A new 2-step testing method for measuring moisture-induced shrinkage of concrete blocks, mortar and masonry assemblies

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Abstract:

Distress in masonry cavity-walls is often attributed to the differential movements between the outer veneer and inner loadbearing members. For structural backups made of concrete masonry blocks, drying shrinkage phenomena are the primary cause of deformations leading to damage and subsequent accelerated deterioration, which are projected to become more severe with rising global temperatures and altered precipitation patterns induced by climate change. Presently, the design of cavity-walls in Canada relies on outdated drying shrinkage data that only refers to individual concrete blocks. This paper is part of a larger climate change design adaptation project co-sponsored by industry, governmental and institutional research funding agencies, to gather new insights on the moisture-induced shrinkage of modern concrete blocks which explores the influence of mechanical interaction between blocks and mortar, and collects presently missing data to calibrate numerical models. A novel 2-step testing method for unconstrained mortared concrete masonry prisms is presented and preliminary results are discussed. After specimens are assembled and instrumented for monitoring in step 1 of testing, they are allowed to dry from a saturated surface dry state over a period of 12 weeks. Then, in step 2, the specimens are tested following the rapid method outlined in ASTM C426. The combination of these two procedures allows for shrinkage-time curves to be inferred over an adequately long period of time for numerical analysis purposes in step 1, while also allowing for the ultimate drying shrinkage of the specimens – needed for most design applications – to be estimated in step 2. Preliminary results – admittedly incomplete and requiring further verification – are in good agreement with those obtained by previous Canadian researchers, and suggest that the presence of mortar joints does not influence in a noticeable manner the shrinkage behaviour of the mortared concrete masonry assemblies tested so far.

Keywords: cavity-wall, concrete masonry, drying shrinkage, climate change

1 Introduction

Recent climate data analysis and modelling have shown that Canada's climate is changing at an alarming pace (Environment and Climate Change Canada 2022). Since 1948, according to historical data on annual mean surface temperature, the annual average temperature over land has increased by approximately 1.7°C in Canada – roughly double the global average level of warming. In 2018, the results of a Climate Change Adaptation Standards Inventory Analysis conducted by CSA identified multiple standards relevant to masonry cavity-wall design as priorities for adaptation to climate change (Sparling et al. 2021). The term "cavity-wall" herein refers to a masonry structure with a double wall separated by an air gap and connected by metal ties. As shown in Figure 1, the inner wall constitutes the loadbearing masonry backup (typically concrete blocks) and the outer veneer (typically clay bricks) transmits external loads to the supporting structure while also acting as a weather-resistant barrier. Metal connectors, or "ties", are anchored to the walls to provide the mechanical connection between the two masonry wythes. Other key components of this system include shelf-angles, movement joints, and insulation. Distress in cavity-walls is often attributed to differential movements governed by concrete masonry drying shrinkage and moisture expansion of the outer clay brick veneer. These unwanted loads are projected to increase with climate change, and may lead to cracks in the outer clay brick veneer, compromising durability. Test data are, however, still scarce, and only refer to the hygrothermal properties of individual blocks/bricks rather than mortared masonry assemblies.

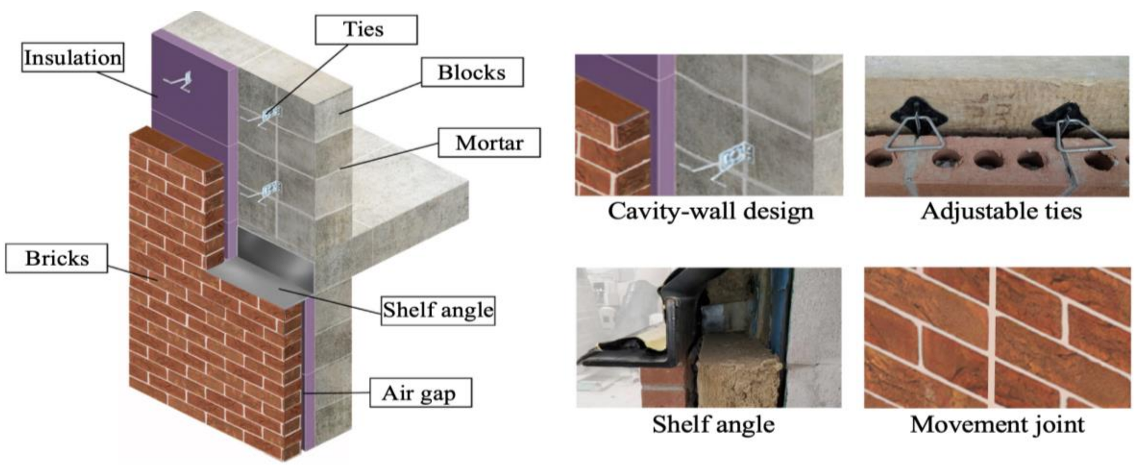

Figure 1. Typical construction details of masonry cavity-wall

To inform future masonry designs and meet more stringent sustainability goals in a changing climate, several research efforts have recently been made to develop sophisticated simulation methods and durability guidelines (Vandemeulebroucke et al. 2021, Lacasse, et al. 2018). To substantiate the implementation of climate-adapted designs in building codes, however, a solid foundation of experimental data is needed, but not yet available. Currently, test data on volumetric changes due to moisture variations of masonry assemblies, a common source of differential movements due to clay brick expansion and simultaneous concrete block shrinkage and a contributing factor for masonry cracking (leading to reduced durability), are limited. Available data on blocks and mortar specimens, were either collected decades ago or originate from tests carried out in-situ on old structures (Kuzik et al. 1999, Shrive et al. 1997, Drysdale and Khattab 1995, Lohonyai et al. 2015).

Conducted in the context of a larger research program on climate change masonry design adaptation led by McGill struct-lab and 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 study focuses on the development and execution of innovative drying shrinkage tests on mortar, concrete masonry blocks and assemblies, the first of its kind ever conducted in Canada. This study will enable, in the next phase of this research project, the development of climate change-adapted design requirements for movement joints and shelf-angles in the case of wider cavities, vital for ensuring adequate thermal performance with increasingly stringent energy codes for buildings.

In this paper, to gather new insights on the moisture-induced shrinkage of modern mortar and concrete blocks, as well as to quantitatively describe the mechanical interaction between blocks and mortar, a novel two-step testing method for unconstrained mortared concrete masonry prisms is presented and preliminary results discussed. The two-step procedure combines two approaches originally conceived for concrete blocks, i.e., one developed by Drysdale and Khattab (1995) (slow method, step 1) and that outlined in ASTM C426 (fast method, step 2). The combination of these two procedures allows for shrinkage-time curves to be inferred over an adequate period of time for numerical analyses purposes in step 1, while also allowing the determination, in step 2, of the ultimate drying shrinkage of the specimens – needed for most design applications. The findings of these experiments will have an immediate impact, adding ready-to-use and more reliable estimates of linear drying shrinkage – vital for ensuring the durability of modern masonry – to the guidance available in the CSA A165.1-14 (concrete masonry units) standard.

2 Previous Canadian data from laboratory and onsite experiments

To provide a point of comparison for the drying shrinkage data, this section references and discusses previous Canadian data from laboratory and onsite experiments. These previous studies neglected the effect of mortar joints, however this effect must be accounted for to enable the use of simplified numerical modelling techniques e.g., those based on material homogenization. By considering the mechanical interaction between blocks and mortar, it is intended to get insight into the moisture-induced shrinking of modern concrete masonry assemblies. The following two Canadian studies, which employ similar methods to those selected for our research as described below, were used for reference:

- *Drysdale and Khattab (1995)* – twenty-four hollow 20 cm concrete block tests were performed over a period of two and a half months, roughly 80 days, in the McMaster University laboratory. Researchers followed the ASTM C426 guidelines (1994 edition) to measure the drying shrinkage of individual blocks along the long horizontal axis using four strain indicators on each of the two face shells. The blocks were first immersed in water for 3 days at room temperature. Strain readings and weights were recorded after draining the specimen to saturated surface dry condition. The blocks were air-dried in a humidity-and temperature-controlled room during which shrinkage and weight measurements were taken at regular intervals. After 2½ months, the blocks reached a stabilized shrinkage value and weight. Final readings and weights were then recorded by oven-drying the blocks.

- *Kuzik et al. (1999)* – five 20 cm hollow concrete blocks were tested following very closely the procedure in Drysdale and Khattab (1995) at 22 °C and a 'very low' relative humidity (exact value not reported). These researchers also presented the results of the differential movement in cavity-walls of a full-scale 21-meter-tall clock tower built in Edmonton, Alberta, and exposed to the outdoor environment. Differential movements between the block and brick wythes were measured using DEMEC points for each wall. In parallel with the field test monitoring, 5 concrete blocks were taken from the clock tower to the lab for monitoring. Similar to Drysdale and Khattab (1995), these specimens were left in a room with controlled temperature and relative humidity to measure the dimensional changes. Interestingly, blocks constructed in the lab and taken from the field exhibited analogous shrinkage behaviour, with only marginal differences. In this paper, therefore, only the results obtained from lab-constructed specimens were considered for comparison.

In Figure 2a and Figure 2b, the specimens tested by Drysdale and Khattab (1995) and Kuzik et al. (1999) are depicted and the experimental results are plotted. Drysdale and Khattab (1995) demonstrated that shrinkage is hardly influenced by drying concrete blocks to a specified moisture content, expressed as a percentage of total absorption. Shrinkage and water content have a better correlation when expressed as an absolute value. Kuzik et al. (1999) reported the average shrinkage value in the final data reading obtained on day 1310, however the shrinkage achieved at day 631 was consistent with the maximum value recommended in the CSA S304.1-94 provisions.

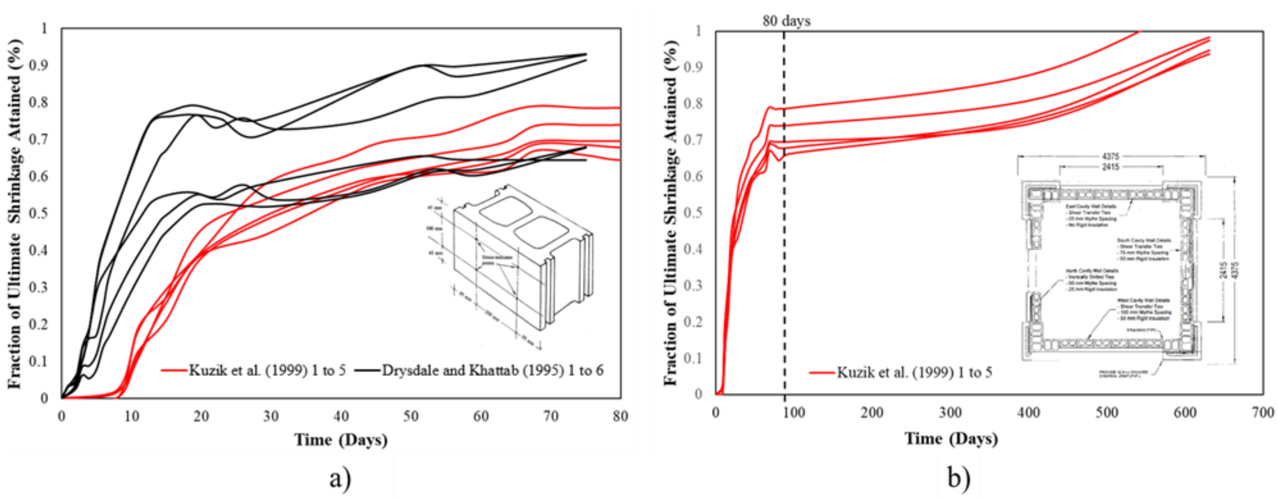

Figure 2. a) Experimental set-up used and results from Drysdale and Khattab (1995) and Kuzik et al. (1999) up to day 80, b) Khattab (1995) and Kuzik et al. (1999) up to day 631

The block wythe shrinkage in the cavity-walls reported by Kuzik et al. (1999) was also in agreement with the shrinkage determined in the laboratory experiments. Such data analysis was crucial for selecting an optimal duration of the long-term drying shrinkage to be considered in step

1 of the proposed procedure that enables the inference of meaningful results in a reasonable timeframe. Pervious experiments, including the one conducted by Kuzik et al. (1999), ran for more than three and a half years – a timeframe seldom compatible with industry and applied research priorities. Notably, graphs from Figure 2b and Figure 2c both display the shrinkage percentages plateau at roughly 80 days, and a gradual slow increase to the ultimate shrinkage strain over hundreds of days. It is therefore plausible to select 80 days (84 days, or 12 weeks, were chosen in this study for the sake of simplicity) – i.e. the period with the largest gradient of linear shrinkage after which deformation becomes negligible. However, the data from laboratory tests referenced above on the shrinkage behavior pertain to concrete blocks only. So far, it is still unknown whether the presence of mortar joints has an effect on the masonry assembly behaviour. Thus, the laboratory data currently available, in addition to being obsolete and having been inferred decades ago, might also not reflect the actual moisture response of modern masonry.

3 Proposal for a new 2-step drying shrinkage laboratory experiment

3.1 Experimental framework and testing infrastructure

The aim of this work is to infer preliminary time vs strain drying shrinkage curves for concrete blocks, mortar specimens and masonry assemblies that can be used for numerical analysis and design. The proposed 2-step testing is applied to unrestrained concrete masonry prisms and blocks and consists of a mixed procedure combining two approaches originally conceived for blocks, i.e., the slow method (step 1, modified from Drysdale and Khattab (1995)) and the ASTM C426 rapid method (step 2). ASTM C596 was used for testing mortar samples. Below, a brief description of the procedures implemented is given. Using standard hollow concrete blocks (19 x 39 x 19 cm) with Type-S (CSA A179-14) preblended commercial mortar on the face shell areas, 2 doublets and 2 triplets (no head-joints, 28-day curing) were tested alongside 4 blocks and 5 mortar specimens. To summarize the implementation of step 1 in our tests, the readers are referred to the following bulleted list:

1. an initial treatment to reach saturated surface dry moisture conditions (see ASTM C426) and measurements (strain and weight) was performed on all specimen,
2. then, prisms were left to dry at a temperature of 22 ± 1ºC and relative humidity level of 42 ± 4% in the lab for 84 days,
3. mortar specimens were tested following the procedure outlined in ASTM C596, with additional measurements taken every 7 days for the full 84-day procedure,
4. deformations were monitored weekly using a DEMEC system.

The procedure for 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. prisms were placed in a drying oven at a temperature of 50 ± 0.9ºC and a relative humidity of 17 ± 2%, until the changes in weight and shrinkage strain are negligible.
2. in this step, all strain gauge measurements were corrected based on temperatures and standard reference bar readings, as per section 8 of ASTM C426-99. [note that in this paper,

due to time constraints, we could not reach 84 full days of testing; data and graphs for step 2 will be updated after the first round of reviews.]

The experimental infrastructure used equipment and apparatus that were in accordance with the ASTM C426 standard. A multi-length strain gauge set with a sensitivity of 0.00254 mm was used to measure strains as seen in Figure 3a. Gauge plugs, specifically DEMEC plugs (9.525 mm in diameter and 12.7 mm in thickness), were bonded with epoxy onto the specimens' side surface to facilitate the drying shrinkage readings. Figure 3b displays the immersion tank in which the blocks and masonry prisms were submerged in water maintained at 23 ± 1.1ºC. For air-drying specimens, a refrigerator with controlled temperature (22 ± 1 ºC) and relative humidity (42 ± 4%) was used as depicted in Figure 3c. Figure 3d shows the airtight drying oven with a constant uniform temperature of 50 ± 0.9ºC and a relative humidity of 17 ± 2% used.

a) b) c) d)

Figure 3. Testing apparatus: a) strain gauge, b) immersion tank, c) fridge, d) airtight drying oven

The specimens retrieved from the drying oven were cooled to a temperature of 23 ± 1.1ºC in a cooling chamber in between the measurements. The drying shrinkage tests were carried out in the Jamieson Structures Laboratory at McGill University using the abovementioned equipment and apparatus. To correlate block and masonry results with joint shrinkage, analogous tests were performed on mortar samples as well.

4 Preliminary experimental results and discussion

4.1 Step 1

Preliminary data on drying shrinkage of concrete masonry prisms, doublets, triplets, and mortar were collected over 10 weeks. All the drying shrinkage results are normalized with respect to the initial length between gauge plugs at the first measurement and are expressed in the form of normalized shrinkage strain (mm/m) over time (days). Figure 4 below shows the shrinkage of 5 mortar specimens, from which it can be gathered that all 5 mortar specimens followed analogous drying shrinkage trends over the first 42 days of measurements – also compatible with findings obtained by other researchers using analogous methods. It is noted that technical difficulties in terms of reading were faced while using the comparator device after day 42; after that point, data may not be reliable.

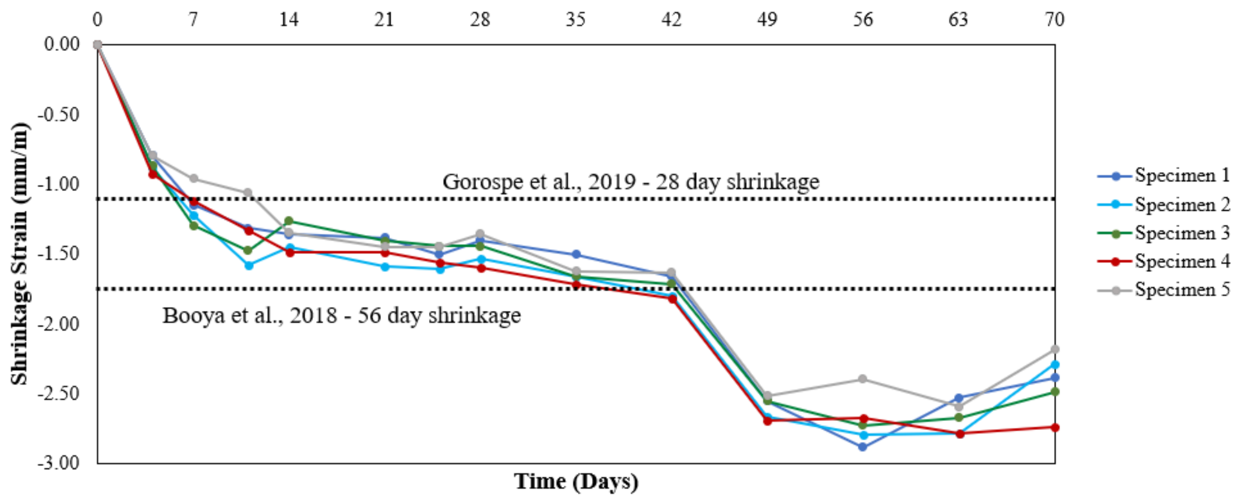

Figure 4. Shrinkage of ASTM C596 mortar specimens versus time, with benchmarks of results from Booya et al. (2018) and Gorospe et al. (2019)

Weekly air-drying shrinkage measurements were also taken over 70 days for 2 single concrete blocks, 2 doublets, and 2 triplets. Horizontal shrinkage results are shown in Figure 5a. Vertical shrinkage values, not reported here for space constraints, followed similar trends. Interestingly, these first results seem to show little differences between block and masonry shrinkage trends.

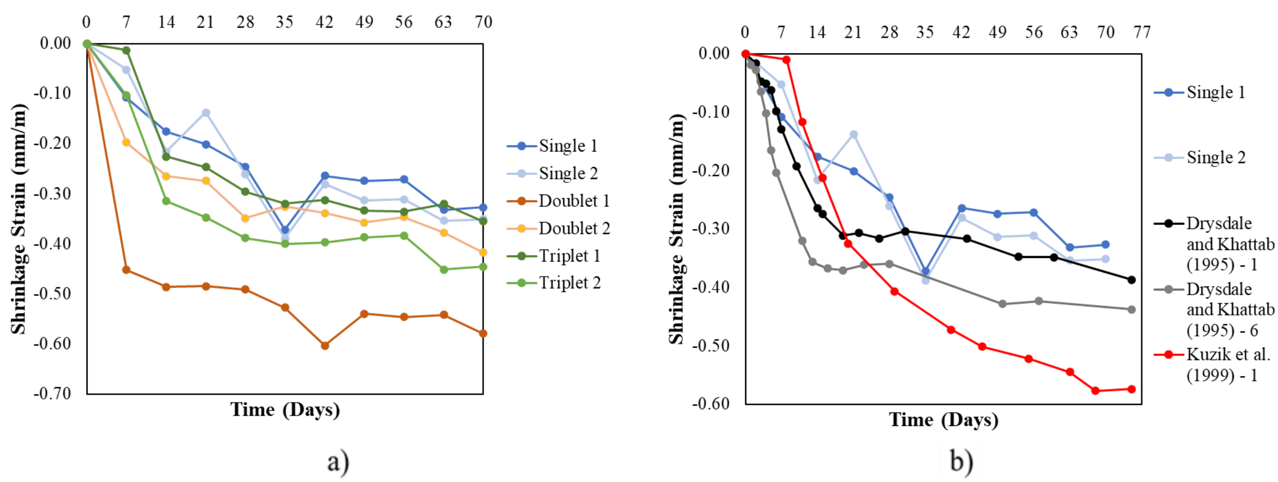

Figure 5. a) Average horizontal shrinkage for each specimen versus time – across the long dimension of faces, b) average horizontal shrinkage for units vs past studies (key data only)

Of interest is also the good agreement between the outcomes of this study for single blocks and the previous shrinkage data inferred by Drysdale and Khattab (1995) and Kuzik et al. (1999), see Figure 5b. Despite some dissimilarities, the plots for each block seem to be following a general trend that is alike. However, the average shrinkage determined in this study is lower than that reported by Drysdale and Khattab (1995) and Kuzik et al. (1999). This may be explained in part by the fact that the relative humidity of the refrigerator in this study was slightly higher as it takes time for it to stabilize when the saturated blocks are put in. It is noted that these results are preliminary and further samples must be tested to determine statistical significance.

4.2 Step 2

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 Figure 6a.

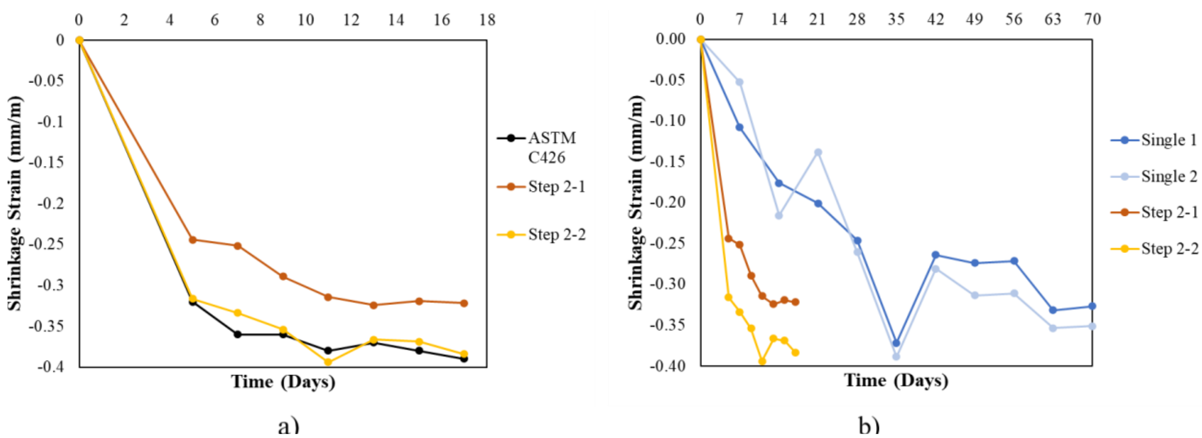

Figure 6. a) Average horizontal shrinkage of single units vs ASTM C426 sample data, b) average horizontal shrinkage of single units in comparison to step 1 single units

The measurements were taken every 5 days until day 17 when negligible weight changes were achieved, as per ASTM C426. The shrinkage results obtained for 2 single blocks are compared with reference curves from ASTM C426 in Figure 6a. Both the blocks are shrinking in a similar fashion with respect to the ASTM standard. A comparison between the results obtained in step 1 and step 2 (fast method only) is plotted in Figure 6b.

From Figure 6b, it can be observed that the slow (step 1) and fast (step 2) testing methods reach very similar ultimate shrinkage values at day 70, albeit, as expected, with different slopes. However, the peak registered around day 35 in step 1 might be due to measurement errors; this aspect is currently under investigation to ensure it is resolved in future tests. Based on the observed trend for step 1, it expected that a better match with step 2 will be obtained after day 84, i.e., the selected duration of 2-step testing. Data for step 2 on masonry prisms (i.e., doublets and triplets) and blocks previously tested in step 1 are currently being collected and will be presented at the conference.

5 Conclusions

Standards related to cavity-wall design have been identified as priorities for climate change adaptation provisions, as outlined in recent technical reports from CSA Group. In this study, as part of a larger research program on climate change masonry design adaptation led by McGill struct-lab and sponsored by various industry and institutional partners, the linear drying shrinkage response of concrete masonry blocks, assemblies and mortar samples are investigated. To this end, a new 2-step drying shrinkage procedure is proposed which enables to obtain, in a reasonable timeframe, both strain vs time curves needed for numerical modelling and ultimate values required for practical design. Preliminary results, show that:

- The linear drying shrinkage behaviour inferred experimentally by previous researchers in 1995 and 1999, seems to be in good agreement with those obtained in this study on modern blocks.
- Mortar joints seem to have limited effect on the shrinkage behaviour of masonry assemblies. Doublets and triplets (no vertical joints) exhibited analogous shrinkage performance when comparing normalized results to those of individual blocks.
- Comparing the results for step 2 (accelerated drying shrinkage test) for individual concrete blocks not previously subjected to step 1 (slow drying shrinkage test) to those inferred from step 1 alone, it can be gathered that for the specimens tested, the selected duration of 84 days is reasonable as ultimate values are similar.

Further testing is currently ongoing at McGill University. Updated and more comprehensive results will be shared with both research and professional communities as they become available.

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