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Ensuring the durability of masonry cavity wall construction in a changing Canadian climate: overview of a transformative industry-driven project at McGill University

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ABSTRACT

In masonry cavity walls, the outer clay brick veneer experiences moisture/temperature-induced strains throughout its service life, while the concrete block backup, protected from temperature/moisture fluctuations by the building envelope, is prone to drying shrinkage. These long-term volume fluctuations, which may become more severe with climate change, cause differential movements between the veneer and backup which may cause distress in cavity walls and affect their durability if not properly accounted for in design. In Canada, masonry cavity wall designs rely on outdated experimental data that does not consider the interaction between mortar and masonry, while lacking substantial evidence from long-term field tests on modern structures. In this paper, preliminary results from a novel 2-step testing method for drying shrinkage on concrete masonry prisms are discussed. Future research includes moisture expansion tests on clay brick prisms, as well as mechanical tests on tie-masonry assemblies and wall-shelf angle assemblies.

INTRODUCTION

Unprecedented changes in climate patterns have been observed worldwide since the mid-18th century. Between 1948 and 2016, the mean annual temperature in Canada rose by approximately 1.7˚C, double the global average temperature increase (Bush and Lemmen 2019). Changes in temperature extremes have also become more severe in Canada as the annual frequency of cold events has decreased and the annual frequency of warm events has increased (Warren and Lemmen 2014). Furthermore, between 1950 and 2010, Canada's annual precipitation increased by approximately 16% (annual rainfall increased by 13% and annual snowfall increased by 4% between 1950 and 2009) (Warren and Lemmen 2014). As such, preventing early deterioration of structures due to acute changes in climate patterns is imperative. In Canada, cavity wall structures are among the most common types of construction in the masonry industry (Baker, Marr, and Drysdale 2004). They feature an inner loadbearing concrete masonry backing (inner wythe) and an outer clay brick veneer (outer wythe) acting as a weather-resistive barrier, separated by an air gap and connected by metal ties which provide lateral stability to the veneer (Martins, Vasconcelos, and Costa 2017). A layer of thermal insulation is typically installed in the air gap. Other components of a cavity wall include mortar, grout, vertical/horizontal/joint reinforcement, and expansion joints (Ismaiel et al. 2022). Another key component is shelf angles, which hold the brick veneer in place (Martins, Vasconcelos, and Costa 2017). In 2018, a Climate Change Adaptation Standards Inventory Analysis was conducted by the Canadian Standards Association (CSA), where all CSA standards referenced in the 2015 National Model Codes were revisited and evaluated based on their susceptibility to climate change effects. CSA identified 3 masonry standards requiring urgent climate change adaptation provisions, one of which (CSA A370-14 *Connectors for masonry*) being flagged as "high priority" (Canadian Standards Association 2018). Furthermore, as sustainability becomes increasingly important in the building industry, designers are required to improve the energy efficiency of buildings to meet stricter building energy code requirements. The minimum effective thermal resistance (R-value) requirement has increased by an average of 25% in the 2017 National Energy Code of Canada for Buildings compared to its previous edition (Ismaiel et al. 2022). For cavity walls, one method to achieve a higher thermal performance is by widening the cavity between both wythes. However, the impact of increasing cavity widths has remained largely unexplored. The structural implication of enlarged cavities on cavity wall components such as shelf angles and ties has not been studied in recent decades. The latest research evaluating the relationship between tie capacity and cavity width was conducted three decades ago (Hatzinikolas, Longworth, and Warwaruk 1982), despite the fact that these elements may require critical design modifications.

In this paper, we present an overview of transformative research addressing these urgent issues with the goal of devising climate change-adapted cavity wall designs led by McGill University's struct-lab and sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Masonry Design Centre (CMDC), the Canadian Concrete Masonry Producers Association (CCMPA), and Mitacs. The study aims to create the first-of-its-kind experimental database featuring modern clay and concrete masonry properties (as well as other components required for standard and large cavities), devise new climate change-adapted designs based on laboratory test outcomes, and develop calibrated artificial intelligence-powered numerical modelling tools to evaluate climate change-adapted cavity walls of various types under different load cases and design configurations vital for design optimization.

PREVIOUS RESEARCH ON MASONRY CAVITY WALL DURABILITY IN CANADA

Kuzik, Elwi, and Hatzinikolas (1999) conducted long-term field tests (1,322 days) on a 21-m tall clock tower located in St. Albert, Alberta, consisting of four insulated and unreinforced cavity walls. Laboratory tests were also conducted on clay brick and concrete block samples removed from the lots used for construction of the tower. This project aimed to explore the drying shrinkage properties of concrete masonry and the expansion properties of clay brick masonry over an extended period of time. DEMEC points were mounted on each wall to measure the differential movement between both wythes, and were also placed on the individual units in the laboratory.

The results from the laboratory tests show that the concrete block shrinkage and clay brick expansion values are consistent with the CSA S304.1-94 standard provisions. As for the field tests, results from the concrete wythe movement are in good agreement with concrete block laboratory results, as seen in Figure 1. However, clay brick wythe movement varied significantly from clay brick laboratory results. There was little vertical movement recorded for the brick wythe, see Figure 1.

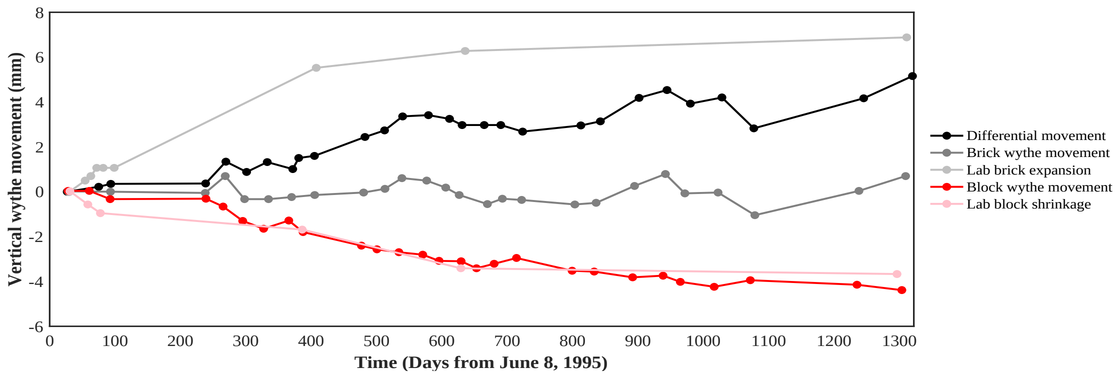

Figure 1. Moisture-induced movements of the north cavity wall (Kuzik, Elwi, and Hatzinikolas 1999)

While previous research suggests clay brick expansion is the primary cause of cavity wall durability concerns, laboratory tests were only conducted on individual brick samples and failed to study the interaction between mortar and brick. The authors suggest that the drying shrinkage of mortar counteracts the swelling of bricks, leading to a dimensionally stable brick veneer. Lohonyai, Korany, and Trovato (2015) conducted research on the same clock tower, but noted that Kuzik, Elwi, and Hatzinikolas (1999) only focused their research on permanent moisture-induced deformations and failed to consider both thermal and reversible moisture-induced deformations, which in total could be 1 to 4 times the permanent moisture-induced strains. Permanent deformations include drying shrinkage of both mortar and concrete masonry, moisture-related swelling of clay bricks, and creep, while reversible deformations include temperature or moisture-induced strains as well as freezing and thawing of trapped pore water. The results from the study show that the maximum total reversible differential movement observed in the field (230±20 µin/in) are much smaller than the predictions of various design guidelines, including 2010 NBCC Commentaries (542 µin/in), S304.1-04 (869 µin/in), and ASTM C1472-10 (826 µin/in). Clearly, more long-term data on modern masonry structures under field conditions are necessary to improve existing masonry design guidelines.

OUTLINE OF PROPOSED RESEARCH

This research is divided into three phases. Phase 1 consists of experimental characterization of material properties to determine the mechanical and environmental response of masonry and other cavity wall components. The main objectives of phase 1 are outlined below.

Mechanical tests on masonry prisms (layered composite of masonry and mortar) will be performed according to CSA S304-14 (Canadian Standards Association 2014b), including:

- Uniaxial compression tests and bond wrench tests on 5 concrete masonry doublets (two-course masonry prisms), 5 concrete masonry triplets (three-course masonry prisms), and 5 five-course concrete masonry prisms, as well as 5 concrete block units;
- Uniaxial compression tests and bond wrench tests on 5 clay masonry doublets, 5 clay masonry triplets, and 5 five-course clay masonry prisms, as well as 5 clay brick units.

Other mechanical tests include:

- Tests on 9 wall-shelf angle assemblies with varying degrees of load eccentricity according to CSA A370-14 (Canadian Standards Association 2014a); and
- Pull-out and push-out tests on 30 tie-masonry doublets (concrete masonry doublet and brick masonry doublet connected by metal ties) with different cavity widths.

Environmental tests on will be performed based on procedures developed by Drysdale and Khattab (1995) and ASTM C426-99 (ASTM International 1999) for concrete masonry, as well as Bremner et al. (2001) and Shrive and Tilleman (1995) for clay masonry, including:

- Drying shrinkage tests on 5 concrete masonry prisms, 10 concrete blocks, and 10 mortar samples; and
- Moisture expansion tests on 10 clay masonry prisms, 20 clay bricks, and 20 mortar samples.

Phases 2 and 3 consist of numerical modelling, which will not be discussed in this paper. In summary, phase 2 consists of numerical calibration, where the experimental results from the small-scale mechanical and environmental tests will be used to calibrate Discrete Element Method (DEM) models. In phase 3, the calibrated models will be used to evaluate the structural impact of climate-adapted designs.

PRELIMINARY EXPERIMENTAL DATA AND DISCUSSION

To date, drying shrinkage tests have been performed on 2 concrete masonry doublets, 2 concrete masonry triplets, 4 concrete blocks, and 5 mortar samples. A proposed 2-step testing method was used to infer drying shrinkage data from the specimens. Step 1 consists of allowing the specimens to dry from a saturated surface dry state over 12 weeks based on the slow method described in Drysdale and Khattab (1995), and step 2 consists of drying the specimens based on the rapid method described in ASTM C426-99 (ASTM International 1999). This novel approach allows shrinkage-time curves to be obtained over a sufficiently long period of time for numerical analysis purposes in step 1, while providing an estimate of the ultimate drying shrinkage in step 2, necessary for most design applications. The procedure outlined in ASTM C596-01 was used for the mortar samples (ASTM International 2001). The specimens at various stages of the 2-step test are shown in Figure 2: specimens placed in the immersion tank with controlled water temperature (23$\pm$1.1°C) before step 1 (Figure 2a), specimens air-drying in the climate chamber with controlled temperature (22$\pm$1°C) and humidity (42$\pm$4%) during step 1 (Figure 2b), and specimens placed in the drying oven with controlled temperature (50$\pm$0.9°C) and humidity (17$\pm$2%) in step 2 (Figure 2c).

(a) (b) (c)

Figure 2. Testing apparatus (a) immersion tank; (b) climate chamber; (c) drying oven (Das et al. 2023)

Figure 3 depicts the average horizontal shrinkage, across the length of the specimens, of 2 doublets, 2 triplets, and 2 single blocks (normalized against the initial length between gauge plugs observed at the first measurement) over a period of 10 weeks for step 1. Average vertical shrinkage was also obtained over this same time period, with data following similar trends as average horizontal shrinkage. A surprising observation from Figure 3 is that drying shrinkage data patterns are similar between single blocks, doublets, and triplets. This seems to suggest that the mortar has a limited effect on the drying shrinkage properties of the concrete masonry prisms, or that the mortar has similar drying shrinkage properties to that of the masonry units. Data from both single blocks are plotted against past drying shrinkage research (Drysdale and Khattab 1995; Kuzik, Elwi, and Hatzinikolas 1999) and seem to be in good agreement, as seen in Figure 4.

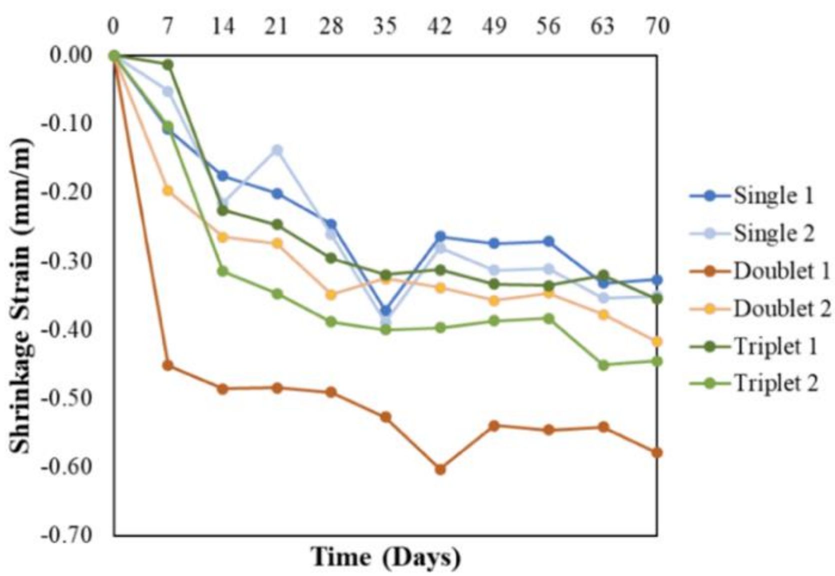

Figure 3. Average horizontal drying shrinkage of the specimens in step 1 (Das et al. 2023)

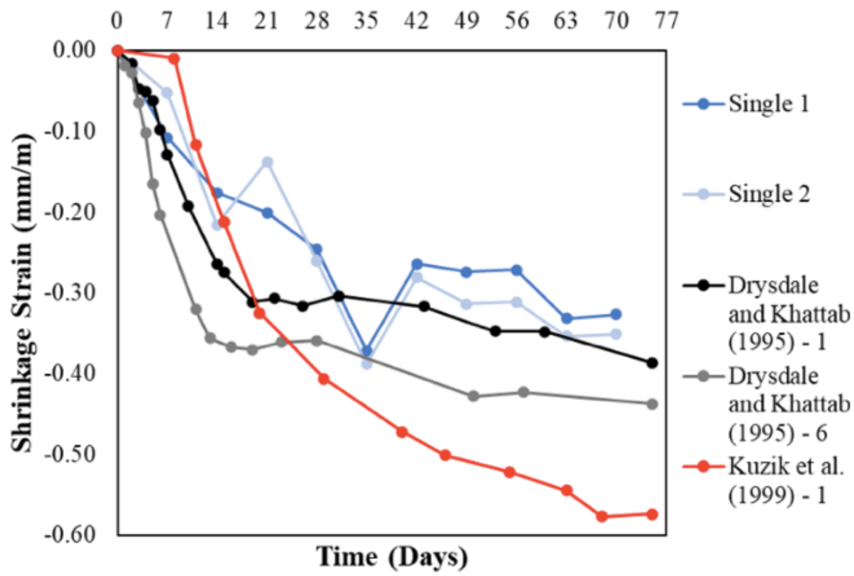

Figure 4. Comparison of concrete block horizontal drying shrinkage data and key data from past research (Das et al. 2023)

The drying shrinkage strains for the 5 mortar samples are presented in Figure 5, whose trends also agree with the findings of previous researchers (Booya et al. 2018; Gorospe et al. 2019). The causes of the drop observed at days 42-49 is presently being investigated.

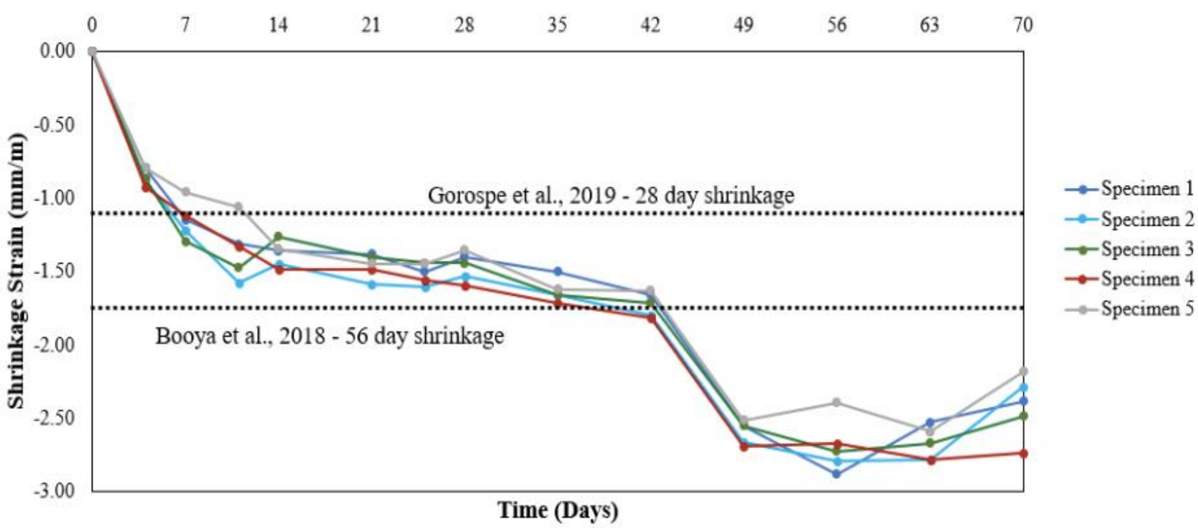

Figure 5. Drying shrinkage of mortar cube samples, with benchmarks of past studies (Menun et al. 2023; Booya et al. 2018; Gorospe et al. 2019)

Thus far, uniaxial compression tests have been conducted on 3 concrete masonry triplets. The force-displacement curves are illustrated in Figure 6. Further tests on concrete masonry doublets and prisms will allow for correlation of data between masonry assemblies.

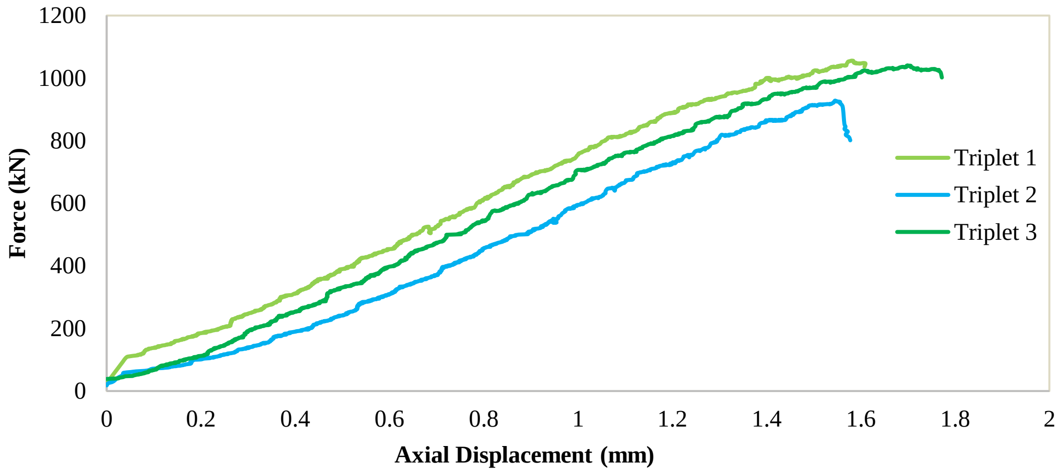

Figure 6. Summary of results from uniaxial compression tests on concrete masonry triplets

FUTURE RESEARCH GOALS

As discussed earlier, mechanical and environmental tests will be conducted on clay brick masonry doublets, triplets, and prisms, as well as Type S and Type N mortar samples. Type N mortar is a general-purpose mortar that is often used for brick veneers, whereas Type S is used for structural load-bearing applications such as concrete backups. To date, five doublets, five triplets, and five prisms (Figure 7a), as well as six mortar cubes (Figure 7b) have been constructed and will be tested under uniaxial compression after a 28-day curing process. Further specimens will be constructed and exposed to controlled environmental conditions for 1 year in order to infer expansion-time curves.

(a) **(b)**

Figure 7. (a) Clay brick doublets, triplets, and prisms; (b) Type N mortar cubes

CONCLUSION

As changing climate patterns particularly affect Canada, improving current Canadian and North American masonry design guidelines is crucial for safeguarding existing and modern infrastructure. There is a lack of information needed to implement climate change design adaptation to cavity wall masonry structures in Canada, as identified by the CSA report published in 2018 (Canadian Standards Association 2018), including the development of an up-to-date database on physical and mechanical properties, as well as other design factors such as durability, of masonry units and other components of masonry structures. Designing more durable and thermally efficient masonry cavity wall structures will enable us to contribute to a more sustainable built environment. Thus far, preliminary testing data on single concrete blocks, concrete doublets, and concrete triplets suggest that the influence of mortar has little effect on the drying shrinkage response of masonry assemblies. Furthermore, experimental data correlates well with past research on individual concrete blocks and mortar samples. As these results require more validation, further research will be conducted on more samples to support these findings. The next research stages include year-long moisture expansion tests on clay brick masonry assemblies, pull-out/push-out tests on tie-masonry doublets, and tests on wall-shelf angle assemblies.

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