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Stability Assessment of Early-Age Masonry Walls Without a Temporary Bracing

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Abstract

Masonry construction is widely used in the building industry due to its cost-effectiveness and durability. However, the structural properties of early-age masonry are not well-documented, making it difficult to establish reliable design parameters during the initial curing stages. Current Canadian codes primarily address fully-cured masonry structures, with limited guidance on temporary bracing requirements for early-age masonry walls under wind loads. This paper presents an assessment of early-age masonry properties and proposes a methodology for designing masonry walls without temporary bracing. A comprehensive literature review highlights existing research on masonry behavior, focusing on out-of-plane loading conditions and the role of wind-induced pressures during construction. The study employs experimental data of masonry wall tests and numerical modeling result from the recent literature to assess flexural tensile strength development at different curing times. Using a wind velocity-based approach, this research evaluates the stability of masonry walls under varying wind speeds without applying reliability-based load factors. The study introduces a sawtooth model to conservatively estimate masonry tensile strength over key construction stages, ensuring safe design assumptions. The results demonstrate that early-age masonry gains significant strength within the first seven days, allowing for the possibility of eliminating temporary bracing in specific conditions. By establishing thresholds for lateral stability and structural integrity, this research provides practical design guidelines for engineers and contractors, enhancing construction efficiency and safety.

Keywords

Early-age mortar, early-age masonry, out-of-plane strength, monitoring of masonry walls, curing time, wind load, temporary bracing.

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INTRODUCTION

Masonry, a widely used and cost-effective structural material, has remained relevant in various construction applications in recent decades [1]. However, due to its heterogeneous nature, understanding the properties of masonry assemblies is complex. These properties depend on several factors, including the materials used—such as concrete blocks, mortar, and the bond between them—as well as the masonry's age [2]. Although international codes provide guidelines to ensure the safe design of fully-cured masonry structures to withstand out-of-plane loads [3], [4], [5], there is limited guidance in Canada regarding the required loads and material resistances for designing temporary bracing systems during construction [4], [6]. While CSA A371 includes relevant information in an informative annex, these details are non-mandatory and offer only a general overview [7]. As a result, designers often rely on engineering judgment, material test data (rather than assembly test data), and past experiences to estimate the properties of freshly constructed masonry when designing temporary bracing systems for masonry walls under construction. This paper aims to provide a guideline for designers to ensure the safety of masonry construction without the need for temporary bracing.

Numerous studies have investigated the properties of masonry walls, primarily focusing on the in-plane and out-of-plane behavior of fully-cured masonry [8], [9], [10]. One commonly used method for applying out-of-plane distributed loads in experimental studies is the airbag system [11], [12]. This technique involves placing an airbag behind the wall and inflating it to apply pressure during testing [13], [14]. In this study, the airbag system was utilized to simulate wind-induced loads on early-age masonry walls. Notably, Abdulla et al. (2017) developed a finite element (FE) model to analyze masonry walls subjected to monotonic in-plane, out-of-plane, and cyclic loads. Their model was validated against experimental data, and ABAQUS was used to evaluate crack propagation in the samples [15]. Several studies [16], [17], [18], [19] have reviewed both experimental and numerical research on the out-of-plane behavior of infilled masonry walls. For example, Pradhan et al. (2021) conducted a detailed literature review on the seismic out-of-plane response of unreinforced masonry infill walls. However, they did not extensively discuss infilled or confined walls, as they are less relevant to modern Canadian construction practices.

Despite the extensive research on fully-cured masonry, limited studies have explored the properties of early-age masonry. For instance, Dunphy et al. (2021) examined the tensile properties of early-age masonry assemblages, specifically two-block concrete masonry prisms. They developed a novel testing setup to assess the tensile strength of masonry prisms through both experimental and numerical investigations. These models established relationships between tensile strength and curing time, as well as modulus of elasticity (E) and curing time [20]. In a follow-up study [2], additional tensile tests were conducted on masonry prisms to reduce data uncertainties and cover a broader range of curing time intervals. Their research also investigated the tensile properties of fresh mortar within the first seven days after construction, ultimately proposing two models for predicting the tensile strength of fresh mortar as a function of curing time. Later, the authors examined the compressive properties of early-age mortar and masonry prisms [21], [22]. Several experimental studies were conducted to evaluate the compressive strength of cubic mortar samples and masonry prisms, followed by developing a numerical model to describe the relationship between the compressive strength of early-age masonry and curing time.

Subsequently, an extensive experimental study was carried out to investigate the properties and behavior of early-age masonry walls, equipping designers and masonry contractors with essential knowledge for designing temporary bracing systems. More than 60 full-scale early-age masonry walls were tested at different curing times, and numerical models were created to quantify masonry wall properties over time [23]. Additionally, finite element models were developed to predict the behavior of early-age masonry walls under lateral loads, addressing curing times not included in the experimental study. This research serves as one of the primary references in the literature on early-age masonry structures and has been extensively used as a foundation for the present study.

The reviewed literature highlights a significant gap in research concerning the temporary bracing of early-age masonry walls. These walls are particularly vulnerable to out-of-plane loads, such as wind-induced forces, making temporary bracing essential during construction. Recent studies [2], [21], [23] have examined the properties of early-age masonry, including mortar, masonry prisms, and masonry walls. This paper aims to provide a guideline for designing masonry walls without temporary bracing by utilizing the masonry properties established in previous research. The findings of this study will offer reliable data for the effective design of early-age unreinforced masonry walls.

ANALYSIS METHODOLOGY AND BRACING DESIGN ASSUMPTIONS

In this section, fundamental concepts, limitations, and assumptions used in the assessment and analysis of this study are mentioned.

Design loads

The structural design and construction of masonry in Canada are governed primarily by two standards, including CSA S304 and CSA A371. CSA S304 titled "Design of Masonry Structures" provides comprehensive guidelines for the structural design of masonry elements, including walls, beams, and columns, under various loads. It includes provisions for both strength and serviceability requirements and incorporates the principles of Limit States Design (LSD). CSA A371 titled "Masonry Construction for Buildings" focuses on the construction practices for masonry structures, ensuring proper workmanship, material selection, and construction techniques. While CSA S304 governs the design, CSA A371 addresses quality control and execution on-site.

The Canadian design standards, including CSA S304, follow the LSD approach. The LSD ensures that structures meet both:

- Ultimate Limit State (ULS): For safety under maximum loads, such as wind, earthquake, or live loads.
- Serviceability Limit State (SLS): For functionality under normal conditions, addressing deflections, vibrations, and cracking.

The LSD approach uses factored loads and factored resistances. Factored loads are loads amplified to account for uncertainties and worst-case scenarios. Factored resistances mean that material strengths are reduced with safety factors to account for variability in properties and construction quality. For load determination, LSD relies on NBC (National Building Code of Canada), such as the calculation of wind load.

The NBC specifies two primary approaches for determining wind loads:

- Factored Load Approach where wind velocity data is factored into a reliability-based analysis to produce design pressures, which are then applied to masonry structures. This approach focuses on adapting wind velocity data to ultimate and serviceability limit states while adhering to the NBC's climatic data and load combinations.
- Wind Velocity Approach which involves direct on-site measurement or estimation of wind velocity and converting it into equivalent pressure for use in design.

In the Factored Load Approach, wind loads are calculated using the NBC's reliability-based framework, which considers statistical variations in wind speeds and material properties. The design wind pressure is determined using Eq. (1).

$$(1)\ P = I_w q C_e C_t C_g C_p$$

Where p is specified external pressure acting statically and in a direction normal to the surface, considered positive when the pressure acts towards the surface and negative when it acts away from the surface (in kPa). I_w is an importance factor for wind load. q is reference velocity pressure (in kPa), which can be calculated based on Eq. (2), Where V is wind speed in m/s. C_e and C_t are exposure factor and topographic factor, respectively. C_g and C_p are the gust effect factor and external pressure coefficient, respectively.

$$(2)\ q = 0.00064645V^2$$

The wind velocity approach uses direct wind velocity measurements taken from site-specific conditions where a wind speed can be approximated as pressure. The measured speed is converted into equivalent wind pressure using Eq. (2). In this research, the wind velocity approach was used to calculate the wind load as the focus of this research is the construction stage and corresponding loads during construction, so there are no applicable NBC clauses here. Because of that, the actual wind speed and the corresponding wind load was used in this research, and there are no reliability-based factors applied since those are intended to account for very large timeframes. In this study, five different wind speeds of 20, 40, 60, 80, and 100 km/hr were considered for parametric study and assessment of temporary bracing for early-age masonry walls, as presented in Table 1. These wind speeds were selected by engineering judgment to address a wide range of wind speeds. Based on the Environment Canada dataset, the range of maximum hourly wind speed during the last 20 years for London, Toronto, Saskatoon, and Montreal were 56-93 km/hr, 37-72 km/hr, 72-105 km/hr, and 55-83 km/hr, respectively. Also, the range of median wind speed during the last 20 years for London, Toronto, Saskatoon, and Montreal were 10-17 km/hr, 10-14 km/hr, 14-17 km/hr, and 13-17 km/hr, respectively.

Table 1: Selected Wind Speeds and Corresponding Wind Reference Velocity Pressure

V		***q* (kPa)**
(Km/hr)	**(m/s)**	
20	5.55	0.02
40	11.11	0.08
60	16.67	0.18
80	22.22	0.32
100	27.78	0.50

In this research, no load factors were considered as it focuses on construction loads and there are no applicable NBC clauses. That is why only the wind speed and actual/average masonry properties were considered in the assessment, and there are no reliability-based factors applied since those are intended to account for very large timeframes.

Assumptions

In this section, all assumptions used for the assessment and design of temporary bracing in this guideline are presented below in detail.

- Masonry properties: Abasi et al. (2024) assessed the flexural tensile strength (f_{mt}) of unreinforced hollow concrete block masonry walls by conducting more than 60 full-scale wall experiments. They tested several masonry walls with two boundary conditions, including free-standing (cantilever) walls and simply-supported walls. As the results of these, two different groups of experiments resulted in the same properties, the results of cantilever wall testing were used in this paper. In Fig. 1, the f_{mt} of early-age masonry walls against t is shown.

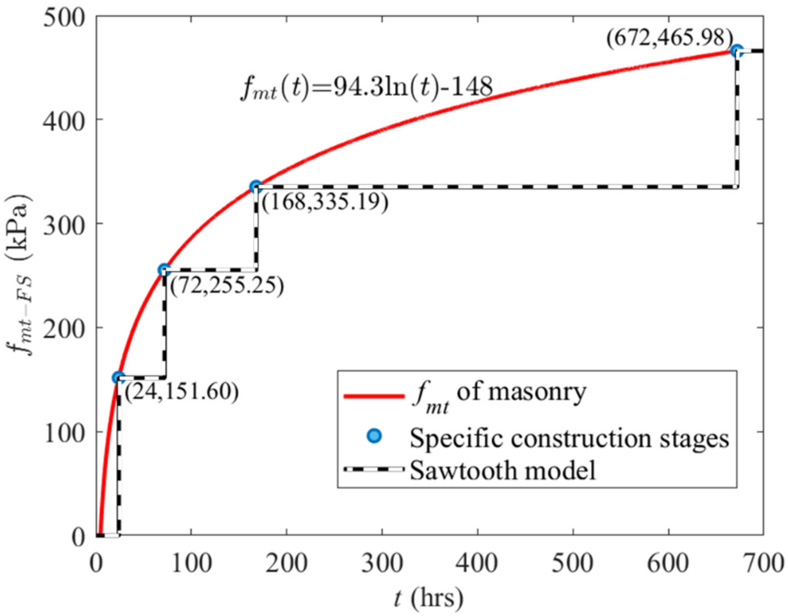

Figure 1: f_{mt} of Early-Age Masonry Walls against t

As illustrated in Fig. 1, masonry exhibited significant strength gains in the initial curing period, reaching 32%, 55%, and 72% of its 28-day ultimate strength at 1, 3, and 7 days, respectively. Based on these substantial strength increases and engineering judgment, the construction process was divided into four distinct stages: 0-1 day, 1-3 days, 3-7 days, and 7-28 days. 1, 3, and 7 days milestones were identified as critical construction stages, as depicted in Fig. 1. To ensure a conservative design approach, a sawtooth model was developed, assigning the minimum fmt value within each stage to the entire stage duration. For instance, the design of temporary bracing for the 3-7 days stage would utilize the fmt value corresponding to 3 days of curing, as shown in Fig. 1.

- Masonry units: The normal weight units (type A) with a density (ρ) of 2,100 kg/m^3 have been considered in this study, based on the Canadian masonry standards. The dimensions of the units are 190×190×390 mm with a solid content of 56%, which means that the weight of a block is equal to 16.56 kg. A ρ of 2,300 kg/m^3 was considered for mortar. The mortar was applied exclusively to the face shells of the blocks, with joints assumed to have a width of 4 cm and a thickness of 1 cm on both vertical and horizontal face shells. Therefore, ρ of the masonry is equal to 1103.75 kg/m^3.
- Design purpose: As the focus of this research is life safety, the lateral collapse and blowing over the wall was considered as the threshold of the assessment.

DESIGN OF MASONRY WITHOUT EXTERNAL BRACING

In this section, the design of unsupported masonry is assessed. The design of unsupported masonry structures, such as cantilevered walls, presents unique challenges because of their inherent slenderness and susceptibility to lateral loads, particularly wind loads. To ensure the structural integrity of such structures, it is essential to consider the time-dependent strength gain of masonry, which significantly influences its load-carrying capacity. This will look at basically cantilevered wall design, how high the designer can go for different wind speeds at various ages of masonry.

To account for the time-varying strength of masonry, a stage-based design approach is proposed. This approach involves dividing the construction process into distinct stages, each characterized by a specific maturity level of the masonry. By considering the strength properties at each stage, a more accurate assessment of the structural performance can be achieved. As discussed in Section 2.2, the construction process was divided into four distinct stages 0-1 day, 1-3 days, 3-7 days, and 7-28 days. By adopting a stage-based design approach, engineers can account for the time-dependent strength gain of masonry and design safer unsupported masonry structures.

The stage-based design approach depends on wind load, masonry strength, masonry self-weight, masonry dimensions, and construction sequences. Masonry strength and construction stages were discussed in Section 2.2. The wind load should be calculated based on the monitored or expected wind speed in the construction site and Eq. (2). As mentioned in Section 2.2, the life safety requirements, which mean the lateral collapse and blowing over of the wall, were considered. Therefore, the maximum height of masonry without external bracing should be equal to the maximum height calculated based on the over-turning of the wall with zero strength of mortar and tensile failure of the mortar joints in masonry.

Eq. (3) can be used to calculate the overturning resistance, where w is the weight of the masonry wall in N. t_b, h, and L are the thickness of the wall, weight of the wall, and length of the wall in m, respectively. P is the lateral load subjected to the wall in N/m^2. Eq. (3) should be modified to calculate the maximum height of the wall based on the lateral load, according to the overturning resistance as shown in Eq. (4). Eq. (4) is used for calculation and assessment in the following sections in this study regarding the fresh masonry walls with zero mortar strength.

$$(3)\quad \frac{wt_b}{2} = \frac{ph^2L}{2}$$

$$(4)\quad h = \frac{9.81\rho t_b^2}{p}$$

Eq. (5) shows the relationship between the f_{mt} and masonry properties and lateral load. Where P_f is the axial load applied on the walls, including the weight of the wall, M_f represents the moment applied on the section due to the out-of-plane load, S_e is the section modulus, and A_e is the effective cross-sectional area. Based on the dimensions of the walls and the properties of the material presented above, P_f can be calculated. Moreover, M_f can be calculated according to the wind load. Eq. (6) is the revised representation of Eq. (5), which should be used to calculate the maximum allowable height of masonry wall based on f_{mt} of masonry.

$$(5)\quad f_{mt} = \frac{M_f}{S_e} - \frac{P_f}{A_e}$$

$$(6)\quad \frac{pL}{2S_e}h^2 - \frac{9.81\rho t_b L}{A_e}h - f_{mt} = 0$$

For all construction stages, both Eq. (4) and (6) were used, and the maximum of the calculated height is reported in Fig. 2. Fig. 2 shows the maximum height of the wall can be constructed based on the wind speed in the construction site and the construction stage. In Fig. 2, a 0-day plot was calculated based on the overturning resistance of the wall with zero strength of mortar (see Eq. (4)). However, the plots regarding the rest of the construction stages were calculated based on Eq. (6).

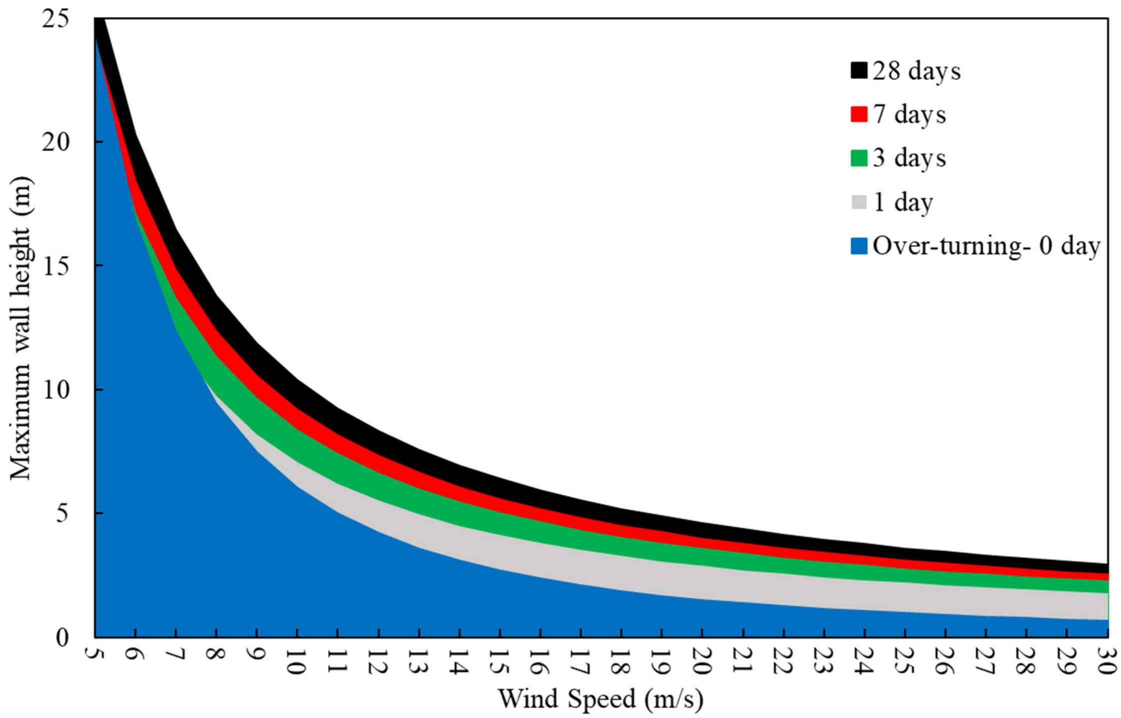

Figure 2: f_{mt} of Early-Age Masonry Walls against t

Fig. 2 illustrates the construction limitations for masonry walls under varying wind speeds. For example, in a construction site with a wind speed of 20 m/s, the wall height can be constructed up to 1.5 m on the first day. Construction should then pause and resume after 24 hours, allowing the wall height to reach 2.9 m. Subsequently, the construction may proceed to heights of 3.5 m, 4.0 m, and 4.6 m at the 3-day, 7-day, and 28-day stages, respectively. It should be noted that continued construction at each stage must be limited by the 0-day construction limitations, as the additional construction at each stage is freshly laid and exhibits zero strength. This implies that the height of construction resumption at each stage should be determined as the minimum of the wall height calculated based on the mortar strength at that stage and the allowable construction height as per the 0-day or overturning calculations. Accordingly, the construction limitations at the 1-day and 3-day stages for wind speeds exceeding 22 m/s and 27 m/s, respectively, require revision, as the resumed construction heights at these stages may exceed the allowable height determined for the 0-day stage.

As illustrated in Fig. 2, for instance, designing a masonry wall to resist a wind speed of 30 m/s requires limiting the allowable wall heights at the 0-day and 1-day stages to 0.7 m and 1.8 m, respectively. However, under this design approach, 1.1 m of the upper portion of the wall would have zero strength, as it falls within the first 24 hours of construction for that specific portion. To mitigate this issue, the construction height for the 0-day stage should remain restricted to 0.7 m, while the 1-day limitations should not exceed twice the 0-day limitations for wind speeds greater than 22 m/s. Consequently, the design limitations must be revised as shown in Fig. 3.

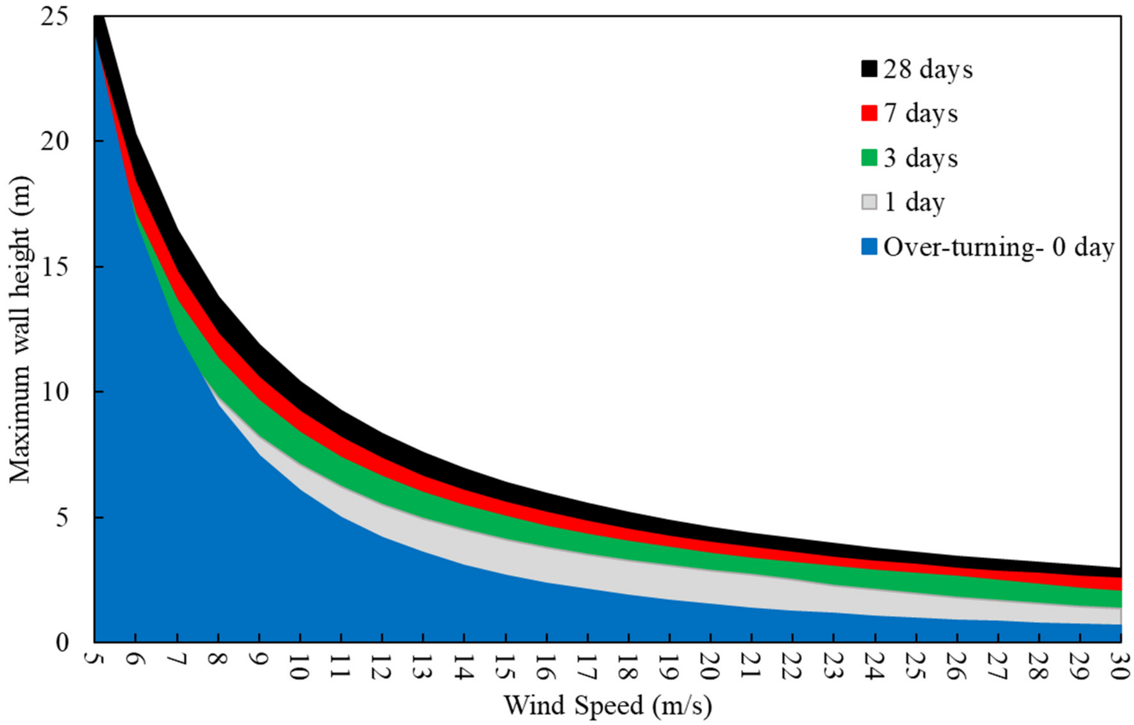

Figure 3: Revised f_{mt} of Early-Age Masonry Walls against t

According to Fig. 3, a construction schedule can be developed for construction sites with different wind speeds as presented in Table 2. As shown in Table 2, for a construction site with a wind speed of 16.67 m/s, the unsupported masonry wall can be constructed up to 2.2 m within the first construction stage. Construction should then pause and resume after 24 hours, allowing the wall height to reach 3.6 m. Subsequently, the construction may proceed to heights of 4.4 m, 4.9 m, and 5.6 m at 3-day, 7-day, and 28-day stages, respectively. As illustrated in Fig. 3, for wind speeds below 8 m/s, certain construction stages must be skipped, and construction cannot be resumed as the flexural tensile strength of the masonry wall does not provide sufficient resistance to exceed the overturning strength of the wall. For instance, in a construction site with wind speed of 5.55 m/s, the wall can be constructed up to 19.6 m during the first stage of construction. Then the construction should pause until 7 days and resume up to 20.6 m. In this case, the construction cannot resume at 1 day and 3 days stages.

Table 2: The Maximum Height of Construction of Unsupported Masonry in Different Construction Stages

V		Maximum wall height at different construction stages (m)				
(Km/hr)	**(m/s)**	**0 day**	**1 day**	**3 days**	**7 days**	**28 days**
20	5.55	19.6	-	-	20.6	22.6
40	11.11	4.8	6.1	7.2	8.0	9.1
60	16.67	2.2	3.6	4.4	4.9	5.6
80	22.22	1.2	2.5	3.2	3.6	4.1
100	27.78	0.7	1.5	2.3	2.7	3.2

CONCLUSIONS

This study addresses a critical gap in masonry construction by assessing the structural behavior of early-age masonry walls under wind loads. The findings indicate that masonry walls gain substantial flexural tensile strength in the first week of curing, reducing the need for temporary bracing in certain conditions. A conservative sawtooth model was introduced to guide the design process, ensuring safety while optimizing construction practices.

By employing a wind velocity-based approach, this research provides a practical methodology for evaluating construction-stage wind loads without relying on reliability-based factors. The results demonstrate that walls designed with appropriate material properties and engineering judgment can safely withstand wind loads without external bracing, improving efficiency and reducing construction costs. The proposed guidelines contribute to safer masonry construction practices and offer valuable insights for engineers, designers, and contractors involved in early-age masonry projects.

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