Structural and environmental characterization of modern concrete masonry for climate change design adaptation

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Abstract. In 2018, the results of a Climate Change Adaptation Standards Inventory Analysis conducted by the Canadian Standard Association (CSA) indicated cavity-wall design as requiring urgent climate change adaptation provisions. Distress in cavity-walls is often attributed to excessive differential movements due to moisture-induced volumetric variations, producing cracks in outer clay brick veneer and compromising durability, which may increase with climate change – test data are, however, still scarce, and only refer to individual blocks/bricks rather than mortared masonry samples. To address these knowledge gaps and devise climate change-adapted design alternatives for cavity-wall structures, a comprehensive research project has recently been launched at McGill University, cosponsored by Natural Sciences and Engineering Research Council (NSERC), Mitacs, the Canadian Masonry Design Centre (CMDC) and the Canadian Concrete Masonry Producers Association (CCMPA). The latter focuses on the design challenges and structural implications related to the use of wider cavities (to augment thermal insulation) through mechanical and environmental tests, as well as numerical modelling, vital for identifying potential criticalities and opportunities in such new climate-adapted designs. In this paper, we present preliminary results from structural and environmental lab characterization studies on modern concrete masonry assemblies, including uniaxial compression tests on masonry units, doublets, triplets and prisms, but also innovative moisture tests specifically conceived to monitor the volumetric variations of both units alone and masonry specimens under controlled temperature and relative humidity, therefore providing a more accurate overview of drying shrinkage. Produced data, combined with those collected in the next research stages through additional tests also on clay brick veneers and building-scale numerical modelling, will enable us to evaluate the combined effects of climate change and multiple design alternatives to meet more stringent sustainability goals, vital for ensuring the durability of the next generation of masonry constructions.

Keywords: concrete masonry, climate change, cavity-wall, sustainability, design adaptation.

1 Introduction

1.1 Impact of climate change on Canada's building sector

Recent analyses of climate data and models have indicated that Canada's climate is changing at an alarming pace [1], with the annual average temperature over land having increased by approximately 1.7°C since 1948 [2], double the global average level of warming as shown in Fig. 1. The Canadian Arctic is warming even faster, with a rate equivalent to three times that of the globe [4]. The Canadian climate patterns are predicted to continue to significantly change in the imminent future as a result of the global phenomenon of anthropogenic climate change [5]. Considering both low and very high greenhouse gas (GHG) emission scenarios, model results predict the average temperatures in Canada to further increase by 1.5°C to 4.5°C by 2070 [6]. Additionally, precipitation measurements show that Canada has gotten wetter in recent decades, with an increase in yearly precipitation of roughly 16% between 1950 and 2009 [7].

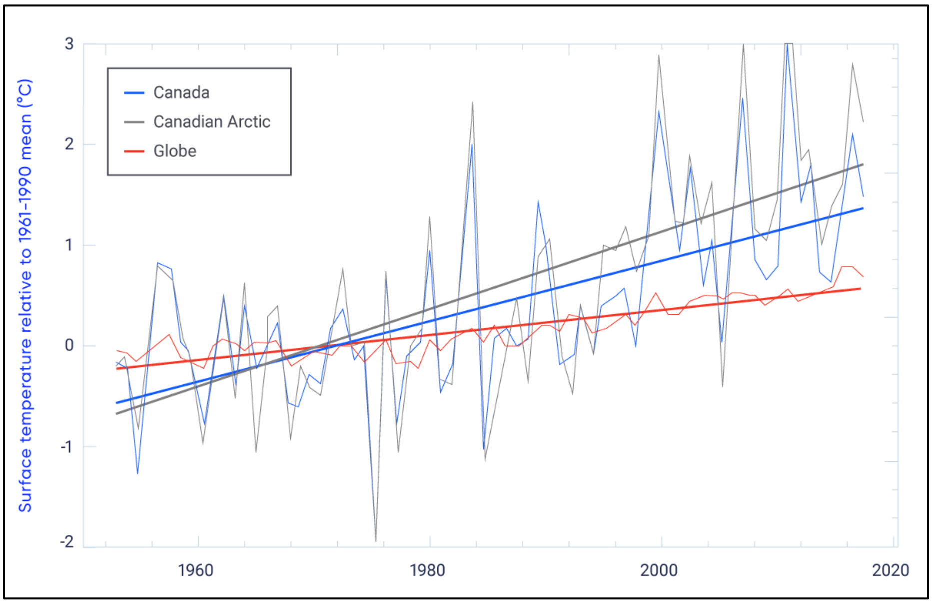


Fig. 1. Rates of warming for Canada, the Canadian Arctic, and the world [2]

Many sectors of the Canadian economy, including the building sector, are impacted by these changes, both in the short and long term [8]. The built infrastructure has been identified as the most susceptible sector to climate change hazards [9], with a direct cost estimated to rise by over $40 billion per year by 2050 [10]. Canada has made the mitigation of climate change impact on the built environment one of its top priorities and has invested in several public initiatives to combat climate change [6, 11-12]. However, until recently, there had been little research into the impacts of climate change on building design and durability. In response, the National Research Council Canada (NRC) established a comprehensive series of research programs to update building codes and design standards for more sustainable and less environmentally impactful structures and infrastructures [11]. It is crucial to take decisive actions to combat climate change, and in doing so, climate risks to physical infrastructure are anticipated to be mitigated. Failure to act could cost Canada $21 to $43 billion annually by 2050, according to projections from the National Round Table on Environment and the Economy (NRTEE) in 2011 [10-11].

1.2 Design adaptation of cavity-wall masonry construction

Cavity-wall structures are one of the most widely used masonry constructions in Canada, albeit their design has recently become a matter of particular concern [12]. The Canadian Standards Association (CSA) has identified the need for urgent adaptation provisions in the design of cavity-walls due to the potential adverse impact of climate change on their mechanical and environmental performance [13]. In particular, variations in freeze-thaw cycles, changes in the corrosion environment of connectors, and increased carbonation rates in concrete – all projected to increase due to climate change – are significant factors affecting cavity-wall assemblies [16-17].

The term "cavity-wall" is herein used to describe a type of masonry structure consisting of two parallel walls separated by an air gap and connected by metal connectors, or "ties" [14]. As depicted in Fig. 1, the inner wall provides the primary loadbearing support, typically made of concrete blocks, while the outer wall, usually constructed with clay bricks, serves as a weather-resistant barrier and transmits external loads to the supporting structure. Metal ties are utilized to mechanically connect the two walls [14], and additional components, such as shelf-angles, movement joints, and insulation, are often incorporated into the system. Differential movements resulting from concrete masonry drying shrinkage and moisture expansion of the outer clay brick veneer are common sources of distress in cavity-walls and can lead to cracking in the outer clay brick veneer, compromising the structure's durability. Despite recent research efforts, test data on the hygrothermal properties of mortared masonry assemblies and their correlation with key mechanical features remain limited, with available data mostly focusing on individual blocks/bricks tested decades ago.

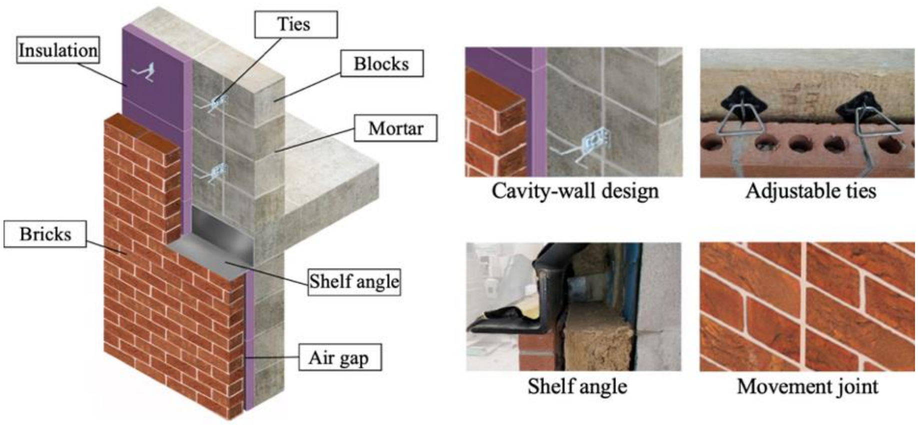


Fig. 2. Typical construction details of masonry cavity-wall

Several recent research efforts have focused on developing advanced simulation methods and durability guidelines to aid in the design of sustainable masonry structures in response to the changing climate [19-20]. However, the successful implementation of climate-adapted designs in building codes relies heavily on a reliable set of experimental data, which is currently unavailable. The availability of data on volumetric changes caused by moisture fluctuations in masonry assemblies, a common cause of differential movements leading to masonry cracking and reduced durability due to clay brick expansion and simultaneous concrete block shrinkage, is particularly limited. Although some data on blocks and mortar specimens are available, they were collected decades ago or obtained from tests conducted on old structures in situ [21-24].

2 Critical CSA standards for climate change design adaptation

While extreme weather events such as heatwaves, floods, and droughts receive much of the attention in discussions on climate change [3], the effects on building materials and structures are also of significant concern. Research groups in Canada [20, 25-26] and abroad [27-29] have assessed how climate change could exacerbate material degradation processes in modern buildings [15], prompting current national research efforts to investigate the effects of changing environmental conditions on building performance and durability [16].

The CSA Group conducted an important study in 2018 called the “Climate Change Adaptation Standards Inventory Analysis”, which assessed the impact of climate change on all 81 CSA standards listed in the 2015 National Building Code of Canada [13]. These standards are projected to be increasingly impacted by climate change, underscoring the need for new climate change-informed design adaptation strategies to ensure that masonry remains a durable option in the future. According to the study, the masonry standard CSA A370-14 (connectors for masonry) was identified as having "high priority" adaptation requirements, along with several other masonry standards including CSA A165.1-14/CSA A165.2-14 (concrete block masonry units) and CSA S304-14 (design of masonry structures). The adequacy of the best practices reported in these standards is projected to be directly and increasingly impacted by the changing climate. As such, new climate change-informed design adaptation strategies are required to ensure that masonry remains a durable option in the future.

3 Overview of a new industry-led research at McGill University

To tackle the abovementioned challenges, a new transformative study on climate change masonry design adaptation has recently at McGill University. Led by *McGill | struct-lab* and co-sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Masonry Design Centre (CMDC), the Canadian Concrete Masonry Producers Association (CCMPA) and Mitacs, this three-year project will fill current knowledge gaps by performing innovative tests on modern key cavity-wall components (i.e. moisture tests on masonry prisms, pull-out/push-out tests on non-prescriptive ties, tests on reinforced concrete (RC) - shelf angle assemblies) and numerical simulations (via Discrete Element Method, DEM [17], where masonry units, their volumetric changes and interaction with ties are explicitly reproduced) on archetypical building sub-systems (i.e. façades) under mechanical (vertical/lateral actions) and environmental (moisture-induced volumetric changes) loads. Artificial intelligence (AI) tools in the form of machine learning [18] will finally be employed to extend produced data beyond the considered design/load cases. In so doing, the aim is to evaluate the combined effects of climate change and multiple design alternatives (i.e. different dimensions of cavities and shelf angle, layout of movement joints). This research direction is innovative, including unique conceptual (the structural implications of climate-adapted designs for cavity-walls have never been investigated in Canada) and methodological (our moisture and shelf angle lab tests will be the first-ever conducted in Canada; the combined use DEM/AI for modelling Canada's cavity-walls has no priors). In what follows and in the next section, a brief outline of research objectives and some preliminary results on mechanical and environmental characterization of masonry units, assemblies and mortar are discussed.

3.1 Outline of research objectives

The main goal of this research is to quantify the impact of climate change design adaptation on new cavity-wall masonry constructions, with special focus on the design challenges and structural implications of the use of wider cavities. To ensure the success of the project and achieve the set goal, three research objectives I, II, III are identified, related to as many conceptual themes, i.e. characterization, calibration, and evaluation:

I. characterization of the environmental/mechanical performance of cavity-wall components via lab tests: this will include conducting pull-out/push-out tests on ties-masonry doublets, tests on RC-shelf angle assemblies under eccentric loads, and moisture expansion/drying shrinkage tests on masonry prisms

II. calibration of new DEM models against lab tests; this aims to achieve reliable simulations at the building sub-system scale and will involve matching the measured time-dependent volumetric changes from moisture tests, as well as the failure mechanisms/force-displacement capacity of tie and shelf angle tests

III. evaluation of climate-adapted design options by combining parametric DEM analysis of archetypical building sub-systems and AI; the structural assessment of multiple representative building sub-systems (i.e. façades) under various loading conditions will enable the uncovering of potential criticalities and design needs, including those related to larger cavity widths and shelf angles, as well as the layout of movement joints.

To make this feasible within the three-year project duration proposed herein, the research activities will focus on a specific two-wythe cavity-wall system. This system consists of an inner loadbearing backup made of standard concrete hollow units (only ungrouted specimens will be tested) and an outer layer made of unreinforced masonry veneer using clay engineering bricks. This configuration is currently prevalent in Canada for low-to-medium rise residential, commercial, and office buildings. Only non-prescriptive engineered ties will be considered, such as adjustable eye-and-pintle steel ties. These ties are crucial for the research since the study will consider cavities larger than those allowed by current standards. CSA A370:14 allows for a maximum cavity width of 150mm by design plus an additional 13mm after construction, and eye-and-pintle ties already allow for this maximum width. However, these adjustable ties exhibit a relevant stiffness variability, which will be monitored during tests and considered in the numerical models as relevant. For the shelf angle and RC anchors, standard commercial models will be used. At this early stage of the project, which started in September 2022, we are working on objective I, and more specifically on the mechanical and environmental characterization of concrete units and assemblies, as well as mortar.

4 Preliminary experimental results

To begin the three-year project, the research team started collecting preliminary results on the drying shrinkage test of masonry prisms for the first research objective (I - characterization). Results of uniaxial monotonic compression testing for both masonry prisms and mortar cubes are also being gathered, for correlation purposes. The preliminary findings through environmental and structural testing are crucial steps in the research process, as they allow for the evaluation of the consistency with the few available previous data. As discussed in what follows, preliminary results from compression testing of mortar and masonry yielded values – still under post-processing – that seems to be compatible with past research (e.g. 1 MN axial resistance for masonry specimens [19], around 25/30 MPa compressive strength for mortar cubes [20], limited influence of mortar joints on the shrinkage of concrete masonry assemblies [21]).

4.1 Experimental framework, testing infrastructure and procedures

As for environmental testing, a new procedure is being developed to gather new insights into the moisture-induced shrinkage of modern mortar, concrete units and assemblies (prisms – 5 units, triplet – 3 units and doublets – 2 units). The objective of this novel method is to describe the mechanical interaction between blocks and mortar in unconstrained specimens. The method is a combination of two approaches initially developed for concrete blocks: the "slow method" (step 1) by Drysdale and Khattab (1995) [22] and the "fast method" (step 2) outlined in ASTM C426 [23]. The 2-step procedure allows for the deduction of shrinkage-time curves over a reasonable period of time for numerical analysis purposes in step 1 while also determining the ultimate drying shrinkage of the specimens in step 2, which is necessary for most design applications. A brief summary of the implementation of step 1 is reported in the bulleted list below:

1. specimens are treated per ASTM C426 to reach saturated surface dry moisture conditions, with measurements of strain and weight taken.
2. specimens are left to dry for 84 days (or 12 weeks, i.e. the period with the largest gradient of linear shrinkage after which deformation becomes negligible, see Menun et al. (2023) [24]) at 22 ± 1ºC and 42 ± 4% relative humidity (RH).
3. mortar specimens were tested per ASTM C596, with weekly measurements of deformations using a DEMEC system over the 84-day process.

Step 2 follows that outlined in the ASTM C426 and begins after the step 1 procedure for drying shrinkage has been completed. Step 2 is summarized in the list below:

1. specimens are dried in an oven at 50 ± 0.9ºC and 17 ± 2% RH until negligible weight and shrinkage strain variations are recorded.

2. strain gauge measurements are corrected based on temperatures and standard reference bar readings during this stage, following Section 8 of ASTM C426-99.

To perform shrinkage tests on concrete, the experimental infrastructure built as per ASTM C426 standard in the Jamieson Structures Laboratory at McGill University is displayed in Fig. 3, and consists of a DEMEC strain gauge system, immersion tank, a custom refrigerator with controlled temperature and RH, and a drying oven.

Fig. 3. DEMEC strain gauge system, immersion tank, refrigerator, drying oven

To measure clay brick expansion, we plan to adopt the procedure developed by Bremner et al. (2001) [25] and Shrive et al. (1995) [26], to be implemented in the next few months. Immediately following construction, the specimens (i.e. bricks, mortar, masonry prisms) will be sealed in polythene for a seven-day moist curing period, and then exposed to controlled environmental conditions for 1 year in the RH/temperature-controlled refrigerator (RH 50-60%, temperature 21 ± 2°C). Vertical/horizontal strains will be measured weekly using the DEMEC system. Results will include the expansion-time curves and their correlation with RH values. As for mechanical testing, preliminary results consist in uniaxial testing of mortar and gypsum (used for capping) cubes, as well as single concrete blocks, triplets and prisms. and was conducted on mortar and gypsum cubes. For mortar and gypsum cubes, uniaxial compression testing was conducted using a smaller 1MN MTS machine with at a monotonic loading rate of 0.008 mm/s (load-control up to 50% of strength, then displacement-control until complete crushing) as per the requirements of CSA A179. The following Fig. 4 shows the testing apparatus for the mortar cubes, depicting the cubes before, during and after testing.

Fig. 4. Mortar cubes compression tests: specimens before, during, after testing

Additionally, compression tests were performed on concrete masonry specimens. In accordance with CSA S304-14 standards, the capping of concrete specimens was done using high-strength gypsum/water mixture and steel plates on the top and bottom of the exterior blocks. The uniaxial compressive force from the 10 MN MTS machine was applied at the top of the steel plate. To measure the strain induced by the monotonic compressive force, four LVDTs were utilized for masonry speicmens, with two on each of the larger faces of the block. The LVDT setup followed the ASTM E 477-92 specification for compression testing. These LVDTs were positioned at mid-height and quarter points along the length of the block, with a gauge length of 15 mm.

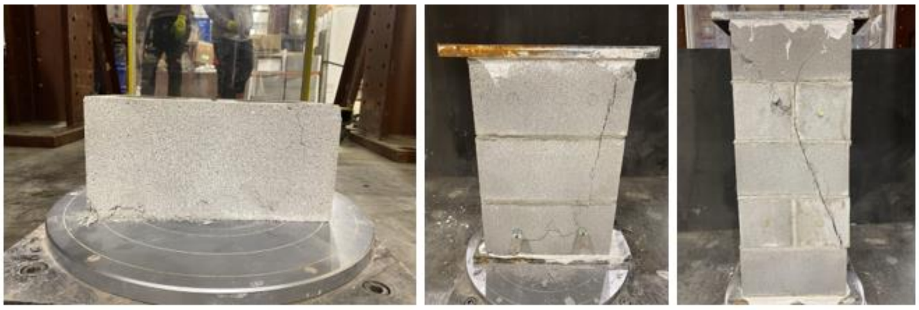


Fig. 5. Block and masonry compression tests: concrete blocks, triplets, prisms

In accordance with CSA S304-14, the load applied to the concrete specimens was performed load-control up until 50% of expected strength. The loading rate was set at 250kN/min until the specimen reached 500kN, as the maximum load reached failure was around 1MN. The second stage was in displacement-control, with a rate of 0.2 mm/min per block stacked on the specimen. Therefore, a triplet had an applied displacement rate of 0.6 mm/min, and a prism had a rate of 1.0 mm/min. This displacement rate was applied until the concrete specimen failed.

4.2 Discussion of drying shrinkage environmental testing

To obtain step 1 preliminary results, weekly shrinkage measurements were taken over 70 days (84 days could not be reached due to time constrains – we will update graphs after the first reviews) for 2 single concrete blocks, 2 doublets, and 2 triplets. Horizontal shrinkage results are shown in Fig. 6. Vertical shrinkage values, followed similar trends. Fig. 6 also shows a comparison of the outcomes of this study for single blocks and the previous shrinkage from Drysdale and Khattab (1995) and Kuzik et al. (1999).

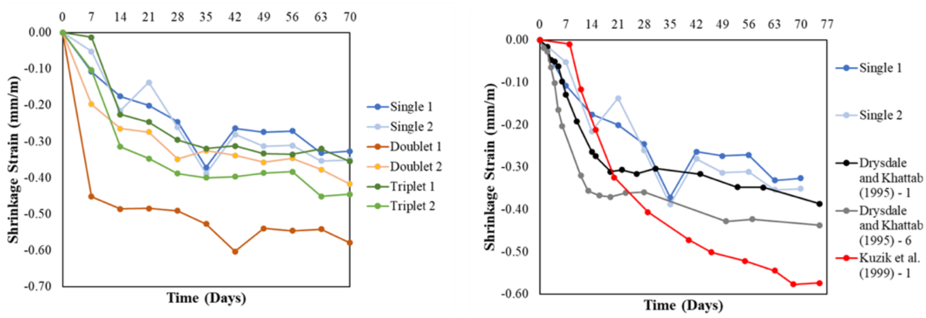


Fig. 6. Average horizontal shrinkage for each specimen versus time – across the long dimension of faces (left), and average horizontal shrinkage for units vs past studies (right)

To present preliminary results for step 2 and reduce testing time, single blocks were tested for oven-drying deformation measurements without previously undergoing step 1. These results are shown in Fig. 7, together with a comparison between the results obtained in step 1 (slow method only up to 70 days – test is ongoing) and step 2 (fast method only). From Figure 6, it can be observed that the slow (step 1) and fast (step 2) testing methods will most likely reach similar ultimate shrinkage values at day 84, albeit with different slopes. Data for step 2 on masonry specimens and blocks previously tested in step 1 are currently being collected and will be presented at the conference.

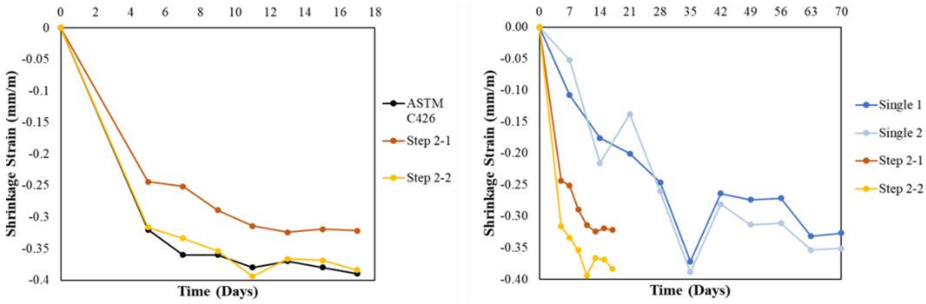


Fig. 7. Average horizontal shrinkage of single units vs ASTM C426 sample data (left), and average horizontal shrinkage of single units in comparison to step 1 single units (right)

This 2-step drying shrinkage procedure enabled us to obtain, in a reasonable timeframe, both strain vs time curves needed for numerical modelling and ultimate values required for practical design. Preliminary findings, still to be confirmed, show that:

- The experimental results from previous researchers in 1995 and 1999 appear to be consistent with the findings of this study on modern blocks.
- The shrinkage behaviour of masonry assemblies appears to be minimally affected by the presence of mortar joints.
- By comparing the results of step 2 with those obtained from step 1 alone, we can conclude that the duration of 84 days is reasonable as ultimate values are similar.

4.3 Discussion of mortar and gypsum mechanical testing

11 mortar and 9 gypsum cubes cured for 28 days were used for testing. 3 gypsum cubes cured for 48 hours and 6 gypsum cubes cured for 3 hours. The compression test results of the gypsum cubes and the mortar cubes are presented in the following Fig. 8.

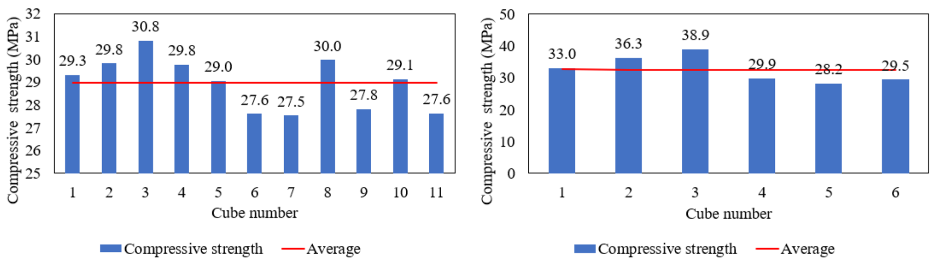
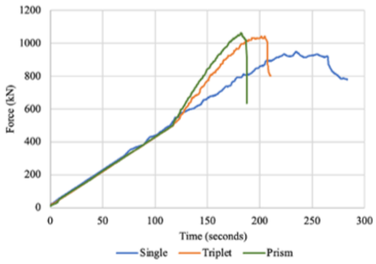


Fig. 8. Compr. strength of 28-day-cured mortar (left) and 3-hour-cured gypsum cubes (right)

According to these preliminary results, the average compression strength of the mortar is 28.9 MPa (c.o.v.=3.9%), while the average compression strength of the gypsum cubes cured for 3 hours and 48 hours are 32.6 MPa (c.o.v.=12.9%) and 38.4 MPa (c.o.v.=6.2%), respectively. These results indicated that gypsum, which was planned to be used as the capping material for compression testing, has a greater compressive strength than mortar. Moreover, it can be observed that there is not a significant difference in compressive strength between gypsum cubes cured for 3 hours or 48 hours.

4.4 Discussion of concrete masonry compression testing preliminary results

So far, compression tests were conducted on a single block, four triplets and one prism. The data presented below in Fig. 9 includes the applied forces over time and the stress main results for each tested specimen. As expected, the blue curve for the single block differed from the other two curves in the test, showing approximately 20% reduction in strength compared to prisms (CSA S304-14, Table D.1, assign a correction factor of 15% to doublets). The compressive strength of triplets, in average, was 3% smaller than that of prisms (CSA S304-14, Table D.1, assign a correction factor of 10% to triplets).



Specimen	Force at 50% strength (kN)	Displ. rate after 50% strength (mm/min)	Failure load (kN)
Single	300	0.2	949
Triplet	350	0.6	1050
Triplet	400	0.6	1037
Triplet	500	0.6	1043
Prism	500	1.0	1062
Triplet	500	0.6	1092
Triplet	500	0.6	1146

Fig. 9. Example of force vs time curves (left), summary of results for each specimen (right)

When testing these training batches, different loading rates were tested to inform future tests. Further experiments, also on clay brick masonry, are currently ongoing.

5 Conclusion

Recent technical reports from Canada Standards Association (CSA) Group have identified cavity-wall design standards as priorities for climate change adaptation provisions. To devise climate change-adapted design alternatives for such structures, including the possibility of using larger cavities to augment thermal insulation, a comprehensive research project has recently been launched at McGill University, co-sponsored by Natural Sciences and Engineering Research Council (NSERC), Mitacs, the Canadian Masonry Design Centre (CMDC) and the Canadian Concrete Masonry Producers Association (CCMPA). The proposed research, started in September 2022, will fill current knowledge gaps through the *characterization* of the environmental/mechanical performance of cavity-wall components via lab tests, the subsequent *calibration* of new based on experimental outcomes, and the *evaluation* of climate-adapted design options focusing on archetypical building sub-systems under various loading conditions, for investigating potential criticalities related to larger cavity widths and shelf angles, as well as the layout of movement joints.

This paper aims to inform the national research community of the main objectives of such a transformative project, about ongoing and planned activities, as well as to discuss preliminary results related to structural and environmental characterization of concrete masonry blocks and assemblies. In summary:

- A new 2-step method for quantifying in a reduced timeframe linear drying shrinkage of concrete masonry blocks and assemblies is being developed
- Preliminary results of the drying shrinkage showed promising agreement with previous Canadian research and suggested that the presence of mortar joints did not significantly influence the shrinkage behaviour of the mortared concrete masonry assemblies tested so far.
- 84 days (12 weeks) were found to be the period with the largest gradient of shrinkage after which induced deformation becomes negligible. Our 2-step method proposes to conduct dry-oven testing after this phase to get ultimate values while also inferring shrinkage vs time curves for numerical models
- Mechanical testing for mortar cubes, gypsum cubes and concrete masonry units and specimens provided preliminary results in good agreement with existing literature, laying the foundation for further testing in the near future.

Additional testing is underway at McGill University. The next research stages consist of additional tests on clay brick masonry specimens, pull-out/push-out tests on non-prescriptive ties, tests on reinforced concrete (RC) - shelf angle assemblies and building-scale numerical modelling. As more information becomes available, the research and professional communities will receive updated and more comprehensive results.

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