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ADAPTING CSA MASONRY STANDARDS TO CLIMATE CHANGE: PART 1-IMPACTS ON MASONRY MATERIALS, DESIGN, AND CONSTRUCTION

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ABSTRACT

The weather is constantly changing, but the climate is static; this assumption has long been the basis for construction codes and standards. Considering our current knowledge of climate change, it has now become necessary to review standards and ensure they provide sufficient guidance for designers. Following an extensive review of its catalogue of standards, the CSA Group identified several masonry standards as medium or high priority for review for climate change adaptation updates. Many prescriptive requirements for resisting climatic and environmental loading (such as humidity, wind, and temperature) are currently included in these standards; given that the factors for which they were selected to resist are now different and expected to continue changing, it is natural that these requirements should be revised accordingly. The CSA Group collaborated with the Canada Masonry Design Centre and York University to review current Canadian masonry standards. The review process was also an opportunity to critically assess the guidance provided in these standards in view of the state-of-the-art in building and material sciences, and in construction practices. In Part 1 of this two-part paper, background information is presented on the various avenues by which the impacts of climate change are expected to influence design and construction in masonry. Impacts discussed include the influence of changing climates on moisture within masonry wall cavities, changing patterns of freeze-thaw cycling on the durability of masonry units, and the impact of more stringent regulations related to building energy efficiency on masonry construction. Part 2 provides recommendations for the CSA standards adaptations, as well as a discussion of research needs and key stakeholder input.

KEYWORDS: c*limate change, durability, building science, CSA standards, freeze-thaw, moisture index, concrete*

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INTRODUCTION

Discussions on climate change often conjure images of recent disasters which have been attributed to climate change (hurricanes, wildfires, droughts etc.), or the thought of displaced and disappearing wildlife, or sea level rise due to melting icecaps. Although these effects have a direct impact on certain populations (large urban centres can also be affected), climate change is also inducing more subtle effects with consequences that may be even more widespread. Certain essential or "post-disaster" structures may need to be designed to withstand the effects of wildfires, flooding, and windstorm events that are more severe than those previously experienced; masonry materials, with their advantageous impact- and fire-resistance, have a proven record of resilience in extreme conditions, and will remain attractive materials for the construction of critical infrastructure. Other structures with a normal importance level will also require adaptation to account for changes in climate patterns that may severely reduce the durability of certain materials and assemblies. It is for the latter case that material, design, and construction standards will need to be updated.

Recently, the Government of Canada published a report [1] indicating trends and forecasts for climate parameters used in design (peak wind pressure, annual rainfall and snowfall, hourly maximum rainfall, etc.). Design standards that specify the use of these climatic data from the National Building Code of Canada are now better adapted to climate change. Conversely, standards that include climate data, or prescriptive requirements may require special care and attention during the cyclic review process to ensure sufficient guidance and up-to-date data is included.

In addition, as part of global efforts to mitigate future climate change by reducing greenhouse gas emissions, energy codes such as the National Energy Code for Buildings (NECB) [2] as well as individual building owners and operators are requiring improved energy performance in buildings, and decreased energy and carbon inputs over a building's lifecycle (including construction, operation and maintenance, and decommissioning). Masonry construction has long been known to have both positive and negative characteristics in terms of its over-all energy performance. Thermal mass and durability reduce energy needs (in heating/cooling and maintenance); however, the production of fired clay and concrete brick and block is energy-intensive, and wall systems incorporating masonry veneers are reaching the limits of insulation thickness that can be practically incorporated.

Ensuring that masonry components of our built infrastructure remain well adapted to the changing Canadian climate, and that they remain viable in the context of mitigating future carbon emissions, will require a comprehensive review of the available literature and targeted research to address knowledge gaps. Only a few recent reports [3] have explored the various possible impacts of climate change on buildings and infrastructure, and these have often included a discussion of masonry construction. This novel paper draws on a wide variety of resources to bring attention to the unique needs of masonry construction.

BACKGROUND

A 2018 internal review by the CSA Group identified CSA A370, *Connectors for masonry* [4] among the standards with a high priority for climate change adaptation. This was due in large part to Annex E, which contains annual Driving Rain Index (aDRI) values for various locations in Canada. Other CSA masonry standards were identified as medium or low priority for adaptation. This review prompted the initiation of a review project in collaboration with the Canada Masonry Design Centre and researchers from York University to perform a comprehensive review of CSA masonry standards and provide recommendations for areas where changes to adapt to climate change may be necessary [5]. In addition, the effects of practices and policies aimed at mitigating further climate change (i.e., reducing CO_2 emission) on masonry standards was identified as important and included in this study.

METHODS

This study involved a thorough review of CSA standards related to masonry materials, design, and construction. The following standards were reviewed:

- CSA A82-14 (R2018), *Fired masonry brick made from clay or shale* [6]
- CSA A165 Series-14 (R2019), *CSA standards on concrete masonry units* [7]
- CAN/CSA-A179-14 (R2019), *Mortar and grout for unit masonry* [8]
- CSA A370-14 (R2018), *Connectors for masonry* [4]
- CSA A371-14 (R2019), *Masonry construction for buildings* [9]
- CSA S304-14 (R2019), *Design of masonry structures* [10]

The review identified areas and clauses where prescriptive requirements related to the resistance to climatic loading (wind, rain, heat, frost etc.) were included. This resulted in the following topics to be investigated further in the current literature:

- Masonry connector durability
- Strength and stiffness of masonry ties
- Masonry cracking and moisture penetration
- Damp-proofing in masonry construction
- Freeze-thaw durability of bricks
- Freeze-thaw durability of mortar
- Thermal response of masonry structures

The literature review for each topic was performed using keyword searches in major science and engineering journal article databases, and manual searches of the proceedings of specialty masonry conferences and symposia. The project was further guided through consultation with key stakeholders in masonry research, design, and manufacturing. The consultation was conducted via a survey questionnaire that solicited over 20 detailed responses, including references to articles for inclusion in the review.

LITERATURE REVIEW

The main findings of the literature review are presented and are grouped by similar topics. This section investigates how various aspects of masonry design, material, and construction may be affected by climate change, and strategies that may be employed to promote evidence-informed design and appropriate durability performance in the future.

Moisture penetration

Moisture is a major driver for many forms of deterioration in masonry walls and associated assemblies; this fact is made apparent in multiple entries related to the deterioration of masonry within Grondin's 1993 report on the durability of structures [11]. Excess moisture can cause severe deterioration through corrosion of steel connectors, reinforcement, and supports. It can also increase the risk of freeze-thaw damage and/or efflorescence in masonry mortar and units. The porous nature of masonry assemblies generally means that some level of moisture penetration must be expected of any element exposed to wetting from outdoor conditions; however, care must be taken to ensure proper detailing is provided to avoid excessive moisture from accumulating, and to promote drying.

In general, there are two main sources of moisture that can have a negative impact on masonry wall assemblies. Moisture from precipitation, specifically wind-driven rain, can permeate through the porous structure of masonry and through any cracks and openings that may be present. Exfiltration of warm moist indoor air through inadequate, or inadequately sealed air barriers can also result in condensation within a masonry cavity, particularly on masonry ties and other connectors. For walls with properly detailed masonry veneers, which include a vented cavity separating the veneer from the insulation, moisture that passes through the outer-most veneer can travel down the inner side of the wall, and out through the weeps. Issues may arise, however, if the detailing in place fails to divert excess water away from the wall, or if drying cannot occur due to climatic conditions, or due to improper venting.

Cracking of masonry walls has been suggested to play a key part in moisture penetration, however various studies have revealed that cracks up to 0.1mm in width are unlikely to contribute to the over-all permeability of a wall [12] [13]. Wider cracks become an aesthetic concern; however, it remains unclear to what extent these might influence moisture permeation.

Mass masonry walls, particularly those of historical structures and which do not include a vented cavity, can be more sensitive to cracking and associated moisture penetration. For walls constructed without a vented cavity, a crack through the wall may result in a direct path for moisture entry into the building's interior finishes. The consequences of this type of moisture penetration, if not properly accounted for, can lead to accelerated deterioration during retrofitting operations where additional interior insulation is applied [14]. Modern masonry construction includes a vented cavity which is meant to promote the shedding of excess moisture and prevent wicking or other transport of moisture through the inner layers of a building envelope [15]. Cracking of exterior veneers must nonetheless be strictly controlled to prevent the penetration of excess moisture, which may increase the risk of corrosion within the cavity, or moisture transfer through the cavity.

The annual Driving Rain Index (aDRI) was developed as a measure of rainwater passing through a vertical plane and has been used to quantify the amount of water projected onto the vertical walls of buildings [16]. This index, however, does not account for wind directionality, or the aerodynamic and sheltering effects of building geometry. Although broad statements have been made with regards to the association between aDRI, moisture in masonry walls and corrosion, no robust quantitative study linking these was found as part of this research study. Other climate indices that have been proposed as measures of the relative severity of an environment with regards to the potential for moisture-related deterioration that may be considered for use in the assessment of a masonry wall include Exposure, the Directional Driving Rain Index (dDRI), Rain and Heating Degree-Days, the Scheffer Decay Hazard Index, the Relative Humidity and Temperature (RHT) Index, and the Moisture Index (MI).

Exposure is loosely defined to compare the relative severity of environmental loading for a particular area. It typically does not account for local climate conditions, but rather assesses whether a structure is sheltered by the local topography, buildings, and/or vegetation, or exposed (e.g., on a flat plain, or a hilltop). The dDRI is similar to the aDRI, in that it is the product of rainfall and wind speed, however it also accounts for wind directionality. It is therefore possible, by applying a driving rain factor and deposition factor (related to building geometry) to estimate the actual amount of water deposited onto a portion of a vertical wall of known orientation [17]. Use of this level of information can, however, be quite onerous, and does not account for drying (or lack thereof) between rain events. The use of annual rainfall and heating degree-days has been suggested as a simple method for defining the relative risk of moisture-related damage, following the principle that warm and moist environments are more conducive to deterioration than cold and/or dry environments. The use of this metric, as proposed by Cornick and Chown [18], differentiates between two climate zones in Canada. Scheffer’s decay hazard index [19] is a more detailed approach to a similar principle by taking the sum of the product of factors related to the monthly average temperature and the number of rainy days for each month. However, it was developed to assist in the determination of the risk of fungal growth, and its applicability to other modes of deterioration is unclear. The Relative Humidity and Temperature (RHT) index was inspired by Scheffer’s index, but using defined threshold values for wood-decay and corrosion, it is calculated using relative humidity and temperature at the location of a structural element – which require either sophisticated instrumentation or a computer model analysis to determine [20]. It is useful in the detailed analysis of a known structure subjected to known environmental loading but can be arduous to apply. A compromise index developed by Beaulieu et al. [20] over the course of the Management of Exterior Wall Systems (MEWS) project is the Moisture Index (MI), which combines the effects of wetting from rain and drying from air temperature and relative humidity. A version of this index is available in the current National Building Code of Canada [21] for various locations in Annex C.2.

Corrosion modeling

In Canada, the use of zinc-coated (galvanized) steel is common for producing masonry connectors for exterior walls. Whereas plain carbon steel is prone to pitting corrosion, which can rapidly reduce the strength of a connector, zinc coatings protect the steel from corrosion through two mechanisms; it provides a physical barrier that protects the steel from moisture, and since zinc is more anodic than steel, it corrodes preferentially and delays the onset of corrosion in the steel. The protection afforded by zinc coatings is, however, limited in its duration. If conditions conducive to corrosion exist, the zinc will oxidize and become depleted over time and corrosion of the underlying steel will eventually be initiated. Since masonry ties are difficult to inspect and replace, it is important for designers to ensure that sufficient corrosion protection is provided to prevent pitting of the steel during the service life of the structure. Since available methods and standards for zinc coatings limit the coating thickness to approximately 550 g/m^2 (ASTM 153 Class b for spun components), the challenge is to determine whether the climate conditions which a wall and its connectors will experience allows the zinc coating to survive the life of the structure, or if stainless steel ties must be used instead.

Various studies have reported a wide range of corrosion rates for zinc-coated steel ties [22] [23] and although the higher rates are often attributed to high aDRI values, no strong correlation between aDRI and corrosion rate was evident in the reviewed literature. Problematic corrosion reported in the literature has also been attributed to improper detailing causing moisture accumulation, or to moisture caused by condensation from exfiltrating air [11]. Recent studies of corrosion rates have used detailed hygrothermal modelling in combination with historical climatic data, and sophisticated corrosion models to determine corrosion rates. Hagel et al. [24] reported promising results when comparing calculated corrosion rates to the observed service life of connector samples extracted from buildings in-service. Key elements of the corrosion model are the time to carbonation of the mortar covering the tie, Time of Wetting (ToW) determined from the hygrothermal modeling, and the concentration of key atmospheric pollutants that can accelerate corrosion (e.g., SO_2). The authors highlighted cases where the modelling system overestimated the service life of ties – these were attributed to deficiencies in the construction and/or detailing that may have resulted in increased moisture and faster deterioration.

Freeze-thaw durability

Freeze-thaw deterioration occurs when water infiltrates into a crack or pore, freezes, and expands, resulting in large forces being applied within the material. Porous materials that are subjected to moisture levels approaching saturation and cycles of freezing and thawing can suffer rapid deterioration through this process. Although climate change is expected to result in a net increase in average temperature across Canada, this does not infer that the severity of freeze-thaw conditions will uniformly reduce. Studies of pavements in the US [25] and Netherlands [26] suggest that in colder regions, warming may cause freezing to be more intermittent, increasing the annual number of freeze-thaw cycles that a material may be subjected to. In Switzerland, a detailed study examining both the projected frequency and severity of freeze-thaw conditions, and accounting for the depression of freezing temperature within the pore-structure of masonry materials, illustrated that the freeze-thaw conditions were projected to increase in severity in Davos, but decrease in Zurich [27]. The general type and detailing of a structure, however, are also important to consider when assessing whether there may be a change to the risk of freeze-thaw related damage; conventional masonry veneer construction in Canada includes a vented cavity behind the exposed wall surface, which is designed to help quickly shed excess moisture and prevent saturation of the masonry. Freeze-thaw damage to a structure will only occur if excess moisture is present at the time of freezing.

Freeze-thaw durability of fired clay masonry bricks has long been identified as a critically important feature for exterior exposed applications in areas that experience below-freezing temperatures. Testing of bricks during the 1950s to 1970s [28] [29] [30] established a correlation between absorption properties of clay brick (i.e., cold-water absorption, boiling water absorption, and saturation coefficient) with freeze-thaw durability. These early tests did not all use the same metrics for the assessment of freeze-thaw durability, and largely sought to categorize bricks as either durable or non-durable to exposure to freeze-thaw effects. Although the acceptance criteria proposed following these early research efforts allowed a small percentage of bricks classified as "non-durable" during testing at that time, to be accepted for applications with exposure to freeze-thaw, similar acceptance criteria remain in place in Canada and the U.S. Note that different test methods for freeze-thaw testing have resulted in identifying the same type of brick as durable and non-durable [29] [31], and that it has been suggested that current testing methods allow for variability in results depending on how the test is conducted [32].

More recently, sophisticated testing and analytical methods have been proposed for the assessment and quantification of the durability of fired clay masonry bricks. Maage [33] suggested that the distribution of pore size of bricks plays an important role in freeze-thaw durability. Using Mercury Intrusion Porosimetry (MIP) it is possible to quantify the volume fraction for various characteristic pore sizes; bricks with a larger fraction of pores with a diameter larger than 3 μm typically exhibit better durability. Others have used Scanning Electron Microscopy (SEM) to assess the pore size distribution as well as their characteristic shape [34]. Circular pores have been associated with good durability performance, whereas elongated pore structures were found to result in greater risk of delamination during freeze-thaw exposure. Frost dilatometry has also been proposed for the assessment of freeze-thaw durability. Of particular interest is the determination of the critical degree of saturation (at which freezing expansion begins to be observed); this material property has been shown to be useful in the assessment of historical masonry structures undergoing retrofitting to increase insulation [14]. For these cases, a sophisticated hygrothermal model can be constructed to study the impact of changing wall insulation (or other interventions) on the temperature and moisture response of masonry to the local weather. Freeze-thaw damage is most likely to occur in cases where an element is permitted to freeze during a period of time when its moisture content is above the critical degree of saturation.

Limited research is available on the freeze-thaw durability of concrete brick and block (relative to the quantity of research on clay brick); existing literature, however, indicates that concrete bricks can have similarly good performance to that of fired clay brick [29]. Although extensive research has been conducted on the freeze-thaw deterioration of concrete as well as on the assessment of the risk of freeze-thaw deterioration, it is not clear to what extent it is applicable to concrete brick and block. Concrete masonry units are typically manufactured differently from normal site-cast or pre-cast concrete; whereas most concrete is cast by pouring a flowable mix into formwork, concrete masonry units are cast using a very dry mix and vibratory compaction. Research on the freeze-thaw resistance of other dry cast concrete such as retaining wall units [35] and roller compacted concrete [36] may help in the assessment of how the characteristic pore structure of these types of concretes affect freeze-thaw durability.

Similarly, limited research is available on the durability of masonry mortar and grout. Some work dating back to the 1980s studied the performance of mortar mixes produced from locally-sourced materials [37]; more recent work from Australia studied the performance of various mortar mixes by assessing their resistance to a "scratch test" over a period of three years [38]. However, most studies found refer only to the short-term characteristics of compressive and bond strength. In general, proportion-specified, cement-lime-sand mortars have exhibited good performance history, and good resistance to freeze-thaw cycling conditions. Much of this durability is attributed to the use of lime within the mortar – an informative annex within CSA A179 indicates that by providing plasticity to the material, lime content helps improve freeze-thaw durability and increases the mortar bond due to the workability of the fresh material (during construction).

Building energy

Both operating and embodied energy for buildings are important considerations when assessing their environmental impact. As increasing attention is being given to reducing all forms of energy usage to mitigate future changes to the climate, designers will need to demonstrate that masonry structures can meet current energy targets.

The thermal properties of masonry assemblies have long been a focus of research. The study of thermal resistance and conductance (R and U values) of hollow block wall assemblies has raised interesting challenges. Heat flow through such walls, with and without insulation fill, has revealed that conventional means of assessing insulation do not always yield accurate results [39]. However, as the insulation requirements for exterior walls have increased in recent years, the relative contribution of masonry materials to the overall system has decreased. The inclusion of metallic connectors and supports (e.g., ties and shelf angles) that span through the main insulation layers within wall assemblies of modern masonry construction are now the main aspects of concern in the assessment of thermal resistance due to their thermal bridging effects.

Various strategies for reducing thermal bridging of ties and shelf angles have been proposed, including the addition of thermal breaks to steel ties (polymer pads separating individual components), and reducing the cross-section of standoffs that support shelf angles. Accounting for the thermal bridging of these components and comparing the relative benefits of mitigation strategies has been performed by some, using sophisticated 3-D thermal modelling approaches [40]; however, it remains unclear to what extent these benefits will be applicable in-situ.

The thermal mass of concrete and masonry within buildings has long been known to have a positive influence on energy consumption by maintaining a relatively stable temperature over the course of daily cycles in exterior air temperature [41]. Benefits have also been observed in the use of exterior masonry veneers [42] regardless of whether the veneer cavity weep holes were open or closed. Since the effects of thermal mass on the dynamic heating and cooling energy needs of a structure are not captured by conventional R- or U-value analysis, researchers from Australia have proposed a dynamic thermal index [43], which may be used to assess assemblies with various combinations of thermal resistance and thermal mass, and determine whether they behave as insulators or conductors.

KEY FINDINGS

The potential effects of climate change on masonry elements are diverse. Changes will be needed to building codes and zoning bylaws to mitigate the effects of climate change-related disasters (e.g., extreme storms, floods, and wildfires). However, updates to the standards for masonry materials and construction will be needed to adapt to cases where changes to long-term average climate conditions may have a negative impact on durability. Whereas historical performance of structural and building envelope systems were reliable indicators of durability, a better understanding of the interaction between building components and climatic loads will be needed to evaluate durability as the climate changes.

The presence of moisture within a building envelope system is associated with many forms of deterioration, including corrosion, wood rot, and damage to internal finishes, as well as being a necessary component for freeze-thaw damage to occur. Several indices, including the aDRI and MI have been proposed as convenient metrics for the evaluation of the relative risk of moisture-related deterioration. However, a more robust correlation between climate and the severity of deterioration conditions within masonry veneer cavities is needed. Additional research quantifying the relation between cracking of masonry and moisture penetration will be useful for the development of accurate hygrothermal models to assess deterioration conditions. As efforts to reduce energy expenditures to mitigate carbon emissions and future climate change increase, continuing efforts will be needed to enable accurate assessments of the thermal performance (steady-state and dynamic) of masonry assemblies.

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