**0.80** (1.2%)	**Pass**
		3	**12.3%** (4.2%)	**15.5%** (4.4%)	**0.80** (0.9%)	**Pass**
	ORANGE	1	**15.4%** (4.5%)	**18.0%** (3.0%)	**0.85** (2.0%)	**Fail**
		2	**15.6%** (2.3%)	**18.1%** (2.7%)	**0.86** (0.5%)	**Fail**
	CORED	1	**8.2%** (1.2%)	**9.8%** (0.7%)	**0.84** (1.4%)	**Pass**
		2	**7.9%** (7.2%)	**9.5%** (4.9%)	**0.83** (2.7%)	**Pass**
		3	**8.3%** (2.4%)	**9.9%** (1.0%)	**0.84** (1.6%)	**Pass**
Old	BERRI-S	1	**17.8%** (3.1%)	**19.2%** (1.8%)	**0.93** (2.8%)	**Fail**
	CRAIG	1	**18.6%** (4.7%)	**20.0%** (5.5%)	**0.93** (1.3%)	**Fail**
	BERRI-NS	1	**18.4%** (3.9%)	**22.0%** (5.2%)	**0.84** (5.7%)	**Fail**
	ROSEMONT	1	**17.0%** (5.4%)	**20.7%** (3.5%)	**0.82** (2.0%)	**Fail**

Clause 12.3 states that if the absorption tests fail initially, they may be redone. If two additional samples of five half-bricks pass the tests, the lot of bricks is considered to have passed the tests. Multiple tests were done for the used bricks, specifically the MILTON and CORED bricks, because the initial tests were marginally failing.

The freeze-thaw test, performed according to Clause 15 of CSA A82:14, complements the 24-h cold water absorption test and the 5-h boiling absorption test. The freeze-thaw test is optional, as long as the bricks pass the requirements of Clause 7.2.2 (Table 1). Otherwise, the results of the freeze-thaw govern over the absorption tests. The prepared half-brick specimens were first submerged in a water tank for 4 h ± 15 min at an average temperature of 21.5°C (Figure 2.8). The specimens were then placed end face down (the face with the smallest area) on 8 mm-diameter stainless steel rods in a stainless-steel tray with an inside depth of 50 mm. The tray was filled with enough water such that the specimens stood in 12 ± 1 mm of water. The trays were placed in a freezer (Figure 2.9) such that the air temperature of the fridge reached at most –9 ± 1°C in 1 h ± 5 min, reached at most –20 ± 2°C in 14 h ± 30 min, and stayed at –20 ± 2°C for the next 6 hours. After 20 ± 1 hours, the trays were placed in the water tank for 4 h ± 30 min to thaw. Hot water was added during the thawing phase to ensure that the water temperature remained above 19°C (Clause 15 requires that the water temperature remains at 24 ± 5°C). Bluetooth-powered temperature monitors continuously recorded the temperature in the freezer and in the water tank to ensure compliance with CSA A82:14. The freeze-thaw cycle was repeated daily, five times a week, for ten weeks. Once 50 cycles were completed, the test was over. The specimens were dried and cooled according to Clause 12.5 and 12.6. The mass loss as a percentage of the original mass was calculated, and if it exceeded 0.5%, the test failed. However, the test can fail before the 50 cycles have been completed if the specimens do not meet the acceptance criteria of Clause 7.2.3.1: 5% mass loss is observed by visual inspection, a crack develops that is at least as long as the minimum dimension of the brick, or if the specimen breaks in two or more pieces.

Figure 2.8. Thawing tank used for the freeze-thaw test

Figure 2.9. Freezer used for the freeze-thaw test

The mass loss for the new bricks is presented in Table 4, and the number of cycles until failure and mass loss at failure for the used and old bricks are presented in Table 5 and Table 6, respectively. COV values are presented in parentheses under the average values. The values indicated in red are considered outliers, and the average cycles to failure excluding the outliers is also presented in red. A second trial was performed for both types of BERRI bricks due to questionable results from the first trial (see Section 3). An additional sample of five BERRI-NS half-bricks was also tested, in which case the red paint was not removed. This data is presented in Table 7.

Table 4. Mass loss of new bricks after 50 freeze-thaw cycles

Specimen name	Mass loss after 50 cycles	Average mass loss
GREY-1	0.09%	**0.09%** (15.6%)
GREY-2	0.09%	
GREY-3	0.09%	
GREY-4	0.08%	
GREY-5	0.12%	
SHALE-1	0.29%	**0.29%** (24.0%)
SHALE-2	0.23%	
SHALE-3	0.39%	
SHALE-4	0.33%	
SHALE-5	0.23%	
GEO-1	0.22%	**0.18%** (21.7%)
GEO-2	0.20%	
GEO-3	0.20%	
GEO-4	0.16%	
GEO-5	0.12%	
BROWN-1	0.09%	**0.08%** (28.3%)
BROWN-2	0.13%	
BROWN-3	0.07%	
BROWN-4	0.08%	
BROWN-5	0.07%	

Table 5. Number of cycles until failure and mass loss at failure for the used bricks

Specimen name	No. cycles to failure	Average no. cycles to failure	Mass loss at failure
MILTON-1	14	**9 cycles** (30.2%)	0.16
MILTON-2	8		0.20
MILTON-3	9		0.17
MILTON-4	8		0.19
MILTON-5	7		0.12
ORANGE-1	10	**6 cycles** (40.7%)	0.55*
ORANGE-2	7		0.41
ORANGE-3	7		0.48
ORANGE-4	3		0.27
ORANGE-5	5		0.30
CORED-1	35	**22 cycles** (55.2%)	0.32
CORED-2	14		0.24
CORED-3	34		0.31
CORED-4	10		0.26
CORED-5	15		0.15

**ORANGE-1 also failed by a mass loss exceeding 0.5%*

Table 6. Number of cycles until failure and mass loss at failure for the old bricks

Specimen name	No. cycles to failure	Average no. cycles to failure	Mass loss at failure
BERRI-S-1	40	**17 cycles** (115.9%) ***3 cycles*** *(78.1%)*	1.87
BERRI-S-2	2		9.13
BERRI-S-3	37		1.59
BERRI-S-4	1		8.31
BERRI-S-5	5		0.26**
BERRI-NS-1	4	**4 cycles** (35.3%)	1.92
BERRI-NS-2	6		0.85
BERRI-NS-3	4		2.36
BERRI-NS-4	2		2.94
BERRI-NS-5	5		1.05
CRAIG-1	6	**10 cycles** (148.3%) ***4 cycles*** *(68.0%)*	0.24**
CRAIG-2	37		4.33
CRAIG-3	1		5.96
CRAIG-4	2		2.25
CRAIG-5	5		4.00
ROSEMONT-1	36	**13 cycles** (106.0%) ***7 cycles*** *(66.0%)*	1.49
ROSEMONT-2	3		25.49
ROSEMONT-3	3		2.19
ROSEMONT-4	11		0.80
ROSEMONT-5	11		1.45

***BERRI-S-5 and CRAIG-1 failed by cracking*

Table 7. Number of cycles until failure and mass loss at failure for the second trial of the BERRI bricks

Specimen name	No. cycles to failure	Average	Mass loss at failure
BERRI-S-6	6	**5 cycles** (29.2%)	0.72
BERRI-S-7	3		***
BERRI-S-8	6		1.99
BERRI-S-9	4		4.09
BERRI-S-10	4		0.80
BERRI-NS-6	12	**10 cycles** (70.5%) ***7 cycles*** *(48.1%)*	0.52
BERRI-NS-7	5		0.76
BERRI-NS-8	5		3.52
BERRI-NS-9	6		5.04
BERRI-NS-10	21		1.18
BERRI-NS-P1	8	**9 cycles** (70.1%) ***6 cycles*** *(30.4%)*	0.54
BERRI-NS-P2	4		0.67
BERRI-NS-P3	5		1.80
BERRI-NS-P4	7		1.33
BERRI-NS-P5	19		1.07

****Complete disintegration of BERRI-S-7. No mass loss recorded.*

2.3 Mechanical characterization of typical Canadian bricks

Clause 7.2.1 of CSA A82:14 states that all EG bricks must satisfy a minimum compressive strength (see Table 1). Uniaxial compression tests were performed for all eleven brick types according to Clause 13. Full bricks were used for the tests, except in the case of the used bricks where half-bricks were selected due to limited supply. Five bricks were tested for each brick type except for three of the old brick types in order to minimize the COV. The average of 60 bricks was taken for the BERRI-S and BERRI-NS bricks, and the average of 40 bricks was taken for the CRAIG bricks. The specimens were capped using Hydro-Stone gypsum cement, with a water to cement ratio of approximately 0.25. Both the top and bottom of the brick were capped using 1.5" thick steel plates as shown in Figure 2.10. A spirit level was used to ensure that the steel plates were properly aligned and levelled. Once all specimens were capped, they cured for a minimum of 24 hours. A final capped brick can be seen in Figure 2.11.

Figure 2.10. Filling the frogs of the MILTON bricks with gypsum cement during the capping process

Figure 2.11. Capped brick

The specimens were tested using the MTS rock frame, a hydraulic press with a 4,600 kN capacity and accuracy of ±5 kN. Before testing began, the top and bottom areas of the bricks were measured using a digital caliper. Afterwards, 50 mm-gauge length extensometers were placed on both of the long faces of the brick, as shown in Figure 2.12. The final setup of the brick in the MTS rock frame, as well as the crushed brick once the test was over, can be seen in Figure 2.13. The loading rate was determined through a trial-and-error process, such that once half of the expected load has been reached, the remaining load is applied between 1 and 2 minutes. This flexible requirement allowed for a loading rate of 0.0085 mm/s for all eleven brick types. The results of all the compression tests are displayed in Table 8. The minimum individual compressive strength is the minimum compressive strength of the five bricks tested for each brick type. COV values are indicated in parentheses. The values highlighted in green are those that have passed the acceptance criteria in Table 1 and the values highlighted in red are those that have failed the acceptance criteria in Table 1. The values highlighted in yellow are those that were close to meeting the acceptance criteria, which are considered a "marginal pass".

The displacements from the extensometers were used to calculate the modulus of elasticity of the bricks instead of the displacements of the MTS machine itself in order to obtain more accurate results. The modulus of elasticity was calculated by using the slope of the stress-strain curve between 5% and 33% of the peak load. The gross area was used to calculate the compressive strength of all eleven brick types. The modulus of elasticity is not a mandatory component in CSA A82:14 and therefore does not affect the pass/fail criterion.

Figure 2.12. Extensometers placed on the long faces of the brick

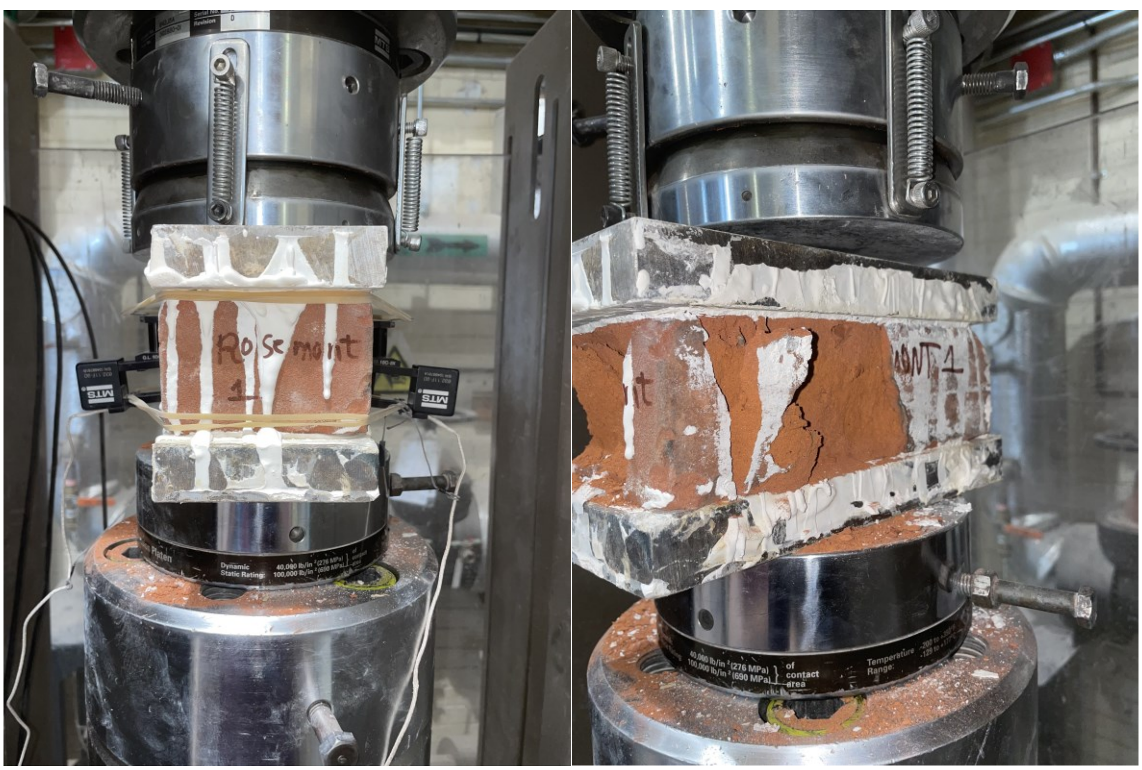


Figure 2.13. Before and after the compression test

Table 8. Compressive strength and modulus of elasticity of the new, used, and old bricks

Brick type	Name	Average compressive strength	Min. individual compressive strength	Modulus of elasticity	Pass/Fail
New	GREY	**89.2 MPa** (10.8%)	**74.1 MPa**	**11,700 MPa** (19.1%)	**Pass**
	SHALE	**56.4 MPa** (19.1%)	**42.1 MPa**	**13,300 MPa** (28.5%)	**Pass**
	GEO	**70.6 MPa** (8.3%)	**62.2 MPa**	**17,300 MPa** (13.5%)	**Pass**
	BROWN	**115.2 MPa** (11.8%)	**99.7 MPa**	**25,400 MPa** (14.6%)	**Pass**
Used	MILTON	**38.7 MPa** (14.6%)	**34.0 MPa**	**12,100 MPa** (52.5%)	**Pass**
	ORANGE	**46.2 MPa** (4.6%)	**43.5 MPa**	**20,000 MPa** (18.5%)	**Pass**
	CORED	**56.2 MPa** (7.8%)	**51.8 MPa**	**23,800 MPa** (25.9%)	**Pass**
Old	BERRI-S	**15.7 MPa** (28.2%)	**6.2 MPa**	**1,700 MPa** (33.4 MPa)	**Fail**
	CRAIG	**33.1 MPa** (21.6%)	**15.4 MPa**	**7,800 MPa** (30.6%)	**Fail**
	BERRI-NS	**27.8 MPa** (12.9%)	**17.1 MPa**	**3,000 MPa** (27.6%)	**Pass**
	ROSEMONT	**23.7 MPa** (23.0%)	**17.0 MPa**	**3,600 MPa** (41.1%)	**Pass**

3 Discussion of results

The new and used bricks all passed the compression tests. The compressive strength of these seven types of bricks significantly exceeded the acceptance criteria in Table 1. Concerning the old bricks, the BERRI-NS and ROSEMONT bricks marginally passed. Although their average compressive strength surpassed the 20.7 MPa limit, the lowest individual compressive strength was very slightly below the limit of 17.2 MPa. However, the difference is extremely minimal and it can therefore be considered a pass. For the CRAIG bricks, the individual compressive strength was below the 17.2 MPa limit so they failed the compression test. The BERRI-S bricks failed the most severely, with an average compressive strength lower than the 20.7 MPa limit. Table 8 illustrates a clear pattern between the age of the brick and its compressive strength. The old bricks, which have been subjected to decades of frost action, are much weaker than the new bricks. The compressive strength of the used bricks lies in between those of the old and new bricks.

All four types of new brick passed the absorption tests and the freeze-thaw test by a considerable margin. The 24-h cold water absorptions, the 5-h boiling absorptions, and the saturation coefficients were well below the acceptance criteria limits (except for SHALE, which had a 24-h cold water absorption of 9.8% which exceeded the limit of 8.0%), and there was no visible damage such as cracking or spalling after 50 freeze-thaw cycles in any of the 20 specimens. There seems to be a correlation between the compressive strength of the bricks and the mass loss after 50 cycles. The larger the compressive strength, the more resistance the brick has against freezing and thawing, and the less mass it will lose. The weakest brick, SHALE, had the lowest compressive strength of 56.4 MPa and the highest mass loss of 0.29%. The strongest brick, BROWN, had the highest compressive strength of 115.2 MPa and the lowest mass loss of 0.08%. Additionally, the SHALE bricks had the highest 24-h cold water absorption and 5-h boiling absorption (9.8% and 14.3%, respectively) while the BROWN bricks had the lowest values (2.2% and 4.4%, respectively). In general, there was a correlation between the saturation coefficient and the performance during the freeze-thaw test with one exception. The GREY bricks had a relatively high saturation coefficient compared to the other bricks despite the fact that they had a low 24-h cold water absorption, low 5-h boiling absorption, and low mass loss. Davison (1975) reported similar trends, where bricks with high saturation coefficients still performed well in the freeze-thaw test due to their low 24-h absorption and high compressive strength.

Regarding the used bricks, the ORANGE bricks failed the absorption tests. However, the CORED and MILTON bricks marginally failed. These results were expected since the ORANGE bricks were known beforehand to be more porous than the other two types of used bricks. The MILTON bricks had an average saturation coefficient of 0.80 whereas the acceptance criteria limit is 0.78, and the CORED bricks had a 24-h cold water absorption of 8.3% whereas the limit is 8.0%. All 15 used brick specimens failed the freeze-thaw test, with the ORANGE bricks performing the worst (the average number of cycles to failure was 6) and the CORED bricks performing the best (the average number of cycles to failure was 22). Two CORED specimens reached 35 cycles, the highest number of cycles reached by any used brick. Based on these results, the used bricks cannot be reused in new construction according to CSA A82:14.

Finally, all 20 old brick specimens failed the absorption tests and the freeze-thaw test by a significant margin. Based on visual inspection and age of the brick, the CRAIG and BERRI-S bricks were known beforehand to be the weakest old bricks, and they both had the highest saturation coefficient of 0.93. The BERRI-S bricks had a higher saturation coefficient than the BERRI-NS bricks (0.84) which was unsurprising, yet the BERRI-S bricks performed better in the freeze-thaw test than the BERRI-NS brick. Another trial was done solely for the BERRI bricks. In this second trial, the BERRI-NS performed better than the BERRI-S bricks. A possible explanation for these varying results is that in older kilns, bricks were cooked in a pile and those on the interior of the pile were undercooked. These bricks, referred to as "building" bricks, were weaker, more porous, and less durable. They were typically used for structural backup purposes, like the BERRI-S bricks. The bricks at the exterior of the pile, called "facing" bricks, were fully cooked and used for non-structural veneer applications like the BERRI-NS bricks. Although separated into facing and building grades (based on colour – the deeper the colour, the more cooked the brick), these brick grades often had a wide range of properties such as porosity and strength (Ritchie, 1971). The facing bricks are subject to degradation over time due to weathering from frost damage. The degradation may render the facing bricks weaker than the building bricks, even though they were originally much more durable. These diverging results, along with the high COV values caused by the outliers, demonstrate the unpredictability of the behaviour of reclaimed brick and the difficulty in assessing their suitability for reuse.

In the second trial of the BERRI bricks, an additional sample of five half-bricks was selected but the layer of red paint was not removed for testing. However, there was no considerable difference between the samples with paint and without paint. Since the brick was entirely submerged, all sides were subjected to water intake. However, in a unidirectional freeze-thaw test, the paint is likely to make a bigger difference in the results.

Interestingly, the failure mode for the used bricks was cracking whereas the failure mode for the old bricks was spalling. Bricks produced in the early 1900s were manufactured differently than those in the mid 1900s. They were manufactured using the "soft-mud" method, where clay and sand were mixed with water to create a material in a plastic state that could be moulded into the shape of a brick. These bricks were generally more porous and less smooth than the extruded bricks that became popular in later years. It is understandable that the bricks produced from these different processes behave differently under freezing and thawing (Ritchie, 1971). The before and after photos from the freeze-thaw tests are shown from Figure 3.1 to Figure 3.7.

Figure 3.1. ORANGE-4 before and after the freeze-thaw test

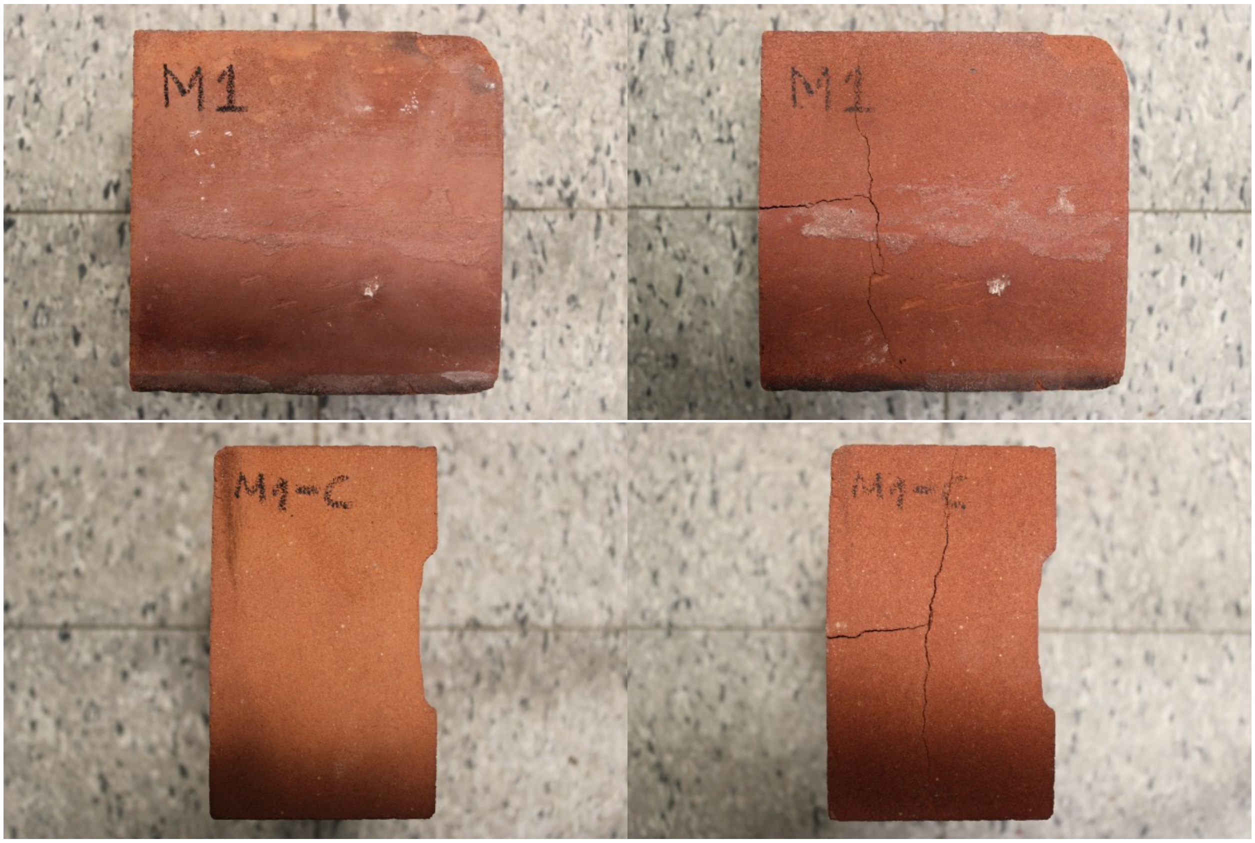


Figure 3.2. MILTON-1 before and after the freeze-thaw test

Figure 3.3. CORED-5 before and after the freeze-thaw test

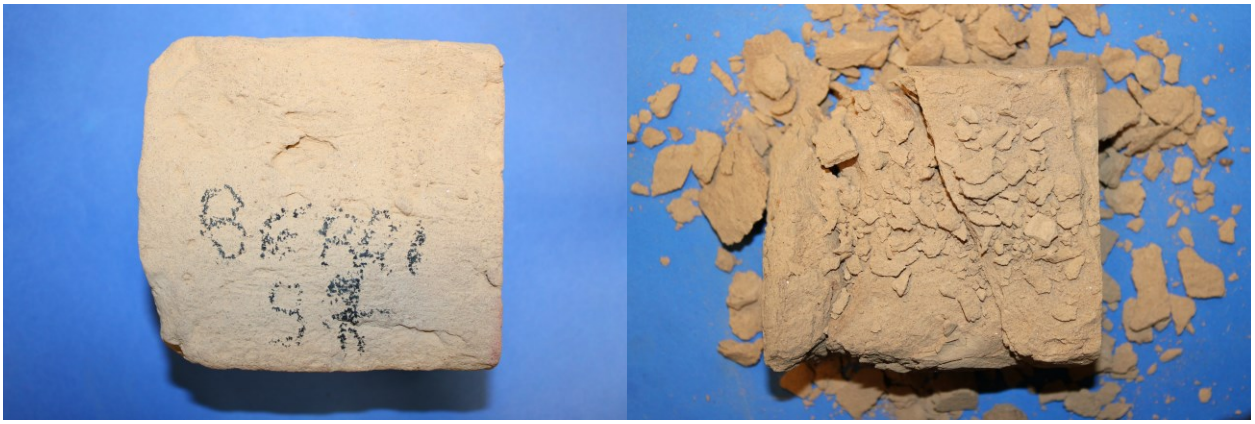


Figure 3.4. BERRI-S-7 before and after the freeze-thaw test

Figure 3.5. BERRi-NS-1P before and after the freeze-thaw test

Figure 3.6. ROSEMONT-2 before and after the freeze-thaw test

Figure 3.7. CRAIG-3 before and after the freeze-thaw test

4 Conclusion

The increase in the number freeze-thaw cycles with climate change is especially concerning for the masonry industry, and it is important to continuously update modern construction codes, standards, and guidelines in order to reflect changing weather patterns and construction practices.

Eleven brick types, both new and reclaimed, were subjected to the mandatory mechanical and environmental laboratory tests in CSA A82:14 to verify their compliance with the standard. The following trends have been drawn based on the laboratory tests:

- There is a correlation between the age of a brick and its compressive strength. The old bricks had a compressive strength ranging from 15.7–33.1 MPa, the used bricks had a compressive strength ranging from 38.7–56.2 MPa, and the new bricks had a compressive strength ranging from 56.4–115.2 MPa.
- There is a correlation between the age of a brick and its absorption values. The old bricks had a saturation coefficient ranging from 0.82–0.93, the used bricks had a saturation coefficient ranging from 0.80–0.86, and the new bricks had a saturation coefficient ranging from 0.51–0.71.
- Regarding the new bricks, there is a correlation between the mass loss during the freeze-thaw test and the compressive strength. The SHALE bricks had the highest mass loss of 0.29% and the lowest compressive strength of 56.4 MPa while the BROWN bricks had the lowest mass loss of 0.08% and the highest compressive strength of 115.2 MPa.
- Regarding the new bricks, there is also a correlation between the mass loss during the freeze-thaw test and the 24-h cold water absorption/5-h boiling absorption. The SHALE bricks have the highest 24-h cold water absorption and 5-h boiling absorption of 9.8% and 14.3% respectively with a mass loss of 0.29% while the BROWN bricks have the lowest absorption values of 2.2% and 4.4% respectively with a mass loss of 0.08%.
- The GREY bricks had the highest saturation coefficient of all the new bricks yet they performed exceptionally in the freeze-thaw test, which agrees with the results of past studies.

Based on these results, the new bricks comply to CSA A82:14 while the used and old bricks do not. The ORANGE bricks failed the absorption tests, and all used bricks failed the freeze-thaw test. The old bricks failed the absorption and freeze-thaw tests, and the BERRI-S and CRAIG bricks failed the compression test. This means that all of the used and old bricks cannot be reused in new veneer construction in Canada according to modern masonry standards. However, ambiguous codes and standards complicate the interpretation of the acceptance criteria for reclaimed brick.

The laboratory tests included in CSA A82:14 have been described as “extremely severe” in the available literature, making it unsurprising that the used and old bricks did not meet their acceptance criteria. However, reclaimed brick may still be viable for reuse in the masonry industry considering they had been salvaged from buildings that have stood for decades or even over a century.

Further research is necessary to update and revise the durability requirements in CSA A82:14 to more accurately reflect the behaviour of new and reclaimed bricks in service and to address evolving climate patterns.

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