STANDARDS RESEARCH

Climate Change Adaptation of Masonry Materials, Design, and Construction

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Executive Summary

Recent analyses of climate data, as well as climate modelling, indicate that the Canadian climate is changing and will continue to do so as part of the global phenomenon of anthropogenic climate change. These changes have both acute and long-term effects on many aspects of the Canadian economy, including our built infrastructure. As part of a review of its collection of standards to assess the need to adapt them to climate change, CSA Group identified several standards as high, moderate, or low priority for adaptation; the current report represents a portion of the efforts arising from the review.

This report to provides recommendations for the adaptation of masonry standards to the effects of climate change. Included is a detailed review of the literature related to the effects of climate and climate change on masonry materials and design, as well as a discussion of how this information may be used to strengthen current standards. The report was informed, in part, through consultation with key experts and stakeholders in the masonry industry.

The following masonry standards are discussed in this report:

- CSA A82:14 (R2018), *Fired masonry brick made from clay or shale*
- CSA A165 Series-14 (R2019), *CSA Standards on concrete masonry units*
- CAN/CSA-A179-14 (R2019), *Mortar and grout for unit masonry*
- CSA A370:14 (R2018), *Connectors for masonry*
- CAN/CSA-A371-14 (R2019), *Masonry construction for buildings*
- CSA S304-14 (R2019), *Design of masonry structures*

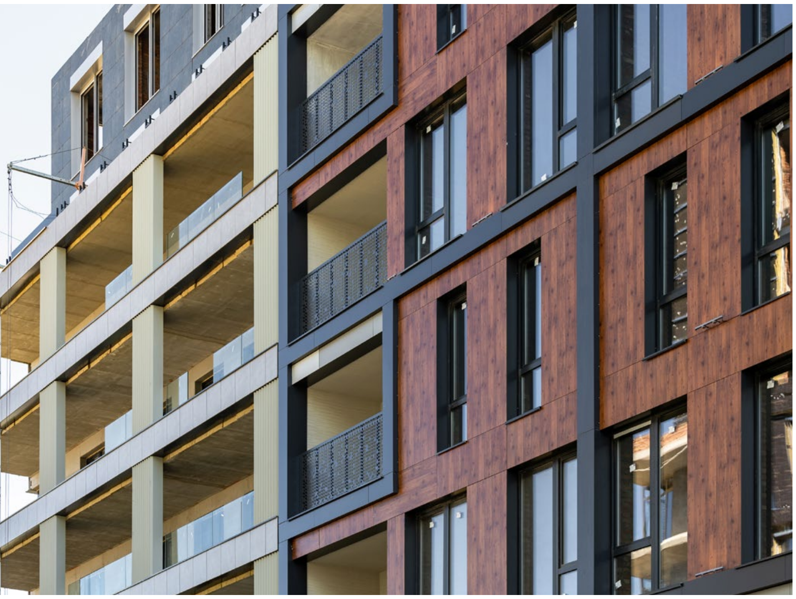
The CSA A370:14 (R2018), *Connectors for masonry* standard was one of the standards identified by CSA Group as a high priority for climate change adaptation, mostly since it includes climate data (a table of annual Driving Rain Index [aDRI] values) for various locations in Canada. Other masonry standards were identified as moderate or low priority for adaptation; however, interesting insights may be gleaned from the literature on how climate effects may be accounted for in future iterations of these standards. These include information related to adapting masonry to the changing climate itself, as well as to changes in practices, policy, and regulations aimed at mitigating future carbon emissions and climate change.

The main recommendations of the report pertain to the criteria used to determine the minimum corrosion protection requirements for masonry ties. As there are many indications of widespread changes in the aDRI across Canada over the past decades, and projections for further changes in the future, these changes should be accounted for. Alternate criteria, such as the use of the National Building Code of Canada's Moisture Index (MI) may also be considered. Other recommendations include the addition of guidance in the standards on the application of sophisticated testing and analysis methods to quantify the durability of masonry connectors, masonry units, as well as mortar and grout.

Research needs identified in this report include the need for new research to determine regional trends in changes to the severity of freeze-thaw cycling, quantifying the relation between climatic factors (e.g., aDRI or MI) on the

corrosion rate of masonry connectors, and quantifying the phenomenon of rain penetration through masonry veneer cracks.

Other considerations discussed in this report arose due to ongoing efforts to mitigate future climate change by reducing CO_2 emissions and energy usage. The design of buildings must now account for the energy and CO_2 emissions embodied within the materials and construction processes as well as the energy efficiency of the finished structure. Many key industry stakeholders identified challenges faced in quantifying the energy benefits and trade-offs of masonry construction, and indicated that fair comparison with other construction materials is often difficult. As material science and building science continue to progress and evolve, there is a growing need for standardized metrics and methods for quantifying dynamic thermal performance, thermal bridging, embodied energy, and long-term durability of building materials.



"With the arrival of the Government of Canada report on Climate-Resilient Buildings and Core Public Infrastructure [6], some of the long-term effects of climate change on building design and durability are beginning to emerge."

1 Introduction – Masonry and Climate Change in Canada

Climate change has been accelerating over recent years, and its impacts on the built environment in certain regions are increasingly evident. Recent weather events have drawn attention to the need for strategies to mitigate the impact of extreme events, such as extreme heat events and flooding [1]. In Canada, increases in temperature and the frequency of extreme rainfall events are expected to occur over the course of the 21st century [2], [3]. Canada's Changing Climate Report [4] focuses on climatic changes that will affect the wild ecosystem, regional hydrology, natural disasters, and human health. Data regarding future peak climatic loads that can be used to inform the design of new infrastructure are only now becoming available. Until recently, little work had been done to study the effect of climate change on the built environment (e.g., due to changes in temperature extremes, changing freeze-thaw patterns, changing moisture loads); to address this, a comprehensive research program was initiated by the National Research Council (NRC) in view of updating building codes and standards [5]. With the arrival of the Government of Canada report on Climate-Resilient Buildings and Core Public Infrastructure [6], some of the long-term effects of climate change on building design and durability are beginning to emerge. Additionally, the rising cost of damages due to climate-related disasters [7] is bringing further attention to this issue. Whereas measures such as changes to building codes and zoning bylaws will be needed to address the increasing risk to property and health of weather-related disasters, updates to standards will help adapt to and mitigate some of the more insidious effects of climate change.

In addition to changing climatic loads and environments, Canada's built infrastructure is also evolving in a move to improve energy efficiency, thereby mitigating the extent of climate change. Special consideration is being given to new construction and to retrofitting existing infrastructure to improve thermal insulation, and to use materials and methods that have lower embodied energy (e.g., materials that require less energy to produce, release less CO_2 during the manufacturing process, or are derived from recycled materials). Currently a large portion of Canada's infrastructure is in a state of disrepair, including 9% of culture and recreation assets being in poor or very poor condition [8]. As these assets are repaired and replaced, necessary care must be taken to ensure they are not only resilient to the expected changes in the Canadian climate, but also have a lower carbon footprint.

Masonry materials have long been an attractive choice for commercial, institutional, and residential buildings, either as a main structural element, or as a durable cladding. The use of these materials and associated construction techniques have continued due to their many beneficial properties, including heat-and fire-resistance, thermal mass and thermal regulation properties, strength, and durability. Modern masonry construction, similar to other forms of construction, has evolved to become more efficient, resulting in decreased redundancy in design. However, capitalizing on these efficiencies will require the changes to the environmental loading and other potential vectors of degradation to be accurately anticipated and captured. This ongoing evolution of design and building practices is being accelerated by changing energy codes and targets for built infrastructure embodied energy. The purpose of this study is to assess the vulnerability of Canadian masonry standards for "full-bed" unit masonry[1], to develop recommendations for changes and updates to the standards, and to identify areas that merit primary or additional research.

2 Background

In 2018, CSA Group performed a Climate Change Adaptation Standards Inventory Analysis, in which all CSA standards referenced in the 2015 National Model Codes were assessed with regards to their vulnerability to climate change. A total of 81 standards were identified as requiring climate change adaptation provisions and were ranked based on their degree of impact and urgency. CSA A370:14 (R2018), *Connectors for masonry* [9] was one of 10 standards identified as "high priority" for adaptation for climate change, and several other masonry standards were also identified as a "medium priority" for adaptation (CSA 165.2-14, *Concrete brick masonry units* [10]; CSA A165.1-14, *Concrete block masonry units* [10]; and CSA S304-14 (R2019), *Design of masonry structures* [11]). Other masonry standards identified as not requiring climate change adaptation (CAN/CSA-A179-14 (R2019), *Mortar and grout for unit masonry* [12]; CSA A82:14 (R2008), *Fired masonry brick made from clay or shale* [13]; and CAN/CSA-A371-14 (R2019) *Masonry construction for buildings* [14]) were also examined as part of this report, for completeness, and to identify areas that may be influenced by secondary effects of climate change, such as changes to energy codes and building practice.

CSA A370:14 (R2018), *Connectors for masonry* [9] was identified as a "high priority" mainly due to Annex E, which lists annual Driving Rain Index (aDRI) values for locations across Canada for use in determining the required level of corrosion protection for connectors. It is noteworthy that this index only reflects the potential wetting of walls and does not account for the effects of temperature or drying on corrosion rates. In the early 2000s, a large-scale research effort on the climatic factors that contribute to the degradation of building envelopes proposed a Moisture Index (MI), which accounts for wetting and drying, to be used as a basis for requiring more stringent moisture-control measures for buildings [15]. However, since that study focused on the impacts of moisture penetration within stud wall insulation cavities, it remains unclear if and how those results could be used for the assessment of the risk of connector corrosion within masonry veneer cavities.

CAN/CSA A165 SERIES-14 (R2019), *CSA Standards on concrete masonry units* [10] and CSA A82:14 (R2018), *Fired masonry brick made from clay or shale* [13] outline the requirements for the most common types of masonry unit materials used in Canadian construction. Since these materials are often employed as an integral part of the building envelope, they must be well-suited to resist environmental loads such as wind and rain, as well as fluctuations in temperature and relative humidity. A review of these standards served to verify that the prescriptive material properties and quality controls justify their resiliency for any environment to which they may be subjected. A review of CSA S304-14 (R2019), *Design of masonry structures* [11] and CAN/CSA-A371-14 (R2019), *Masonry construction for buildings* [14], which outline the design and construction requirements for all masonry structures, was needed to confirm they remain relevant to current design and construction practices, and that all prescriptive requirements remain adequate for all Canadian jurisdictions. New Canadian standards for durability (e.g., CSA S478:19, *Durability in buildings*) [16], requiring designers to account for the service life of structures, mean that additional guidance will be needed to aid in the determination of expected in-service longevity of the various components of masonry structural systems.

The influence of various climatic loads (e.g., wind, rain, temperature flux) on structural masonry has been, and continues to be studied (e.g., [17]-[20]); however, much

1 Typically made from units at least 90 mm in thickness, full-bed masonry is constructed by stacking subsequent courses of units and bonding them to one another with a layer of mortar (mortar bed). This technique results in a wall that is free-standing, or intermittently supported, and behaves differently from thin masonry veneers, wherein individual units are adhered to a vertical structural backing or wall.

of the current literature focuses on the preservation and rehabilitation of historical masonry structures (e.g., [21]-[24]). Thus, additional research may be needed to allow CSA codes and standards to remain relevant to new and emerging construction techniques and changing climatic loads.

2.1 Project Goals

The main goal of this report is to recommend changes to current masonry standards to improve the resiliency of masonry structure to the effects of climate change. More specifically, masonry standards have been reviewed in order to identify potential vulnerabilities, and a targeted literature review is leveraged in order to propose modifications, and determine areas in need of further research. Focus has been placed both on areas where adaptation may be needed to allow masonry to remain durable in a changing climate, and areas where the standards may better support the mitigation of future climate change through decreased embodied and operating energy of buildings.

2.2 Methods

Research questions based on the vulnerabilities identified through a review of the standards were explored individually according to tailored plans. For each research topic, a literature review was conducted to understand the current status and identify gaps in our current knowledge. Sources consulted include the proceedings of masonry specialty conferences and symposia, peer reviewed journal article databases, and relevant reports and standards.

To supplement the insights and specialized knowledge of the project team while conducting the literature review, a survey questionnaire was distributed to key external stakeholders representing manufacturing, construction, materials testing, and academic research. The survey questions invited respondents to share their insights and perceptions related to the current state of masonry standards and on specific areas of concern where climate change adaptation may be needed in certain standards. In this manner, a wide breadth of potential impacts of current and proposed Canadian standard provisions are presented in this report.

3 Literature Review

The literature review characterizes the state of knowledge in select fields that are relevant to the effect of climatic loads and changing climate on the durability of masonry materials and masonry buildings. Select topics related to the mitigation of climate change through improved energy performance of buildings are also discussed.

3.1 Masonry Connector Durability

Corrosion has long been an important design consideration in masonry veneer and cavity wall construction. Since masonry assemblies generally possess some degree of porosity, where masonry is exposed to the outdoor elements (and/or indoor humid conditions) moisture will inevitably reach the reinforcing materials resulting in conditions conducive to corrosion. Designers must therefore ensure design considerations are included to manage moisture ingress as well as take other steps to promote the long-term durability of the structural systems supporting masonry veneers. Currently, the aDRI is the main climatic factor available to designers to determine the severity of the long-term corrosion environment to which masonry connectors will be exposed. The use of this metric has been carried forward from the 1950s and 1960s when the index was developed as a relative measure of the quantity of water that is likely to strike the side of a structure (and possibly permeate through the siding material) [25].

Several weaknesses of the aDRI have been identified, including that it does not account for building geometry and aerodynamic effects. These effects have been shown to account for more variation in the amount of water striking a vertical surface than the aDRI itself [26]. Another important aspect not accounted for by the aDRI is average atmospheric humidity and drying potential. Various climatic indices and approaches have been proposed to better reflect the relative severity of climatic conditions with regards to corrosion of masonry connectors; however, correlation between these indices and observed corrosion rates remains a work in progress. Methods of accounting for changes to climatic factors that affect the corrosion environment of masonry connectors are also under development. This is therefore an opportune time to reassess the traditional methods for determining the relative severity of corrosion environments, consider alternative approaches, and provide evidence-informed recommendations on which methods should be applied.

Corrosion models for masonry ties are improving, and researchers have recently been able to predict with reasonable accuracy the corrosion rates of ties within masonry joints, given sufficient climatic information [27]. Such detailed analysis will not be practical in all design situations; however, this work could lead to better evidence-based design decisions, and possibly more accurate generalized regional corrosion rates for certain construction applications. With changing precipitation patterns due to climate change (with respect to both annual precipitation and precipitation intensity), and increased atmospheric CO_2 concentration, it will be important for designers to account for these important changes as well.

Continuing care and attention will be needed with regards to building envelope detailing. Only with effective standardized construction methods that limit accidental accumulation of moisture within wall assemblies (through effective drainage and venting, and by limiting condensation from air leakage and thermal bridging) can analytical methods be effectively and accurately applied to inform the design of dependable solutions. Additional research into the elements of design, materials, and components that increase or decrease the severity of exposure will also provide needed information. We can determine with increasing confidence the external environment to which our buildings will be exposed (i.e., average conditions, the frequency of extreme events, as well as the effects of climate change); strict construction method requirements are needed to achieve the same level of confidence in the response of structures to these conditions.

3.1.1 Buildings and Climate Change

As the global average temperature increases, local climatic conditions are affected in various ways. Much of the attention around climate change has been focused on factors that directly affect human, animal, and plant life (e.g., extreme heat, floods, and droughts); however, these changes are not necessarily those which have the most severe impact on structures. A wide variety of environment-related material deterioration processes that may be impacted by climate change have been identified by research groups such as Lacasse et al. [28]. Of particular interest to masonry construction are anticipated changes to freeze-thaw cycles (e.g., annual number of cycles experienced by a building or portion thereof) [29], as well as changes to the corrosion environment of connectors due to changing precipitation and humidity patterns. Increasing atmospheric CO_2 concentration has also been linked to increasing rates of carbonation in concrete, which can also accelerate the onset of corrosion [30]. Work is currently underway to quantify these changes to environmental conditions that have an impact on building durability and performance [31]. To the extent that these changes can be anticipated, they must be accounted for in the design of structures to avoid widespread failures and costly repairs.

3.1.2 Driving Rain, Moisture Index, and Other Moisture-Related Climatic Loads

The annual Driving Rain Index (aDRI) is a value proportional to the annual average quantity of water passing through a vertical plane of a specified area. Given that wind is obstructed by walls, it is self-evident that this index is not equivalent to the amount of water annually sprayed onto the surface of a wall; it has, however, been used as a convenient way of estimating the relative severity of exposure to moisture in various regions. In Canada, a map indicating regional values of aDRI was first developed by Boyd in 1963 [25]; a version of this map has long been used as a measure of relative severity of corrosion conditions for masonry connectors. Various studies have demonstrated that the amount of rain deposited on the vertical surfaces of a building can vary widely (e.g., [32], [33]). Refined methods for estimating the amount of rainwater projected onto vertical walls, accounting for wind directionality, and aerodynamic effects (Rain Admittance Function) have been developed, but can be cumbersome to implement [26], [34], [32].

Given that multiple factors affect the amount of moisture entering a wall system (wind-driven rain, condensation, drying potential), attempts have been made to develop methods to account for regional

"Given that multiple factors affect the amount of moisture entering a wall system (wind-driven rain, condensation, drying potential), attempts have been made to develop methods to account for regional and local differences in climate."

and local differences in climate, leading to differing potential for moisture-related degradation of wall assembly and cladding materials. A wide variety of indices and other metrics are described in the literature that account for wetting and drying in different ways. These include the following:

Annual Driving Rain Index (aDRI): Often reported in units of m^2/s, the aDRI is the product of average wind speed and total annual rainfall [25]. Although windspeed and precipitation are not entirely independent variables, this index, when multiplied by the Driving Rain Factor (DRF) to account for the effect of the relative horizontal and vertical velocity components of falling raindrops, produces a simple and reasonable estimate of rain passing through a vertical plane normal to wind direction [32].

Directional Driving Rain Index (dDRI): Similar to the aDRI, the dDRI is the product of windspeed and rainfall depth; however, it requires coincident measurements of windspeed, wind direction, and rain depth [15]. This index is typically shown plotted on a polar graph in which the summation of rainfall and windspeed products are shown for wind directions corresponding to the cardinal (and intermediate) directions.

Rain and Heating Degree-Days: A combination of annual average rainfall and heating degree-days has been proposed as a method of defining climate zones where the risk of moisture-related deterioration is high or low. Cornick et al. [15] suggest that warm and humid regions (where average annual rainfall exceeds 1100 mm and heating degree-days (HDD18) are less than 5000) could be classified as "Zone 2", where additional considerations for moisture management are needed; all other regions would be classified as "Zone 1".

Scheffer Decay Hazard Index: Developed to determine the relative risk of decay for above-ground wood products, this index accounts for the amount of time materials are likely to be both wet and above a threshold temperature conducive to fungus growth [35]. It is calculated as follows:

$$\textit{Decay Hazard Index} = \frac{\sum_{Jan}^{Dec}[(T-35)(D-3)]}{35}$$

Where T = Average monthly temperature, and D = number of days of a month with 0.01 inch or more of rain.

Exposure: The term "exposure" is loosely used to describe the local environment of a building, including aspects that may not be covered by other climate indices. This may refer to proximity to a body of water (fresh or salt water), relative exposure to wind (e.g., exposed on a hilltop vs. surrounded by other structures), or the position of a specific structural element of interest (e.g., to account for the effect of an overhang, or to differentiate between indoor vs. outdoor conditions) [36]. With rising sea levels associated with climate change, significant changes to the exposure of buildings in coastal areas should be expected.

Moisture Index (MI): Many formulations of this index have been proposed; however, the general principle is to generate an index that is representative of the amount of time an exposed structural element is under wet conditions by combining factors that lead to wetting (Wetting Index or WI) with factors that lead to drying (Drying Index or DI). In their NRC report, Moisture Management for Exterior Wall Systems (MEWS), Beaulieu et al. [37] used wind-driven rain in the prevailing direction (using Straube's method) for WI, and the potential for drying based on average temperature and relative humidity for DI. The moisture index listed in the current National Building Code [38] uses the same DI as in the MEWS report, but substitutes the directional wind-driven rain for total rainfall as WI. Both publications used normalized WI and DI values to determine MI as follows:

$$MI = \sqrt{WI^2 + (3 - DI)^2}$$

The index is meant to estimate the relative severity of a regional climate in regards to the potential for moisture-related deterioration.

Relative Humidity and Temperature Index (RHT): First proposed in the MEWS report [37], this index is meant to be measured within a wall cavity (or other local environment) or determined based on simulation data. It is by nature a function of exterior and interior climate, as well as the properties of the wall assembly. Similar to the Scheffer Decay Hazard index, it is a summation used to assess the duration and severity of exposure to temperature and humidity over a two-year period (730 days). Adaptable to both corrosion and wood decay, the index may be expressed as follows:

$$RHT(X) = \sum_{i=0}^{i=73} (RH_i - X)\,(T_i - 5)$$

where RH is the percent relative humidity, T is the temperature in °C, X is the reference relative humidity (80% for corrosion, 95% for wood decay), and the index i refers to a 10-day period over which the RH and T values are averaged (73 ten-day periods, over two years). Note that only positive values are included in the summation.

Correlating the severity of the wetting environment with deterioration risk has proven to be complicated. The sensitivity of the climate indices to specific variations in climatic factors and the range of values observed across Canada has been studied [39]; however, the relation between these indices and the deterioration of masonry connectors remains unclear. For example, the MEWS report [37] identified exceptions to the generally positive correlation between MI and RHT in their simulation of various wall systems subjected to a typical two-year weather cycle for seven locations from across Canada and the US. The findings of the MEWS report have been suggested to be useful to the determination of Serviceability Limit State analysis for wood stud construction (including wood stud with masonry veneer) [40]. The most recent analyses on moisture-related deterioration of structures due to the local climate now account for the effects of climate change. For example, Nik et al. [41] have demonstrated that changes to the local climate in Sweden under various Global Climate Models (GCMs) will have an impact on the water content of typical wall construction, irrespective of large uncertainties in the calculation methods for wall hygrothermal response.

3.1.3 Masonry Tie Corrosion

Masonry connectors are typically located in regions of wall assemblies that are at least partially open to outdoor conditions. Being sheltered from direct precipitation and sunlight and partially embedded in mortar, they are in an environment with a less severe potential for corrosion than elements that are directly exposed. Carbon steel ties will corrode over time in regions where rainwater has the potential to enter a wall cavity (through cracks and other openings, or by capillary action), and in cold environments where warm and moist indoor air is allowed to escape into a wall cavity. Current design practices involve determining whether zinc coatings (galvanizing) of carbon steel ties will provide sufficient protection (sacrificial layer) for the expected service life of the structure or if stainless steel or otherwise non-corroding [42] connectors should be specified.

Since carbon steel has a tendency for pitting corrosion, which can very rapidly reduce the strength of an element, the life expectancy of a tie in a corroding environment is typically deemed to be no longer than that of its zinc coating. A wide variety of corrosion rates for galvanized (zinc-coated) steel ties have been reported in the literature, often loosely correlated to rain and exposure characteristics. Grimm [43], [44] suggests that corrosion rates ranging from 5 to 50 g/m²yr are probable for areas of the US and UK with aDRI of 2.5 to 5; a similar range in corrosion rates was reported by Maurenbrecher and Brousseau [45] for observed corrosion rates in Canada. Calculated corrosion rates based on two ISO models for a variety of locations in Canada indicate that corrosion rates range from 5 to 185 g/m²yr (the highest rate is for a coastal location with high wind and rain) [46]. Most recently, a sophisticated modelling approach has been developed [27]; by applying local weather conditions to a calibrated hygrothermal wall simulation, the corrosion environment of masonry connectors was estimated, and the service life of zinc coatings accurately predicted. The main drawback of this approach is that it is cumbersome; it relies heavily on detailed climate data and modelling of moisture infiltration through masonry veneers (i.e., using a sophisticated hygrothermal simulation) in its determination of corrosion rates. The authors have also acknowledged that the results are very sensitive to imperfections in detailing or construction that may lead to additional moisture reaching the ties (e.g., due exfiltration of moist indoor air).

3.1.4 Detailing and Moisture Ingress in Masonry Walls

Masonry assemblies are porous and some permeation of moisture is inevitable, particularly through the porous mortar material. However, it is important to implement design controls to prevent moisture from the outside environment from breaching the envelope of a structure, and to minimize moisture in all areas of wall assemblies so that the associated risks of corrosion and freeze-thaw action are reduced. Masonry veneers are often applied to structures as a rain screen. Meant to shed the bulk of the rainwater, they protect the underlying insulation and structural backing from various environmental loads. The air space between the masonry veneer and the rest of the wall assembly is a critical part of this type of wall design, as it allows moisture that has infiltrated through the veneer to escape the cavity without transferring to the backing wall. In contemporary construction, the vapour barrier placed within the wall cavity is nearly completely impervious, preventing moist indoor air from escaping the building and outdoor moisture from penetrating to the structural backing. However, a remaining area of the wall where corrosion is of concern is in the wall cavity and within the veneer itself. Some have suggested that cracking of masonry veneers is a significant contributor to moisture ingress into wall cavities [47]; however, research by the Canada Mortgage and Housing Corporation (CMHC) [48], and other analyses by Straube and Burnette [32] suggest that proper cavity venting (pressure equalization) as well as surface tension forces greatly reduces the influence of cracking rain penetration. In cases of observed corrosion rates being faster than anticipated, detailing problems are often blamed [27]. Documented problems have been attributed to wall cavity bridging by mortar droppings [49] and the consequences of an inadequate air barrier (e.g., [50], [51]); however, extensive guidelines are available to help designers achieve safe designs (e.g., [52]-[54]).

Other aspects to consider are the sheltering effects of elements such as roof overhangs on low-rise houses, which have a strong positive effect on keeping cavity moisture to a minimum [55]. Additionally, care must always be taken in the design and placement of flashings and damp-proof courses, to ensure they effectively shed any moisture they are subjected to, and do not act as a path for moisture ingress further into a wall assembly. Water-repellant coatings on exterior wythes of masonry may also help reduce the amount of moisture penetrating the walls. Tariku and Simpson [56] found that the coatings they used effectively reduced the moisture content of veneer bricks and did not significantly affect the drying process.

3.1.5 Carbonation and Chlorination

In order for masonry connectors to corrode, the passive protection provided by the alkaline mortar must first be overcome. Additionally, chlorides, if present due to exposure to salt-laden air in coastal environments, or de-icing salt, act as an electrolyte to accelerate corrosion reactions in progress. The process of carbonation, by which the pH of concrete decreases over time due to atmospheric CO_2 (eventually depleting the protection capacity of cementitious materials and allowing corrosion to initiate) has been studied extensively for concrete construction, but its impacts on masonry construction are only now emerging in scholarly research [57], [58]. Current research in concrete construction accounting for anthropogenic increases in atmospheric CO_2 concentration and climate change [30], [59], [60] suggest that these impacts must be considered in masonry design. Current research estimates that carbonation of mortar joints allow corrosion to begin within the first five years of service [27], others suggest that mortar joints should be expected to be fully carbonated within 10 years of service [45]. With atmospheric CO_2 concentrations continuing to rise, time to carbonation of mortar joints can be expected to shorten further.

3.2 Strength and Stiffness of Masonry Ties

The minimum strength requirements for individual masonry connectors specified in the current CSA A370:14 (R2018), *Connectors for masonry* standard have proven to be adequate, given their historical performance during severe wind events [55], [61]-[64]. Several studies have also been completed examining variations in the distribution of wind loads to masonry ties and anchors for different types supporting systems (back-up wall stiffness). Finite element models [65] and plane frame analysis [43] indicate that flexible backing systems result in higher concentrated loads near the top and bottom of masonry veneer walls. Physical testing performed for the CMHC ([66], [48]), however, suggests that these effects are mitigated by the restraint offered by sealant at the top of the wall and the support shelf at the base. The distribution of tie forces along the height of a vertically spanning veneer may be accommodated in design by decreasing tie spacing in these regions or increasing the strength of individual ties. Although the friction response of base support has been studied [67], it is sensitive to the specificities of the materials used. Additionally, some uncertainties in tie response (i.e., variable stiffness and mechanical free-play) can complicate the calculation of expected tie forces [68]. Of particular interest is the behaviour of eye-and-pintle type connectors, which have been shown to exhibit up to a tenfold difference in stiffness across their range of adjustability [69]. Although connectors conforming to current requirements of CSA A370:14 (R2018), *Connectors for masonry* [9] are required to achieve minimum stiffness requirements across their range of adjustability, the difference in stiffness for a single connector, depending on its position within the range of adjustability, reported in available product datasheets remains significant.

The high stiffness of uncracked masonry veneers allows them to effectively distribute locally applied forces over a large area, generally reducing the load applied to individual ties. Impact resistance tests (windborne wood missiles) performed by Bennett et al. [70] demonstrate that uncracked masonry veneer effectively redistributes localized impacts up to loads that cause perforation of the wall. Dynamic response of brick veneers to wind loads remains largely unexplored, although testing on reinforced concrete masonry unit (CMU) walls [71] indicates that neglecting those effects likely does not reduce conservatism in design.

Climate change adaptation and mitigation efforts present competing demands for masonry connectors. Adaptation to the increasing frequency and severity of major windstorm events may require designers to consider the use of higher strength ties, or closer spacing thereof; however, attempts to mitigate the impact of the built environment will encourage wider spacing of connectors to reduce the impact of thermal bridging. Greater understanding of the effects of connector strength, stiffness, and spacing on the strength and behaviour of masonry veneer construction will be required to optimize resilient design solutions.

3.3 Masonry Cracking and Moisture Penetration

Masonry is a porous material, meaning that even an intact (uncracked) assembly without openings has the potential to allow moisture penetration through capillary effects. Modern masonry construction exposed to the exterior is vented to allow any moisture that penetrates the exterior face of masonry to escape; a vapour barrier placed beyond the exterior-most masonry elements (often a masonry veneer or rainscreen) prevents any moisture from penetrating further into the building envelope. Moisture penetration through masonry therefore only becomes a problem if it is excessive and/or if provisions are not in place to shed excess moisture. Various researchers have suggested that cracks narrower than 0.1 mm do not contribute to moisture penetration through masonry walls [72], [32], while others have indicated that larger cracks may not pose significant problems as long as wall cavities are appropriately vented (pressure equalized) [73], [50]. Volumetric expansion and contraction of masonry elements due to changes in humidity and temperature can cause significant cracking if not properly accommodated. Various guidelines and best practices are now available to assist designers to properly account for cracking. An emerging concern related to cracking is its effect on carbonation. Studies of concrete materials indicate that cracks may accelerate the carbonation process, resulting in concerns for reinforcement corrosion. Changes in temperature and humidity due to climate change, as well as the rising concentration of atmospheric CO_2, may exacerbate these effects.

3.3.1 Best Practices

Early Canadian guidance for designers [74], [75] highlighted cracking as a major source of moisture penetration, often caused by inadequately controlled building movements (expansion/contraction, and differential movements). More recent guidance by the CMHC [52], [53] acknowledge the inevitability of certain types of cracking, and offer prescriptive guidance for moisture management, proposing limits on deflection to control cracking, and requiring that a moisture barrier is provided beyond masonry rain screens. For buildings up to three storeys in height, deflection of L/360 (where L is the unsupported length of a wall) is said to be adequate; however, limiting elastic deflection of the backing at service loads to L/600 or even L/720 is said to be desirable, in order to restrict crack opening size [52], [50]. Deflection limits for lintels and supporting shelf angles are similarly restrictive to avoid cracking. It should be noted that these best practices generally recommend that cracking be restricted, but that avoiding cracking would be impractical in most cases; although structural backing stiffness helps reduce maximum crack size, the cracking load of masonry veneers is controlled by the flexural strength of the veneer [48].

Expansion of clay brick masonry as it absorbs moisture over its service life and contraction of concrete unit masonry as it dries, as well as seasonal cyclic thermal expansion and contraction are well documented ([73], [76]-[78]). These volumetric changes have the potential for causing serious cracking and degradation if not properly accommodated by expansion or control joints. Climate change will affect regional average relative humidity and the range of annual temperature fluctuations – these changes will affect the range of expansion and contraction of exposed masonry elements.

3.3.2 Cracking Behaviour Studies and Testing

Generally, it is accepted that some moisture will penetrate exposed masonry due to its porosity, and through the vents of pressure-equalized cavity walls and veneer assemblies. Cracking of masonry would naturally be expected to increase its permeability; however, significant research has been conducted to determine the level of cracking at which increased moisture penetration through cracks could lead to decreased durability. Fine capillary pores may draw in moisture, but do not contribute to permeability since a large amount of pressure is needed to expel this moisture due to capillary suction (surface tension). Garden [74] suggests that capillary pores finer than 0.01 mm do not contribute to permeability. In their discussion of the Norwegian test method for rain penetration, Birkeland and Svendson [72] suggest that cracks larger than 0.1 mm contribute most to rain penetration, and that wind pressure is needed to force water through cracks narrower than 0.5 mm. Further discussion is offered by Straube [32] who explains that since water has a surface tension of roughly 75 μN/m, 750 Pa of pressure is needed to drive water from a 0.1 mm crack; although pressure of this

"Over time, carbonation of masonry mortar reduces the pH of the porewater solution to the point where corrosion of connectors and reinforcement can initiate."

magnitude is often produced by wind action, such a force would not occur by hydrostatic head in typical brick construction. Straub's estimate for determining the width of cracks allowing moisture penetration is likely conservative, since it does not account for crack roughness and tortuosity (straight or winding); Wang et al. [79] have reported that cracks greater than 0.05 mm are needed in order to significantly increase the permeability of concrete subjected to 3 kPa of pressure head (Straube's equation underestimates the pressure required to drive moisture from a crack of the reported size by a factor of two). Grimm [73] further suggests that cracks up to 0.38 mm should not cause alarm. Compelling evidence that masonry cracking is a lesser concern for permeability is provided through research on wall assemblies by Drysdale and Wilson [48], who observed that flexural cracking of masonry only contributes significantly to permeability when a pressure differential exists across the masonry veneer (unvented cavity). Other research groups ([80], [81]) have studied the flow of water through larger cracks (1 mm–5 mm); however, given the small scale of the tests, their conclusions are difficult to relate to the behaviour of in situ masonry assemblies.

Based on these findings, there is a consensus that cracks narrower that 0.1 mm do not increase permeability of veneers or mass masonry walls, regardless of whether or not they are vented (pressure-equalized). Cracks up to 0.5 mm wide seem unlikely to have a significant effect on permeability of veneers, as long as proper pressure equalization is provided. However, further experimental research is needed in order to quantify the expected permeability of veneer walls for different crack sizes and differential pressures.

Another durability factor affected by cracking is carbonation. Over time, carbonation of masonry mortar reduces the pH of the porewater solution to the point where corrosion of connectors and reinforcement can initiate. Increased crack width has been shown to allow faster penetration of a carbonation front during accelerated concrete carbonation tests [82]. Mortar carbonation models that account for cracking will be critical to the accuracy of the life-cycle estimate of corrodible embedded reinforcements and connectors.

3.4 Damp-Proofing in Masonry Construction

In modern construction, masonry is typically not used as an impermeable component of a building envelope. Rather, masonry veneers are designed to protect other elements of the building envelope (insulation and load-bearing members), shielding them from the bulk of precipitation, as well as UV radiation and accidental abrasions. Since moisture is capable of permeating through masonry, appropriate detailing and flashings are needed to evacuate excess moisture from behind the masonry veneer, and other materials are needed to prevent moisture from penetrating the building envelope (typically a polymer sheet, or bituminous compound). A sealed air barrier prevents moisture-laden air from being driven through the building envelope by differential air pressure. This type of air leakage must be prevented since it results in unnecessary energy losses in heating and cooling, and can lead to condensation within sensitive regions of a building envelope. As building envelope and insulation systems continue to improve in order to achieve the energy performance targets needed to mitigate further anthropogenic climate change, it will be of critical importance to ensure masonry construction techniques remain compatible with these new systems. With increasing insulation and impermeability, the relative impact of minor deficiencies is magnified. Whereas minor leakage around connectors may not have been significant in a structure with inadequate sealing around windows and door jambs, if proper care is not taken, this type of leakage can result in a large proportion of the energy loss and condensation in a properly sealed modern building.

3.4.1 Best Practices

The mid-20th century saw significant changes in construction practices and technology. In some instances, these changes outpaced the development of the necessary scientific knowledge needed for safe and durable design. In his article featured in the first volume of The *Masonry Society's Journal*, Mikluchin [83], discussed emerging and identified deficiencies common in masonry construction, and qualitatively outlined methods to resolve them. Masonry construction practices have continued to evolve since the Mikluchin's article, however many of his recommendations remain relevant (e.g., water penetration at joints and junctions, and condensation due to migration of moisture laden indoor air are identified as critical areas of concern). Best practices guides developed by the CMHC in the 1990s for brick veneer-steel stud construction [52], brick veneer-CMU backing construction [53], and flashings [54] all stress the importance of design to allow for the evacuation of moisture from a cavity wall, and to provide a continuous air barrier to separate the indoor from the outdoor environment. Sample detailing figures illustrating the location of flashings and waterproofing membranes are included in these documents.

3.4.2 Moisture Permeation in Buildings – Studies

Field investigations over the years have attempted to diagnose the cause of observed premature deterioration in modern masonry construction. Some opportunities for such investigations have presented themselves in the form of post-disaster inspections of buildings that suffered damage during extreme weather events such as tornados. For example, Bryja and Bennett [55] found no signs of moisture-related problem in masonry-clad single-storey dwellings following the 2002 Tennessee tornados. Various case studies and other works discussed in Grondin's 1993 report for the Institute for Research in Construction [51] indicate that identified moisture problems are often associated with deficiencies in flashing, sealing around openings, and air barriers. Improper flashings and deficient sealing can lead to direct paths for water to penetrate a building envelope into areas that are required to stay dry (e.g., the stud cavity, or interior finishings). Grimm [84] further states that air leakage is a more important issue than water vapour control for buildings in colder climates. Deficient air barriers can result in warm, moisture-laden indoor air to escape into colder regions of the wall assembly (e.g., air cavity, or stud cavity), causing condensation. Another symptom of an ineffective air barrier can occur during wind-driven rain events; if rainwater is projected onto a surface where a pressure gradient exists between the indoor and outdoor air, and where air leakage is occurring, water may be drawn through the building envelope. Further studies are needed to quantify the impact of various site conditions and design provisions on the behaviour of structural systems in service to better inform design. For example, pressure equalization of masonry veneer cavities has been found to dramatically reduce the amount of moisture permeation through cracks in masonry veneer [48], but the effect was not quantified. Air barrier systems are described in the literature as either effective or ineffective, however no threshold value of acceptable air leakage appears to have been studied.

3.5 Freeze-Thaw Durability of Bricks

As average temperatures are expected to increase across most of Canada [6], patterns of freezing and thawing will also be affected. A study of the effects of climate change on roadway maintenance in the US indicated that increasing temperatures are expected to result in increased freeze-thaw deterioration in certain regions due to a shift from “high freeze” to “moderate freeze” conditions [85]. Similar results were reported in the Netherlands, where some regions are anticipating increased freeze-thaw damage in porous asphalt pavements, and others will see a decrease [86]. While masonry walls are subjected to different environmental loads than roadways, these studies nonetheless suggest that the potential for changes to the severity of freeze-thaw conditions for exterior exposed masonry should be investigated. For example, recent research from Switzerland considering a wide range of climate change scenarios is projecting an increase in the risk of freeze-thaw damage for certain types of masonry walls in Davos, and a decrease in Zurich [87].

Extensive research has been performed in an effort to determine the in-service durability of clay brick to freeze-thaw action. Early research work and field observations have shown that variations in the minerology, extrusion process, and firing temperature of clay brick can result in bricks that are abrasion-resistant and practically invulnerable to freeze-thaw action, or bricks that can crumble after a few years of out-door exposure. Fired clay brick such as that used in modern construction is a complex composite material with a hierarchical structure [88]. The physical and chemical/mineralogical properties of the various levels of this hierarchical structure have different effects on absorption and pore structure characteristics; this complex system makes fast and effective determination of brick durability difficult.

The main mechanisms affecting brick durability include resistance to freeze-thaw action, resistance to salt crystallization forces, and resistance to efflorescence. Since salt crystallization can largely be avoided through operational measures (reducing exposure to de-icing salts), and efflorescence is mainly an aesthetic problem, studies of brick durability have been centred on resistance to deterioration by freeze-thaw action of absorbed water. Early studies focused on correlating absorption properties with resistance to controlled exposure to freeze-thaw action. The trends observed in these early tests are used to this day as some of the main indicators of durability in Canadian and US standards. Although more sophisticated methods of assessing the resistance of brick to freeze-thaw action have been proposed, including the use of frost dilatometry, Mercury Intrusion Porosimetry (MIP), and methods involving Scanning Electron Microscopy (SEM), agreement on criteria that will consistently discriminate between durable and non-durable bricks remains elusive.

Some recent work has focused on assessing the risk of freeze-thaw deterioration while accounting for both the properties of the masonry, as well as the exposure environment. Finite element models that account for the degree of saturation and severity of individual freeze-thaw cycles show some promise of leading to life-cycle durability estimates. It is interesting to note that as global average temperatures rise, the frequency and severity of freeze-thaw cycling events may increase in some regions. Although modern masonry construction that includes a vented cavity to promote drying experiences lower risks of freeze-thaw deterioration, retrofitting historical mass-masonry structures to improve their energy-efficiency (increased insulation) poses special challenges.

3.5.1 Absorption and Freeze-Thaw Durability

Since cyclic freeze-thaw testing is time-consuming, many early tests of clay bricks have attempted to correlate freeze-thaw durability with other physical properties which are more readily measured. For example, McBurney and Johnson [89], Davison [90], and Robinson et al. [91] recorded the strength, 24-hour cold water absorption, 5-hour boiling water absorption, and compressive strength of bricks, and calculated the saturation coefficient and total porosity. Each of these researchers employed a different strategy to assess the durability of the bricks being studied; McBurney and Johnson [89] used a 5-year yard exposure environment (half buried in soil and exposed to outdoor weather and freeze-thaw action), whereas Davison [90] compared laboratory freeze-thaw testing (1500 cycles) and 12-year yard exposure, and Robinson et al. [91] reported results from a freeze-thaw test regimen of 50 cycles.

Although these researchers were able to determine threshold values of strength, absorption, and saturation coefficient that discriminated between most durable and non-durable bricks, no combination of criteria were found that rejected all non-durable bricks while still accepting most of the durable bricks. This problem was later highlighted by Marusin [92] in an article pleading for more stringent testing.

3.5.2 Sophisticated Methods of Assessing Durability

More recently, researchers have attempted to use other forms of testing to better quantify the freeze-thaw durability of bricks, or to discriminate between bricks that are suitable and non-suitable for use in environments where they could be subjected to freeze-thaw action. Kung's three-part report [93]-[95] describes an attempt at correlating brick durability to firing conditions and minerology; trends regarding the types of clay most suitable for the production of durable brick and common kiln conditions that can lead to the production of non-durable brick were identified. Maage [96] first proposed the use of Mercury Intrusion Porosimetry (MIP) to characterize the pore structure of bricks, and correlate that structure to freeze-thaw durability. His proposed equation suggests that durability increases with the proportion of pores with a diameter greater than 3 μm, and with the inverse of total pore volume. Later research by Marusin [92] suggests that pore shape, observed using Scanning Electron Microscopy (SEM), is also an important criterion to consider; elongated "capillary shaped" pores were found in bricks with low absorption that exhibited delamination in service, whereas bricks with otherwise similar absorption properties that had a more circular-shaped pore structure performed well in service. A review paper by Mallidi [97] provides a good overview of the extent of early work on the characterization of brick durability based on pore properties. Koroth and Fazio [98] and Koroth et al. [99] later built on this body of work to propose that porosity characteristics (total pore volume, and percentage of pores larger than 3 μm) can be correlated back to absorption characteristics (boiling absorption, cold water absorption, and capillary absorption); using these correlations and Maage's durability index as a guide, the authors produced a new durability index with a strong linear correlation with the log of the number of laboratory freeze-thaw cycles passed. In another study, Koroth et al. [100] suggested that Ultrasonic Pulse Velocity (UPV) measurements could be used instead of absorption characteristics to assess brick durability; however, their method was developed based on data extrapolation, and yields a wide range wherein the UPV test would yield an uncertain durability classification.

Despite the apparent success of sophisticated methods for assessing and quantifying the durability of clay bricks, the variety of freeze-thaw durability test procedures used by different research groups make the conclusions difficult to interpret. Even where consistency exists in experimental methods between researchers, it is unclear whether laboratory freeze-thaw tests effectively reflect probable in-service durability of bricks. For example, Liu and VanEngelenhoven [101] point out that the method for thawing bricks specified in the ASTM C67 freeze-thaw testing standard (immersion in warm water) causes a significant temperature shock, resulting in forces unlikely to be experienced during in-service exposure. The impact of the thermal shock was also observed to vary greatly depending on the temperature during the freezing cycle, which may account for variability in freeze-thaw test results between testing laboratories. Other reported laboratory freeze-thaw test procedures include a unidirectional freeze-thaw test [102] (said to better reflect the frost conditions in a wall), and more rapid tests such as a single-cycle frost expansion test of vacuum-saturated specimens [103] and one which employs the principles of frost dilatometry to determine the critical degree of saturation [104]. Additional testing by Šveda and Sokolář [105] suggest that cyclic freeze-thaw tests could be coupled with measurement of irreversible expansion, and changes in water absorption, total pore volume, and median pore diameter to better assess durability; changes in these values are indications of damage to the brick body.

Relatively few studies have been reported on the freeze-thaw durability of concrete bricks and blocks. Concrete bricks from one manufacturer included in Davison's study [90] survived 975 freeze-thaw cycles before losing more than 3% of their mass. Ghafoori and

Smith [106] reported absorption alone as a measure of durability. Although sophisticated investigations assessing the durability of concrete to freeze-thaw action have been conducted (e.g., [107]-[109]), little work appears to have been done on the application of these methods to concrete brick masonry construction.

The most recent scholarly works have focused on the testing of new materials (new clay deposits, or the introduction of industrial waste materials) for their suitability in the production of fired clay bricks. The test reports give an indication of which state-of-the-art methods researchers perceive to be most valuable when assessing brick durability. Absorption and strength characteristics are typically reported, often with reference to ASTM C62 requirements. Bertelson et al. [110] cite the results of strength and absorption testing alone to justify a marine clay deposit as a promising source for commercial brick manufacturing, however more sophisticated methods are often reported as well. Bauluz et al. [111] indicate that the increasing percentage in larger pore sizes (measured by MIP) justify a higher firing temperature for increased durability in the clay bricks they studied. Benavente et al. [112] used MIP and Backscatter Electron Imaging (BSEI) to determine mean pore size and roundness, respectively, and reported a strong correlation between increases in those two parameters and resistance to a (very severe) Na_sSO_4 salt crystallization durability test. Binici and Yardim [113] reported durability results of sulfate attack as well as freeze-thaw durability tests. Cultrone et al. [114] present the results of digital analysis of SEM images, which measured pore size distribution and pore shape, which they used to assess the relative durability of bricks from different raw materials fired at different temperatures; they refer to the work of Elert et al. [115] which correlated pore size distribution and the level of vitrification with resistance to freeze-thaw and salt crystallization deterioration processes. Kazmi et al. [116] as well as Lin et al. [117], who studied the effects of partial replacement of clay with waste glass products in brick production, attribute increased observed durability to reduced open porosity, which they assessed using absorption measurements and SEM image analysis. The higher resistance to salt crystallization tests of bricks with increasing firing temperatures is also attributed to higher density (reduced porosity) and vitrification in a study of natural clay deposits by De Rosa and Cultrone [118].

3.5.3 Freeze-Thaw Durability Modelling

Other research groups have assessed the freeze-thaw process within wall systems and buildings. Kralj et al. [119] developed a micromechanical model for use in finite element analysis of wall sections subjected to moisture (saturation ratio) and freezing conditions. A study by Williams and Richman [120] effectively expresses many of the complicating factors when assessing a structural brick assembly for vulnerability to freeze-thaw deterioration. The field investigation and accompanying materials testing suggest that the number of freeze-thaw cycles experienced by a brick wall is highly dependent on its orientation and exposure to the sun; risk of frost-related damage is also highly dependent on the likelihood of a brick reaching its critical degree of saturation. In an attempt to quantify the risk of freeze-thaw damage to a brick element more accurately than is possible with conventional freeze-thaw cycle counting, Zhou et al. [121] propose a Freeze-Thaw Damage Risk index (FTDR) based on summing the quantity and severity of cycles of changes in the degree of ice saturation within the brick pore structure. This method allows small and large temperature fluctuations to be accounted for proportionally and addresses the fact that liquid water freezes progressively from the face of a brick, displacing unfrozen water, and that latent energy during freezing and thawing slows temperature fluctuations within a brick. This novel FTRD index appears to have little relation to the conventional method of counting freeze-thaw cycles in the study areas, and neither method has been robustly correlated to observed deterioration.

The deleterious effects of freeze-thaw action on masonry constructions are most often observed in historical masonry construction. Mass structural masonry exposed to the exterior on one side is susceptible to accumulating moisture, and without an air cavity, these types of walls can only dry from one side. In such structures, the effects of freeze-thaw action were historically mitigated by poor insulation,

"The deleterious effects of freeze-thaw action on masonry constructions are most often observed in historical masonry construction."

which allowed the indoor heating system to maintain the exterior brick at a relatively high temperature during periods of cold weather. When such buildings are retrofitted with interior insulation, rapid deterioration of the exterior masonry can ensue if appropriate measure are not taken to ensure the masonry material is sufficiently durable [122], [123].

3.6 Freeze-Thaw Durability of Mortar

Traditional and current proportion-specified (Portland cement, lime, sand) mortar mixes have a long history of use and known durability performance. Currently, non-proportion specified mixes are required to meet certain strength and other short-term performance criteria (often in comparison to proportion-specified mortar); however, their durability and long-term performance remains difficult to assess. The majority of the literature assessing the performance of mortar has focused on 28-day compressive strength and flexural bond strength; however, other than Harrison and Gaze's 1989 study [124], very few results of durability tests on mortar are reported. They report that lime and air entrainment have a beneficial impact on durability but can result in decreased bond strength. They suggest that sulphate resistant Portland cement and lime both contribute to increased sulphate resistance in mortar. Other research groups such as Mendes [125] and Jeannings et al. [126], which have studied cement-lime mortars, compare the performance of mixes using bond strength alone. Reports introducing new or innovative additions, such those by Amde et al. [127], who discussed the advantages of polymer-modified mortars form improved bond strength, and Piaia et al. [128], who discussed the addition of bottom ash to decrease moisture migration through mortar joints, also do not report the results of any durability testing. As mortar is an integral component of masonry elements, assurance of durability properties is needed in order to avoid not only the cosmetic problems of mortar chipping and subsequent repointing, but also to avoid excessive cracking leading to uncontrolled moisture ingress – which can lead to significant damage to building envelope and structural systems. It is common for local builders to develop a preference for a certain type of mortar (often produced from locally-sourced raw materials) that has a good history of performance in the area; given the paradigm of climate change, local performance history may no longer be a suitable indicator of durability in some regions, and new acceptance criteria may be needed.

3.7 Thermal Response of Masonry Structures

The determination of thermal properties of masonry wall assemblies continues to be a complex challenge for designers. With increasing pressure from clients and building authorities to improve energy efficiency of buildings, the need for accurate methods for determining the thermal performance continues to grow. Various simple and more sophisticated methods are available to calculate expected resistance to heat flow through the complex array of heterogenous materials that overlap and bridge various portions of a wall cross-section, however these methods often do not accurately represent the effects of thermal bridging in masonry construction. Complex finite element model analysis is now readily available to estimate the thermal performance of various standardized wall assemblies, but it is difficult to assess whether these accurately reflect probable as-built performance. Additionally, masonry construction typically provides benefits vis-à-vis energy consumption due to its dynamic thermal response (effects of thermal mass), however this effect is not accounted for by conventional R-value (or U-value) calculations. Various methods of quantifying the dynamic thermal contribution of masonry have been proposed, but no consensus seems to exist on how this effect should be accounted for in design. As targets for energy efficiency in buildings continue to drive increasing insulation values for walls, accurate methods for determining the energy performance of masonry systems during the design phase will be needed to ensure a fair comparison can be made with competing construction methods, and so that finished structures perform as designed when in-service. The development of a dynamic thermal response parameter such as the "T-value" proposed by Alterman et al. [129] may be a part of the solution.

3.7.1 Thermal Resistance (Insulation Value)

Testing of thermal resistance properties of masonry wall assemblies at steady-state conditions has been reported since at least the 1970s. Johnson et al.'s 1976 report [130] describes a guarded "hot-box" test set-up for testing the thermal conductance (U-value) of masonry assemblies and indicates that the results of masonry panel tests are generally consistent with those of tests performed on individual bricks. Similar testing is also reported in contemporary works such as Behrens and Tanner's report [131] on autoclaved aerated concrete blocks. If the wall sections being analyzed are relatively solid and uniform (including a full bed mortar joint), thermal conductance is relatively simple to calculate and is proportional to thickness; however, hollow masonry unit walls, and particularly those with insulation in the cells, have presented difficulties [132].

In addition to physical testing of wall panel specimens (e.g., using a hot-box test set-up), several methods have been proposed to calculate the effective thermal resistance of a wall assembly based on the properties of its constituent materials. The most popular and simplest of these are the isothermal planes, and parallel paths methods. These methods can offer quick estimates of the global properties of a wall assembly, but often render inaccurate results. In her report on hollow block masonry walls with cell insulation, Van Geem [132] reported a discrepancy of up to 40% between the thermal resistance values determined by hot-box testing and those calculated based on isothermal planes. A later discussion by Holm [133] suggests that the isothermal planes method can only reliably be used for low density hollow concrete masonry units due to the variability in thermal properties of normal weight aggregates. Other researchers [134]-[136] suggest that more sophisticated finite element models are required to obtain accurate results.

3.7.2 Thermal Bridging

Thermal bridging is known to severely affect the insulation properties of masonry walls. Whereas continuous insulation on the exterior surface of a wall is the most effective type of insulation, masonry veneers necessitate supporting shelf angles and ties that bridge across this insulating layer, and have a large impact on heat flow through a wall [137]. Although methods of mitigating this effect exist (e.g., by increasing the spacing of supporting elements [138], by minimizing the area of penetration through intermittent support of shelf angles [139], or through other clever detailing [140]), the calculation of effective thermal resistance (R or RSI) values that accurately account for thermal bridging remains difficult. Only sophisticated 3D finite element modelling technology, such as that described by Wilson et al. [139], has been shown to effectively predict the thermal resistance of masonry veneer and cavity wall types of construction. It remains unclear whether even these sophisticated results are representative of as-build building performance.

3.7.3 Thermal Mass

Due to their thermal mass, masonry elements have a marked effect on the dynamic thermal response of a structure. Since masonry elements require a relatively large amount of thermal energy to change their temperature, they have been shown to reduce heating and cooling energy demands on a building beyond what would be expected through steady-state analysis alone [84]. The most marked effects have been recorded in studies of mass masonry walls such as concrete block walls and double-wythe brick. Hamid and Tanzler [141] recorded a 50% reduction in dynamic heat flow rates compared to steady-state heat flow through masonry walls, and Peavy and Powell [142] suggest that these effects can result in the overestimation of peak energy usage by over 30% (if using steady state calculations and the coldest temperature values for design). These results are generally consistent with observations by Dituri et al. [143] who compared the energy usage (electricity usage in all-electric homes) for a large sample of brick and wood-frame homes in Utah; brick masonry homes consumed on average 22% less energy per unit area than wood-framed homes. Additional benefit from thermal mass is achieved when insulating material is placed on the outer side of a massive masonry wall element [141], [142], or even thinner single-wythe brick masonry [144]. Although exterior masonry veneers do not provide as much benefit from thermal mass as heavier types of construction [145], adding a masonry veneer to a conventional insulated wood stud wall (which only marginally improves the thermal resistance R-value) can significantly reduce heating/cooling energy consumption requirements [146], [147]. Huygen and Sanders [148] further found that open weeps (which allow limited air flow behind a brick veneer) had little impact on the thermal mass benefits from masonry veneers. To quantify the dynamic thermal response in the thermal design of masonry walls, Alterman et al. [129] suggest a Dynamic Thermal Response (DTR) parameter or "T-value". Based on a plot of interior versus exterior wall surface temperature during a typical sol-air cycle, the T-value represents a measure of whether a wall system behaves as an insulator or a conductor. This technique shows great promise as a tool to compare the thermal performance of dissimilar types of construction as it accounts for the effects of thermal mass and thermal resistance.

4 Discussion

There are many aspects of the current standards documents where revisions, or additional guidance for designers could be beneficial in view of the anticipated effects of climate change. After reviewing existing formative and state-of-the-art literature, as well as other published codes and standards, recommendations for possible modifications to the current standards are provided. These recommendations have also been informed by consultation with key academic and industry stakeholders through responses to a survey questionnaire.

4.1 CSA A370 – Connectors for Masonry – Section 5: Durability & Annex E: aDRI

A unique approach to corrosion protection requirements for masonry ties is described in CSA A370:14 (R2018), *Connectors for masonry* (Section 5). The use of aDRI as the primary criteria for specifying corrosion protection requirements is not found elsewhere in codes or standards, although it is presented in CSA A478:19 *Durability in buildings* as an indicator for the risk of moisture penetration for building envelopes. The requirement for higher levels of corrosion protection for masonry more than 13 m above grade to mitigate the risk of failure is an indication of the uncertainty in the current A370 approach. Other design standards have opted to specify or recommend corrosion protection levels based on use and location independently from climate. For example, the *Eurocode 6 – Design of Masonry Structures* [149] defines five exposure classes (MX1 to MX5) based on the type of use and exposure of a masonry element (e.g., whether it is subjected to wetting, freeze-thaw action, salt, and/or harsh chemicals), and differentiates between the severity of wetting using a sub-class system. A slightly different, but related approach is in use in Australia and New Zealand, wherein masonry ties are rated for exposure classes ranging from R2 to R4 depending on the proximity to a coastline, and whether that coastline is sheltered, or "breaking surf". In the US, TMS 402 [150] provides little indication of what level of corrosion protection is appropriate for masonry ties, indicating only that wall ties should be galvanized or epoxy-coated, or made from stainless steel; no guidance on the relative level of protection afforded by these different types of corrosion protection nor on how a designer should decide between these options is given. For other "metallic accessories" (anchors, plates, or bars), the US standard indicates that they must be protected from corrosion only if they are exposed to soil or exterior conditions, or indoor relative humidity greater than 75%. The Brick Industry Association offers a bit more guidance in a technical note [151], indicating that different levels of protection could be needed depending on whether a metallic element is fully embedded in mortar or grout, exposed to an air space, or exposed in a corrosive environment. The review of relevant academic literature indicates that some links have been made between local climate conditions (e.g., moisture index, aDRI) and the corrosion conditions for ties within masonry cavities; however, more research is needed to ensure safe designs can be consistently produced.

Other CSA standards also follow the trend of specifying durability requirements based on more general exposure classes, as opposed to local climatic factors. CAN/CSA-O80 SERIES-15 (R2020) *Wood Preservation* [152] defines seven use categories for wood products related to exposure to moisture, soil or fresh water, or salt water. A table of common wood products, their use, and specified use category is also provided. A series of additional tables indicate the necessary preservation treatments by type of wood product, wood species, and by use category. For concrete materials, CSA A23.1:19 *Concrete materials and methods of concrete construction* [153] defines six general "classes of exposure" and a total of 20 subdivisions of these classes related to exposure to moisture, chlorides, freeze-thaw action, sulphate, harsh chemicals, or if the concrete is for residential use. Again, no local climatic factors are considered; however, the class of exposure dictates the level air entrainment required, and the minimum concrete cover. CSA S413-14 (R2019), *Parking structures* [154] introduces a few additional options to help mitigate the risk of corrosion of steel reinforcement. Listed protection systems include the introduction of a waterproofing membrane, corrosion inhibiting admixtures, chloride resistant concrete, or a sealer, and the use of other alternatives such as cathodic protection is also permitted; a focus of this standard, however, appears to be on maintenance and inspection in order to diagnose and mitigate any issues in service. CSA S6:19, *Canadian highway bridge design code* [155] also offers many examples of how environmental exposure and associated durability considerations can be addressed in design standards. In this document, concrete durability is achieved through the use of concrete covers dictated by the type of member, in addition to other generic prescriptive strategies such as avoiding alkali aggregate reaction (AAR) and chlorides in mix designs, and ensuring proper curing. For wood bridge construction, wood preservation techniques are prescribed regardless of member type, exposure, or local conditions, and corrosion protection requirements for steel fasteners, spikes, and connector plates are dictated solely by their type and the aggressivity of the wood preservation chemical used. For structural steel bridges and bridge elements, a more comprehensive table of corrosion protection requirements is included based on the type of structural element and the exposure to moisture, chlorides, or an industrial atmosphere; the use of weathering steel, coatings, metallizing, galvanizing, or greasing (for rollers and rockers only) are listed in the types of protection requirements.

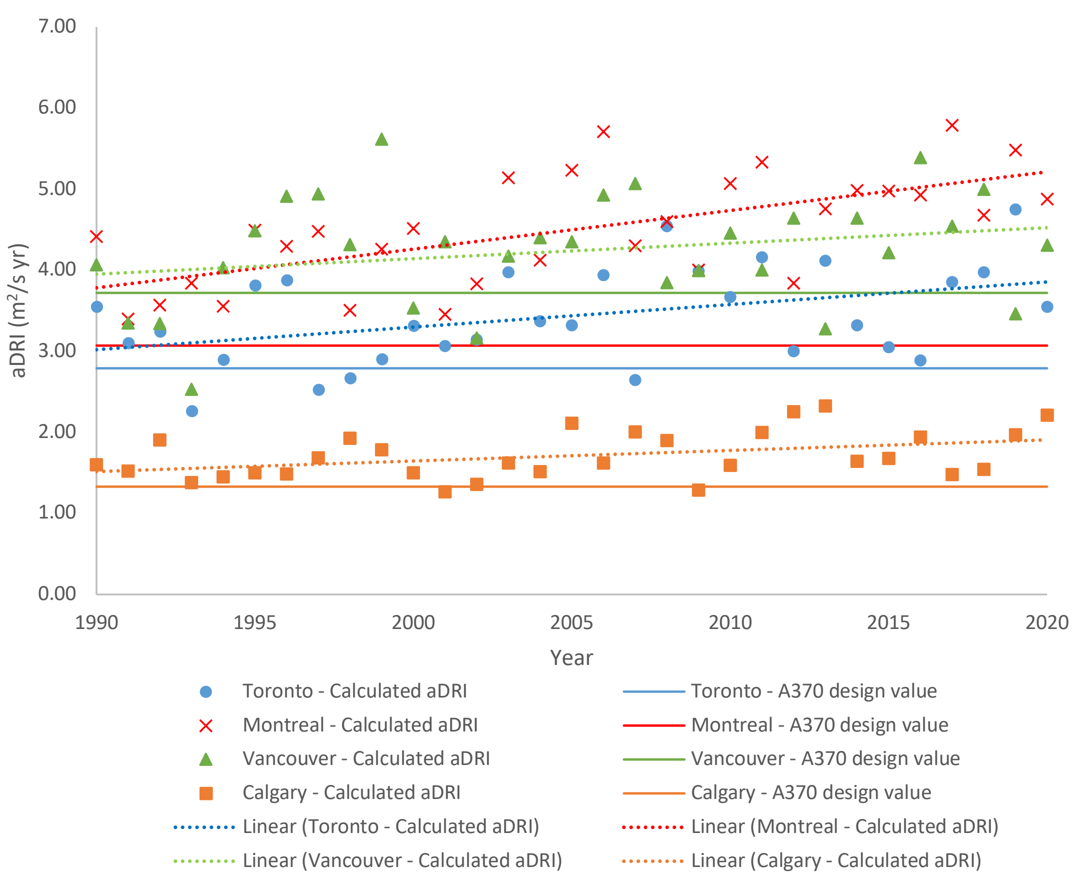
It is also noteworthy, that CSA A370 only includes three classes of corrosion protection. Whereas US technical literature and standards, as well as the Eurocode differentiates between the performance of different classes galvanic coatings (e.g., ASTM A153 class B – 600 g/m^2 vs. class C – 380 g/m^2), CSA A370 does not. Furthermore, other tie materials identified elsewhere (e.g., polymer/FRP ties, and epoxy coated ties) are not acknowledged in CSA A370.

None of the codes or standards reviewed provide guidance for the quantification of expected durability or service life of structural elements based on environmental exposure. Given the requirements of CSA S478:19, *Durability in buildings* [16], designers will increasingly require such guidance to ensure durability targets can be met. For the case of masonry ties which are difficult or impossible to inspect non-destructively in service, and on which it is expensive to perform maintenance or replacement operations, certainty in the durability performance is required. Simple generalized methods do not appear to accurately account for the wide range in corrosion rates observed in masonry ties within wall cavities. More sophisticated and precise methods based on hygrothermal modelling of masonry wall systems, time of wetting analysis, and ISO corrosion models will be necessary. Although there are obvious benefits to relating corrosion protection requirements with the local climate (including decreased over-conservatism in regions with relatively benign corrosion environments), special attention will be needed to account for the effects of climate change as regionally applicable practices that account for the uncertainties of climate change over the expected service life of masonry buildings are refined.

4.1.1 Recommendations

The Canadian climate is changing, including changes to precipitation patterns. As shown in Figure 1, the aDRI has increased in Canada's most populous cities over the past 30 years; the trends for Toronto, Montreal, and Calgary, for that period, are all significant at the 5% level (using the t-test), indicating that CSA A370 Annex E should therefore be reverified. Such an exercise would need to include consideration for future ongoing changes to aDRI values by region and by locality, accounting for anticipated trends in greenhouse gas emissions. The latest Government of Canada report on Climate-Resilient Buildings and Core Public Infrastructure [6] indicates that there is

Figure 1: Recent trends in calculated aDRI[2] compared to design values from CSA A370 [9] for four major Canadian cities



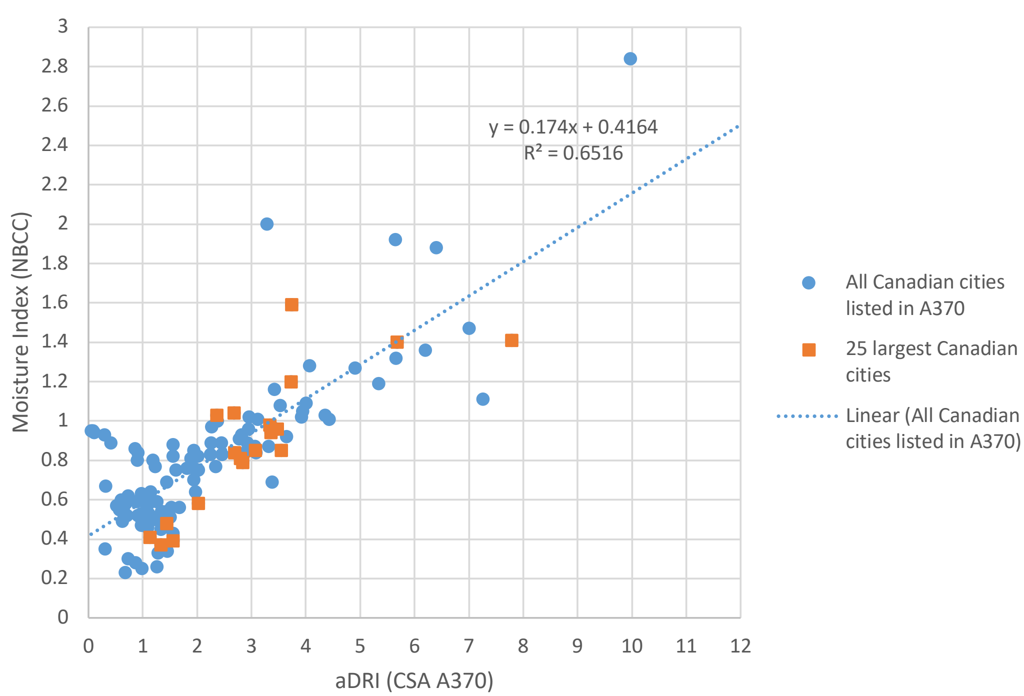
2 Historical (1990–2020) annual rainfall (mm) and average annual windspeed (km/h) data collected from the Government of Canada (https://climate.weather.gc.ca/) via the website WeatherStats (www.weatherstats.ca).

"high confidence that annual precipitation and rainfall will increase in Canada with global warming", with projected increases at 1 °C of warming ranging from 6% in Ontario to over 15% in Northern Canada. The projected changes in average windspeed are less well understood [4], however certain regions in Canada are expected to experience significant increases in peak windspeeds (1/10 yr and 1/50 yr events) [6]. Updates to the aDRI should be consistent with the values presented in Annex C of CSA S478:19, *Durability in buildings.* The list of locations for which an aDRI value is provided would also need to be revised to ensure adequate guidance is available for locations where most masonry construction activities occur (major urban centres).

Given the technical challenges associated with maintaining updated climate data within a CSA standard, other criteria may be considered for establishing minimum levels of corrosion protection. For example, Moisture Index (MI) values currently included in the National Building Code of Canada have a reasonable correlation to the aDRI values from CSA A370:14 (R2018), *Connectors for masonry,* as shown in Figure 2.

The impact of a potential migration from the use of aDRI to MI as the main indicator for corrosion protection requirements on construction practices in major urban centres is illustrated in Figure 3. This figure indicates the aDRI and MI values for cities among the top 25 most populous in Canada; however, Hamilton, Kitchener, St. Catharines, Oshawa, Kelowna, and Barrie were excluded from the figure since their aDRI values are not listed in the current edition of CSA A370. As an example, a threshold MI value of 0.8 appears to correspond well to the current threshold aDRI value of 2.75. Most large urban centres in Canada that have an aDRI greater than 2.75 also have an MI greater than 0.8; conversely most locations that have an aDRI lower than 2.75 have an MI lower than 0.8.

Figure 2: Plot of aDRI [9] and MI [38] values for Canadian cities[3]



3 Only locations for which an entry exists both in CSA A370 and NBCC are shown.

The impact of climate change on the moisture index is not addressed in the Government of Canada report on Climate-Resilient Buildings and Core Public Infrastructure [6]; however, the component parameters of the moisture index are all projected to change. Increases in projected rainfall and temperature, and minor, if uncertain, increases in relative humidity make the global effect on moisture index difficult to assess.

Additionally, the format of the current expression of minimum levels of corrosion protection is cumbersome. Some separation of protection requirements related to exposure (i.e., use, location within a structure, special conditions of the site) and those related to climatic conditions could bring increased clarity to this section of the standard. If new materials or coatings or additional categories of corrosion protection are added to the standard (e.g., epoxy coatings, ties which include polymer thermal breaks, or ties made entirely or in part from polymers or FRPs), their recommended use relative to climate and exposure conditions will need to be specified.

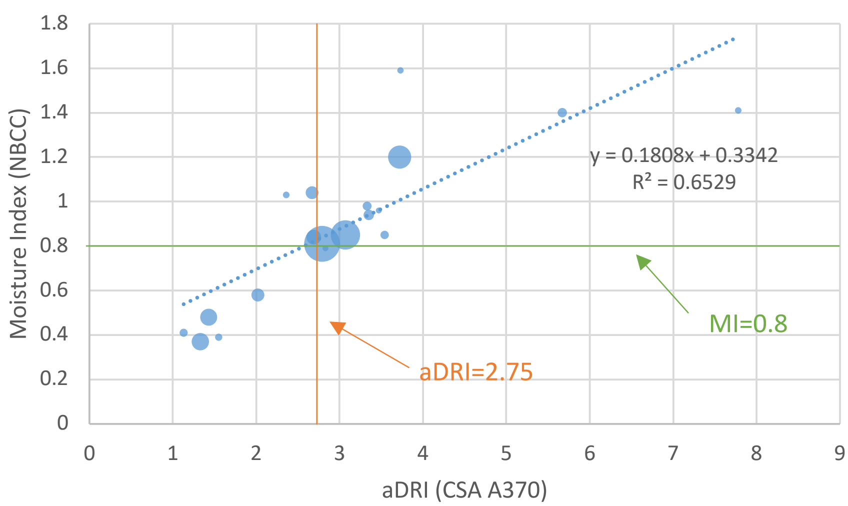
4.1.2 Research Needs

The effect of average climate conditions (aDRI, moisture index, or other) on the severity of the corrosion environment within vented masonry veneer cavities remains poorly understood. Available work has largely been inconclusive given the variability of effects from improper detailing leading to indoor air leakage into the veneer cavity. Further study is needed to firmly establish a causal link between climate conditions and corrosion rates, and thereby begin to assess the effects of climate change on the durability of masonry connectors.

4.2 CSA A370 – Connectors for Masonry – Strength and Spacing

CSA A370 specifies the minimum ultimate strength for masonry ties (1 kN) and for wall anchors (1.3 kN if the specified normal load is less than 0.24 kPa, and 1.6 kN otherwise). In all cases, the designer must nonetheless ensure that any loads applied to a wall or veneer can

Figure 3: Plot of aDRI [9] and MI [38] values for the 25 most populous cities in Canada[4], where the area of the marker is proportional to the 2019 estimated population [156]



4 Only locations for which an entry exists both in CSA A370 and NBCC are shown.

be effectively transferred through the tie or anchor to the supporting element (using no more than the factored resistance). Rather than specifying a minimum ultimate strength, the US standard TMS 402 prescribes a minimum gauge (steel wire diameter or sheet thickness). Other international standards provide a wider variety of strength categories depending on use. In Australia and New Zealand, AS/NZS2699.1 identifies three classifications of masonry ties with different specified minimum characteristic strength (Light duty 0.2 kN, Medium duty 0.4 kN, Heavy duty 1.0 kN). In the UK, seven tie types are available, in conformance with PD6697 or BS 5268-6.1, with different minimum declared compression and tensile load capacities. Each tie type corresponds to different structural applications and allowable building height. For example, Type 5 ties, which are meant for use with wood frame structures up to three storeys in height where wind speeds do not exceed 27 m/s, have a characteristic load capacity of 0.6 kN in tension, whereas Type 1 (heavy duty) ties, required for any building taller than 18 m, have a characteristic strength of 2.5 kN in tension. Little discussion is available in the literature on what would be a rational justification for implementing a minimum strength of individual ties or anchors.

Similarly, the spacing of ties must also be controlled to ensure they can transfer an applied load to the supporting structure. Whereas increasing the strength of ties should allow them to transfer loads from a larger area of wall, maximum tie spacing limits are in place to avoid failure in the veneer spanning between ties. The maximum tie spacing in CSA A370 corresponds closely to those in TMS 402, however other jurisdictions have different restrictions. For example, the *Eurocode 6 – Design of Masonry Structures* [157] does not specify a maximum spacing of ties, indicating simply that the combined strength of the ties in a given area should be greater than or equal to the applied loads for that area. However, the UK's National House Building Council (NHBC) specifies a maximum horizontal spacing of 900 mm and a maximum vertical spacing of 450 mm [158]. In Australia, technical documents indicate that tie spacing should not exceed 600 mm in either orthogonal direction [159], and certain manufacturers recommend different tie spacing depending on the grade of the tie (normal- or heavy-duty) and environmental factors, such as windspeed [160].

4.2.1 Research needs

Energy targets are driving a need to reduce energy losses through thermal bridging. Increasing the spacing between ties may be an effective method for decreasing thermal bridging effects. Current standards for minimum strength and maximum spacing of ties appear to be conservative, however additional research is needed to determine if masonry veneers can be permitted to span longer distances between supporting ties. Strength requirements for wider-spaced ties, as well as necessary restrictions for veneer supported by sparser ties must also be determined.

4.3 CSA A370 – Connectors for Masonry – Section 9: Stiffness and Mechanical Free-Play

Stiffness and mechanical free-play appear to only be a concern in the US and Canada. Adjustable ties (e.g., eye and pintle type) are not in common usage in Europe or Australia – in Europe, maximum stiffness values are specified for ties to limit sound transmission through multi-wythe walls. CSA and TMS standards for mechanical free-play and stiffness are similar. Although many experimental programs have demonstrated that the strength and stiffness of certain types of adjustable ties can vary widely within the range of adjustability, the effect of these variations on the structural integrity of masonry veneers remains unclear. Tests performed on masonry veneer walls indicate that the stiffness of the back-up wall does not have much influence on the cracking load of the veneer, but that increased stiffness of the support (tie and backup wall) could play a role in minimizing crack width. The effect of veneer cracking on overall wall permeability and durability remains a subject of contention.

4.3.1 Research Needs

Although it is clear that very fine cracks (< 0.1 mm) are unlikely to increase the permeability of masonry veneers, and that large cracks and open joints can lead to excessive ingress of free water, it is unclear how cracks in the range of 0.1 mm to 2 mm impact the durability of ties and other detailing elements of a masonry wall. Research programs are needed to establish the following:

"Energy targets are driving a need to reduce energy losses through thermal bridging."

- The relationship between veneer crack opening width and the stiffness of the supporting ties and structural backup; and
- The relationship between crack width and moisture penetration, quantified by differential pressure and crack width.

Such relations are important to the life-cycle analysis of masonry ties as well as the brick veneer itself. If water infiltration through cracks is a significant source of moisture within veneer cavities, it will be critical to quantify its effects in the hygrothermal analysis for the assessment of corrosion of ties and other exposed metallic elements, and for freeze-thaw deterioration of bricks and mortar.

4.4 CSA A370 – Connectors for Masonry – Section 10: Prescriptive Connectors

Many prescriptive ties described in CSA A370 do not allow sufficient cavity space to accommodate insulation. The various corrugated ties allow from 25 mm to 40 mm of total cavity space, which fall within the range of recommended width of air gap. Welded ladder and trusses, Z-ties, and rectangular ties are permitted with cavities of 125 mm to 150 mm; however, significantly wider cavities are often needed to accommodate the insulation necessary to meet the National Building Code of Canada (NBCC) [38] and National Energy Code of Canada for Buildings (NECB) [161] target RSI values for walls. Unless guidance can be provided as to how these ties can be used within wall systems that meet current energy and building code requirements, reference to these systems may be relegated to an annex or removed altogether.

4.5 CSA A370 – Connectors for Masonry – Annex C: Corrosion & Annex D: Resistance to Water Penetration

The informative Annexes C and D in CSA A370:14 (R2018) could benefit from being updated and expanded upon. Methods of accurately determining the service lifespan of ties are emerging, and the various influences of climate change on service life are becoming clearer. References to the latest research and literature could be included as important guidance for designers on how to demonstrate that their designs conform to the durability targets set out in CSA S478:19 *Durability in buildings.* Masonry connectors are prohibitively expensive to inspect and repair, and their failure may have the potential to cause injury or loss of life, they must therefore have a design service life greater than or equal to that of the building. Many of the typical application for masonry veneers (e.g., residential, mid-rise commercial, hospitals) have a minimum design service life of 50 years [16]. Given the severity of potential adverse effects of excessive moisture penetration (including condensation) on masonry assemblies, proper detailing to avoid the accumulation of moisture is critical.

4.5.1 Recommendations

There is some overlap of information presented in Annex C of CSA A370 and Annex C of CSA S478, including data on rainwater pH and concentration of SO_2. These data, along with the rate of chloride deposition and time of wetting (TOW), have been used following ISO methods to accurately estimate the corrosion rate of masonry connectors [27]. Methods for determining the time to carbonation of mortar joints (dependant on relative humidity, CO_2 concentration, and mortar thickness) also need to be developed. Efforts to ensure current conditions as well as trends continue to be accurately reflected in standards resources should be made.

Additionally, tools for quantifying moisture ingress through various means (infiltration through porous mortar or masonry units, infiltration through cracks, moisture entering through openings) to assist in hygrothermal modelling are needed.

4.6 CSA A165 – Concrete Masonry Units: Durability

Little is said about the durability of concrete masonry bricks and units in CSA A165 SERIES-14 (R2019), *CSA Standards on concrete masonry units.* The standard indicates that concrete block units should be kept dry to avoid freeze-thaw durability issues, and that concrete bricks have the inherent durability properties of concrete, adding that air entrainment can enhance freeze-thaw durability. Exterior grade (Grade 1) differs from interior grade bricks by a modest increase in strength and decrease in water absorption (similar to US provisions regarding facing vs. building bricks). The only durability testing regimen mentioned in the CSA A165 standard is ASTM C1262, which is a cumbersome freeze-thaw test; designers are encouraged to use past field performance as an indicator of durability. Additional tests are cited in CSA A23.1:19 *Concrete materials and methods of concrete construction,* which could be transferrable to testing of concrete masonry units; for example, characterization of the entrained air (air content and air-void system parameters) could be useful to the quantification of concrete brick durability.

The few available reports in the literature which have studied the durability of concrete bricks (as well as field experience) indicates little concern; however, the adoption of quantitative durability testing could be useful as justification of expected service life with regards to the requirements of CSA S478:19 *Durability in buildings.*

4.6.1 Recommendations

Methods of quantifying the resistance of concrete brick and block to freeze-thaw deterioration are needed. Concrete brick veneers are less commonly used than clay bricks, but experience has demonstrated that they can perform equally well. Certain conditions that allow moisture to accumulate, however, can accelerate the deterioration of bricks. Although these can mostly be avoided with proper detailing, guidance on methods for determining the durability of bricks exposed to extreme environments (e.g., near horizontal surfaces, or exposed to moisture and salt) would be useful.

4.6.2 Research Needs

Although experience has demonstrated that concrete brick and block can perform well in certain climates if proper detailing is provided, the standard cautions against exposure to moisture saturation and salts. Research is needed to determine what physical properties of concrete blocks might qualify them for severe exterior exposures (similar to concrete brick). The conditions (if any) under which concrete masonry block construction could be permitted in wet environments that include exposure to freeze-thaw cycling will also need to be determined. This would also require more stringent and clearer inspection conditions to limit defects that may be detrimental to freeze-thaw durability.

4.7 CSA A82 – Clay/shale Bricks: Durability

Canadian and US standards both designate bricks approved for freeze-thaw exposure based on strength and absorption characteristics as a substitute for more cumbersome freeze-thaw testing. Although these criteria discriminate between most durable and non-durable bricks (based on observed performance and laboratory testing), some clay brick testing research programs have identified bricks that achieve the target strength and absorption set out by the standards but have failed in situ or laboratory freeze-thaw exposure tests. The current acceptance criteria in CSA A82:14 (R2018), *Fired masonry brick made from clay or shale* also lack an assessment that would assist in the quantification of expected service life given a known exposure. Various sophisticated methods are described in the literature that could be useful to identifying and quantifying durability characteristics of commercial bricks. Of these, there are three methods of particular interest: Mercury Intrusion Porosimetry (MIP) used for the determination of pore size distribution in fired clay bricks (higher fractions of larger pore size have a positive correlation with durability); Scanning Electron Microscopy (SEM) used for the determination of the characteristic shape of pores (bricks with round pores are associated with better durability than bricks with elongated pores); and frost dilatometry that correlates the moisture content of bricks, temperature, and strain to assess the risk of frost damage.

A robust system for quantifying the durability of bricks that accounts for pore size distribution and pore shape has yet to be developed. One impediment to any such development is uncertainty with regards to the best freeze-thaw testing regime against which the system should be calibrated; there is a significant amount of variability in the freeze-thaw test methods employed by different research groups, as well as indications that some tests could be sensitive to the way they are performed.

Another approach to determining brick durability could be to correlate freeze-thaw resistance to resistance to salt crystallization forces. Physical properties that lead to good freeze-thaw durability also improve resistance to salt crystallization. In the Eurocode, bricks are rated both for their durability to freeze-thaw action and to salt crystallization forces. Tests that involve exposing a porous medium to cyclic crystallization of hydrous and anhydrous $NaSO_4$ are significantly more aggressive than freeze-thaw tests and could provide a relatively rapid assessment of durability.

In any case, quantifying the expected service life of clay bricks will remain difficult given the wide variety of parameters that affect freeze-thaw durability, including the characteristics of the freeze-thaw exposure. The CSA A82.1-M87 standard included information on the weathering index for various regions in Canada based on the annual number of freeze-thaw cycles. Any method for quantifying the expected service life of a brick will necessarily need to include an assessment of the severity of the environment to which it is exposed, including freeze-thaw action. Climate change is expected to have a strong effect on the exposure to freeze-thaw cycling, with increasing severity in some regions and decreasing severity in others.

It is noteworthy that modern masonry wall construction, which includes water-shedding detailing as well as an air cavity to promote drying, is significantly less susceptible to freeze-thaw deterioration than historical mass masonry construction. Bricks that may have been considered non-durable in previous applications where they were exposed to severe weathering may perform adequately if proper detailing were applied to minimize moisture permeation.

4.7.1 Recommendations

Testing of bricks revealed the limitations of absorption characteristics as a measure of durability. These are currently reflected in the informative Annex B of CSA A82:14 (R2018). Although the current durability requirements appear to work well for established domestically produced products, it is unclear whether they fully characterize the long-term durability of imported products or novel/emerging products, particularly in cases where they may be subjected to an unusually harsh environment. It is important for designers to consider the performance history of the bricks they are specifying (if available) and that they be made aware of additional available tools for assessing the expected durability of bricks. In addition to the absorption and freeze-thaw tests described in the standard, guidance for designers on the assessment and interpretation of properties using more advanced methods should be provided as part of the informative annex on durability. This may be particularly useful as new products with lowered embodied energy and carbon are developed (manufactured from different raw materials, or fired at a lower temperature), or when using reclaimed materials.

For cases where greater assurance of good in situ performance is needed, or where the brick may experience a severe weathering environment, the following tests may be considered by the designer:

- Mercury Intrusion Porosimetry
- Scanning Electron Microscopy
- Sodium Sulphate (Salt Crystallization) Test
- Frost Dilatometry

Results from frost dilatometry testing are particularly useful since this test established the critical degree of saturation at which freeze-thaw degradation may begin to occur. This information is important in the context of detailed hygrothermal analysis of a building or component – such analyses have been undertaken in retrofitting projects but may also be beneficial in the context of new construction.

4.7.2 Research Needs

Studies have shown that some regions that are experiencing increasing average temperatures also have an increasing potential for freeze-thaw deterioration, due the increased frequency and/or severity of freeze-thaw cycles (e.g., [85]-[87]). A Canadian regional assessment is needed to determine where the risk of freeze-thaw deterioration is increasing, and where methods and materials for masonry construction that have previously exhibited adequate performance may need to be reassessed.

4.8 CAN/CSA A179 – Mortar and Grout: Durability

Performance targets for mortars in the current CAN/CSA-A179-14 (R2019), *Mortar and grout for unit masonry* standard is based on the notion that traditional proportion-specified mortars, which include cement, sand, and lime, provide acceptable performance. The large collection of masonry buildings in Canada that have been constructed with this type of mortar, and which are still standing and require minimal maintenance are a testament to this time-tested material. In practice, when designers specify performance criteria for mortar, they are limited to those that can be measured in the short term, making long-term durability of a performance-specified mortar (i.e., comparing it to that of a proportion-specified mortar) difficult to assess. The Canadian concrete standard CSA A23.1:19, *Concrete materials and methods of concrete construction* provides a template for the way in which mortars could be specified, allowing for prescriptive performance requirements. An additional tool that could be of use in the assessment of durability of mortar is the “scratch test” specified in Australia and New Zealand within their AS 3700:2018, *Masonry structures standard* [162].

Current Canadian proportion-specified mortars have characteristics that contribute to their long-term durability (e.g., the inclusion of lime improves freeze-thaw durability, improves the hardened plasticity/deformability, and reduces permeability); methods for assessing these features in performance-specified mortars may be needed. Complete characterization of property-specified mortars will become increasingly important as pressures to reduce the embodied energy and carbon in construction forces the development and adoption of new materials.

4.8.1 Recommendations

Additional guidance on the determination of durability properties of mortar may be beneficial. Developing guidance on the determination of the following properties of property-specified mortars should be considered:

- Freeze-Thaw Resistance
- Abrasion Resistance (Scratch Test)
- Deformability/Plasticity (Hardened State)

4.8.2 Research Needs

As targets for embodied energy and carbon emissions continue to become more stringent, it will be advantageous to account for any carbon sinks within a

"Complete characterization of property-specified mortars will become increasingly important as pressures to reduce the embodied energy and carbon in construction forces the development and adoption of new materials."

structure. Consultation with key stakeholders indicate that further study is needed to effectively quantify carbon capture through carbonation of mortar and grout over the life cycle of a building.

4.9 CSA S304 – Masonry Design: Durability of Metallic Elements

The nature and function of shelf angles and other related metallic elements is different from that of masonry connectors; however, the S304-14 (R2019), *Design of Masonry Structures* standard refers the designer to CSA A370 clauses in the determination of appropriate corrosion protection, specifying different corrosion protection requirements depending on whether Level 2 or Level 3 corrosion protection is required for the ties. Although the standard permits an alternative to galvanization as a form of protection (primer paint conforming to CSA S16:19, *Design of steel structures*), allowing other methods of ensuring corrosion resistance may be useful. Any corrosion protection measure should be appropriate for the application, wherein inspection and/or repair and replacement is prohibitively expensive. The CSA S6:19, *Canadian Highway Bridge Design Code* offers a few additional strategies that may be applicable to shelf angles within masonry structures. Clause 10.6.3 of CSA S6:19 allows a significant degree of freedom to the designer to specify alloying, coatings, or other means of corrosion protection for steel elements. A summary of recommended corrosion protection methods (coat, epoxy coat, increase section thickness, use weathering steel, galvanize/metalize, grease) for various bridge components and exposure conditions is also provided. A similar table could be useful to designers considering corrosion protection methods for shelf angles (and other structural steel elements commonly incorporated into masonry structures) in common types of exposure conditions.

4.9.1 Recommendations

Additional guidance on the factors affecting the corrosion environment of shelf angles and associated supports, as well as appropriate corresponding corrosion protection measures, should be considered for inclusion in the CSA S304 standard. The corrosion environment to which a metallic component is exposed can vary depending on the materials used and the detailing provided. Although different requirements for shelf angles are specified depending on whether effective flashing and moisture protection is provided, other properties of the local environment may have a significant effect on corrosion (e.g., masonry deflection and cracking, proximity to a soffit/overhang). Further guidance on the effect of cracking of veneers and lintels (due to deflection) on moisture penetration and the corrosion environment may also be useful to the assessment and assurance of durability targets in CSA S478:19 *Durability in buildings.*

4.9.2 Research Needs

Further research is needed to quantify the relation between cracking and moisture penetration. See section 4.3.1.

4.10 CAN/CSA-A371 – Masonry Construction: Hygrothermal Detailing

Limited guidance is provided in CAN/CSA-A371-14 (R2019), *Masonry construction for buildings* regarding the application of damp-proofing, air barrier, and insulating materials within masonry systems. With the increasingly stringent energy targets set out by the NBCC and NECB, additional guidance for constructors on how these targets are achieved may be needed. Additional focus on achieving continuity of insulation materials and proper sealing of air barrier materials (with explanatory detail drawings) could be beneficial. Air leakage targets for air barrier systems in both the NBCC and NECB are quite stringent (0.2 $L/s/m^2$ at 75 Pa differential pressure, including leakage through joints, in the NECB). It is also noteworthy that the NECB permits designers to account for the effect of thermal mass on building energy usage by demonstrating the building meets energy performance requirements (Part 8). To do so, the Code requires a comparison of the energy usage of the building being designed to that of an equivalent structure made from light-weight construction (whole building analysis). Guidance on how such an analysis can be achieved and insight into probable results/benefits would be useful.

4.10.1 Recommendations

Drawing details are provided in CSA A370:14 (R2018) to illustrate the installation of various masonry connectors (Annex B); similar drawings may be useful in CAN/CSA-A371 to illustrate the details required to prevent moisture ingress, and how to achieve insulation continuity. Additional language and/or sample details may also be useful to clarify what is meant by “a reasonably uniform insulating value over the entire surface of the insulated area” [14] for a system that includes thermal bridges (e.g., masonry ties, shelf angle supports).

4.11 General Stakeholder Feedback

Through consultation with key stakeholders in masonry design, manufacturing, and construction, it is clear that some of the most severe effects of climate change on masonry construction may be indirect. Masonry construction has been and will continue to be a durable building material, well adapted for resisting extreme weather events associated with a changing climate; however, the demands of new energy codes with regards to thermal insulation and energy performance, as well as embodied energy and embodied carbon targets to mitigate carbon emissions and further climate change, may make it difficult for masonry construction to remain competitive with other structural systems. This is partly due to current methods of calculating energy performance that focus on steady-state analysis of insulation. The limitations of current construction methods that limit the amount of insulation that is feasibly installed within a wall cavity and that introduce thermal bridges (ties and standoffs) can also hamstring energy performance. It must also be recognized that masonry units (both fired clay and concrete) are produced using relatively energy- and carbon-intensive methods. As innovation in materials and design practices arise to mitigate these effects (e.g., ties and standoffs with low thermal conductivity, low carbon masonry units), it will be important for available information on material properties and analytical methods to be in place to allow designers to accurately determine and express the benefits of their use.

4.11.1 Recommendations

Steps are needed to facilitate the calculation of embodied energy as well as the determination of operating energy inputs for finished buildings. Since standardization is needed across disciplines for multiple construction materials, a focus on coordinating and collaborating with influential entities in concrete, steel, and wood/timber construction will be required.

Structural masonry walls, as well as exterior masonry veneers, have been shown to contribute to the thermal regulation of buildings through dynamic thermal effects (thermal mass). Guidance for designers is needed on how to account for these dynamic effects in whole-building analysis that is compliant with the NECB. This may be facilitated if masonry manufacturers publish thermal mass data as part of their technical documentation.

With the emergence of ties and standoffs with lower thermal conductivity (reduced thermal bridging), there may be a benefit to the standardization of how the thermal performance of these components are reported. Some manufacturers have produced documentation that show the expected performance of their product within a wall assembly; however, expressing the thermal properties of the product alone would allow designers to perform their own analyses for the specific needs of their project and facilitate the comparison of competing products.

Finally, other benefits of masonry relevant to its life-cycle analysis are currently poorly defined. Masonry facades are more resistant to accidental impacts, abrasions, and vandalism compared to some lighter-weight finishes. Quantifying this type of resistance to wear-and-tear may help designers and building owners/operators make informed decisions when selecting exterior finishing.

5 Conclusions

Changes in the Canadian climate are expected to have a wide range of impacts on our built infrastructure. Efforts to mitigate further changes to the climate by reducing CO_2 emissions are also having a profound effect on the way construction materials are selected and how structures are built. Following a thorough review of CSA's suite of masonry standards and available scholarly literature on the durability of masonry assemblies to climatic loading, as well as having consulted key stakeholders and experts in the field of masonry, the following conclusions may be drawn.

A review of the literature on the corrosion of masonry connectors indicates that wetting from rain can have a strong effect on corrosion. Care must be taken, however, to account for the effects of the building geometry (which may shelter some regions of a structure and increase wetting in others) and minimize wetting from other sources (e.g., condensation from escaping indoor air). More research is still needed to quantify the relation between regional climate conditions and corrosion rates within masonry cavities; the use of a climate index that accounts for drying as well as wetting (e.g., the moisture index listed in the current NBCC's Table C.2) may be considered for this purpose. As aDRI values for some of Canada's largest cities appear to be increasing, and rainfall patterns across Canada are expected to change, the values currently listed in CSA A370 should be revised, or a different approach for assessing the risk of corrosion of masonry ties may be considered. Additional research, however, would be needed to provide an evidence-informed recommendation. Furthermore, since the factors affecting the corrosion process of masonry ties is becoming better understood, information supporting sophisticated analyses of the hygrothermal response of masonry assemblies and corrosion of masonry ties would be useful to include in the CSA A370 standard.

Design standards governing the strength and spacing of masonry veneer ties appears to be conservative. However, there is limited literature on the effects of variable stiffness and mechanical free-play of ties on the distribution of applied loads. Since masonry ties can often significantly reduce the effectiveness of insulation in wall assemblies due to thermal bridging, the development of strategies that would allow wider spacing of ties may be beneficial; however, these would need to account for the strength and stiffness of ties, as well as the unsupported span of masonry veneers. More guidance is also needed on the use of non-conducting materials (such as fibre-reinforced polymers) for the design of masonry ties, as well as on methods of reporting and accounting for the thermal properties of ties.

Given the porous nature of masonry assemblies, some moisture penetration is unavoidable; however, to ensure their long-term durability, moisture ingress must be kept to a minimum. Sophisticated hygrothermal modelling techniques are now available to assess the impact of moisture ingress on the deterioration of masonry materials over time. Although these techniques work well to assess responses in idealized conditions, they are not always applicable to as-built structures. The effect of masonry cracks on the order of 0.1 mm to 2 mm on overall moisture permeability is currently the subject of contention. Additionally, vapour barriers and other damp-proofing elements are typically assessed in binary terms (effective/ineffective); a quantified assessment of the long-term in situ performance of materials and detailing assemblies may be needed to justify compliance with the durability targets set out in CSA S478, *Durability in Buildings.*

There are many examples of masonry materials and structures that have exhibited exceptional durability and resistance to freeze-thaw cycling. Current acceptance standards based on absorption characteristics seem to discriminate well between bricks with good and poor freeze-thaw durability properties; however, proper care must always be taken with detailing to avoid wetting and promote drying. Where further assurance of durability in unfavourable conditions is needed, sophisticated techniques involving the use of MIP and SEM are now available. Frost dilatometry techniques have also shown some promise in helping quantify the risk of freeze-thaw deterioration when combined with hygrothermal building models. Similarly, for concrete bricks and blocks, sophisticated testing methods currently specified in concrete materials standards (e.g., air content and air-void system parameters) may be useful to the quantification of durability and service life. Detailed guidance on the assessment of the durability properties of bricks and other masonry units will be critical as new products with limited performance history (e.g., products which may be otherwise desirable due to lower embodied energy and carbon) are considered for use in construction. As the Canadian climate changes, research will be needed to identify regions where the frequency and severity of freeze-thaw cycling events may be increasing; designers in those regions may need to adapt their designs to new and more severe environmental conditions.

Few research articles are available on the durability of masonry mortars; however, conventional proportion-specified cement-lime-sand mortars have a good history of performance in Canada. Further efforts may be needed to ensure that testing and quality controls sufficiently characterize property-specified mortars to ensure they offer the same long-term performance as proportion-specified mortars. Current methods for assessing the durability of concrete may be applicable for the assessment of masonry mortars and grout.

Much of the efforts towards the reduction of future CO_2 emissions have focused on preventing energy losses for building heating and air conditioning. The effects of the thermal mass of large masonry (or concrete) elements on the dynamic thermal response and energy needs of a structure are well known, but not always easy to account for in thermal analyses. Thinner masonry elements, including exterior masonry veneers, have also been shown to have a positive effect on thermal regulation of buildings. Conversely, masonry ties and other connectors often behave as thermal bridges and have a negative impact on energy conservation. The importance and overall impact of these characteristics on a building's energy usage varies widely depending on the type of construction. A standardized method of expressing the thermal properties of masonry materials and connectors (units, mortar, grout, ties, standoffs, and supports) and of calculating the expected thermal performance of masonry assemblies (including thermal bridging and dynamic thermal effects) is needed.

In addition to in-service energy performance, embodied energy and carbon within the materials and construction processes are often considered in the whole-building energy analysis. Metrics and methods that would allow for a fair comparison of the embodied energy of different materials and construction techniques are still needed. Such methods would need to account for the high energy demands for manufacturing masonry products, but also their long-term low maintenance needs and any carbon captured through the carbonation process.

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