15th Canadian Masonry Symposium
Ottawa, Canada
June 2-5, 2025

Impact of Grout on Axial Compression Behaviour of Interlocking Dry-Stack Concrete Masonry Wallettes

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ABSTRACT

Interlocking dry-stack masonry has shown to accelerate the wall construction compared to conventional mortared masonry, however the widespread adaptation of interlocking dry-stack masonry is hindered due to the lack of design provisions. The compressive strength and stress-strain behaviour of dry-stack masonry should be known to appropriately design such walling systems. In this study, an experimental campaign was conducted to understand the compressive behaviour of dry-stack concrete masonry. To this end, five different interlocking dry-stack concrete blocks were acquired from across Australia. These blocks were used to construct either four- or five-course high, dry-stack concrete masonry wallettes with and without core fill grouting. In total, 80 wallettes were tested with strength of core-filled grout being varied from 20 MPa to 40 MPa. The results have been analysed in terms of failure patterns, compressive strength, and deformation characteristics. The results showed that the grouted dry-stack concrete masonry wallettes exhibited similar failure patterns as those of conventional grouted concrete masonry, which has mortar joints. The average axial compression strengths of tested grouted dry-stack wallettes ranged between 9.6 and 18.6 MPa, whereas the ungrouted wallettes varied from 4.8 to 11.8 MPa. The grouted dry-stack concrete masonry demonstrated better performance than the ungrouted dry-stack concrete masonry in terms of stiffness and load carrying capacity. The grouted wallettes exhibited higher strength, deformation capacity, and elastic moduli with increasing grout strength.

KEYWORDS

Dry-stack masonry, Concrete blocks, Axial compression behaviour, Grout, Stress-strain behaviour

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INTRODUCTION

The global proliferation for buildings has resulted the integration of rapid, economical and less labour-intensive construction techniques. This phenomenon also demands altering conventional methods of masonry construction, which is encumbered by exacting workmanship prerequisites and constraints on construction pace [1, 2]. In this context, the adaptation of interlocking concrete blocks to develop dry-stack masonry, accelerates the construction process by minimising the dependency on skilled workers [3]. The interlocking concrete masonry blocks have keys and grooves that improve the frictional connections between blocks in the wall and dismiss the use of mortar joints. Commonly, dry-stack concrete masonry walls are fabricated with three different interlocking geometric configurations as standard, end, and half units to suit the specific placement requirements, similar to conventional concrete blocks [2, 3].

The use of dry-stack concrete masonry in structural applications is uncommon, as further assessments are required to evaluate its behaviour under different loading conditions [4]. Existing literature claimed that the mechanical properties of the dry-stack concrete masonry can be comparable to the conventional mortared masonry [5]. Although the absence of mortar helps in accelerating the construction of dry-stack masonry, the overall quality is affected by the geometrical imperfections, surface texture issues, and random interstices [6]. In addition, the lateral load resisting capacity of dry-stack concrete masonry is critical due to lack of bonding. In this regard, the overall performance of dry-stack concrete masonry can be enhanced by using internal grouting and reinforcement [7, 8].

The compressive strength is a critical parameter for designing load bearing masonry elements under in-plane shear and out-of-plane flexural effects. The compressive strength of masonry primarily relies on the geometry, strength of units and bonding attributes [9], and it is determined by empirical formulations or tables proposed in the design guidelines [10-12]. Alternatively, the masonry compressive strength can be determined by testing two to five blocks high course prisms or wallettes, respectively and testing under compression. The same testing methods are applicable for measuring the compressive strength of ungrouted and grouted dry-stack masonry. Zahra et al., [8] assessed the axial compression behaviour of grouted dry-stack concrete masonry experimentally and analytically by varying reinforcement and aspect ratios. The load displacement behaviour was substantially influenced by grouting and block types. The ungrouted dry-stack concrete masonry walls displayed initial settlement due to the imperfection of the dry joints prior to the axial load-resisting mechanism [5, 13]. However, grouted dry-stack concrete masonry walls exhibited different behaviour as the grouting directly impacted the mode of failure and axial strength [14].

Though considerable studies were carried out to assess the compression characteristics of the dry-stack concrete masonry, the existing masonry codes, such as Canadian CSA S304-14 [11], Australian AS 3700-18 [10] and American TMS 402/602-16 [12], do not specify design provisions for dry-stack concrete masonry. This lack of specific design standards has hindered the widespread adoption of the dry-stack concrete masonry. Until now, *Design and Construction Guidelines for Dry-stack Concrete Masonry* (TMS 1430-21 [15]) have been developed as an initiative framework for designing of dry-stack concrete masonry system. This document provides tabulated values for determining the compressive strength of dry-stack concrete masonry for different block strengths and surface characteristics, however, the effect of grout is not considered.

This study is mainly focused on the axial compression characteristics of the grouted dry-stack concrete masonry, which can help in developing its compressive strength prediction. Four to five-courses high wallettes were constructed with five different types of interlocking concrete blocks sourced from various suppliers across Australia. In addition, the influence of different grout strengths was examined by incorporating grout strengths of 20 MPa, 32 MPa and 40 MPa for grouted wallettes along with ungrouted wallettes. The experimental results have been analysed in terms of their mechanical behaviour, failure mechanism and stress-strain responses.

MATERIALS AND METHODOLOGY

The mechanical properties of blocks and grouts used are provided in this section. The wallette construction procedure and their specifications, along with the testing methods are also explained.

Materials

Five different types of interlocking concrete blocks were sourced from different suppliers across Australia. Based on the manufacturers' references, these blocks were called Island (I), Lock (L), Connex (C), Versaloc (V) and Penta (P) blocks. The geometry of the blocks and their dimensions are marked in Fig. 1. All the blocks had double concrete webs, except the Penta blocks, which contained cross steel ties as middle webs. The length and height of the blocks were 400 mm and 190-205 mm, respectively, whereas the width varied between 140-200 mm.

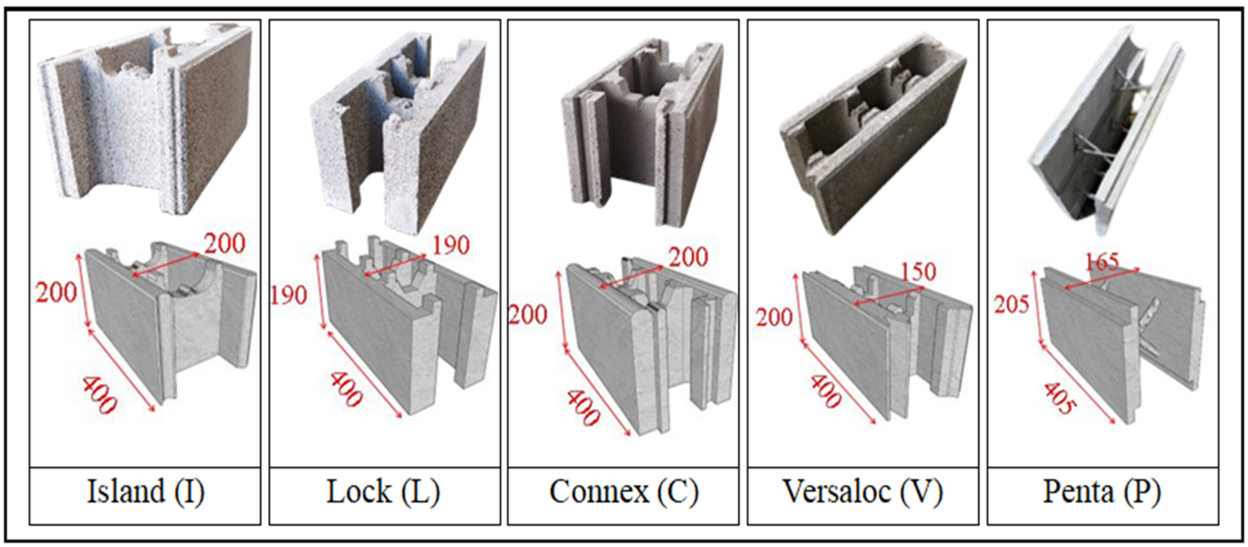

Figure 1: Interlocking dry-stack concrete masonry blocks used

Four blocks were randomly selected from each stock supplied, and their compressive strengths were evaluated according to AS/NZS 4456.4 [16]. Timber capping (6 mm thickness timber capping) was used on the face shells of the blocks. The timber capping was used in accordance with AS 3700 [10] and AS/NZS 4456.4 [16] for testing dry-stack blocks. The compression testing was performed in a 2000 kN universal testing machine with the displacement-controlled loading rate of 1 mm/min. Figs. 2(a) and (b) show the experimental setup along with the failure obtained during the testing. The average compressive strengths of Island (I), Lock (L), Connex (C), Versaloc (V) and Penta (P) were measured as 26.2 MPa, 25.7 MPa, 27.6 MPa, 24.4 MPa and 18.4 MPa, respectively. To obtain the strain characteristics of the blocks, Digital image correlation (DIC) analysis was carried out, for which the block shells were speckled with dots of black paint. Further, detailed explanation and testing criteria adopting DIC can be found in Sathurshan et al. [17]. The average stress-strain behaviour of each block is shown in Fig. 2(c).

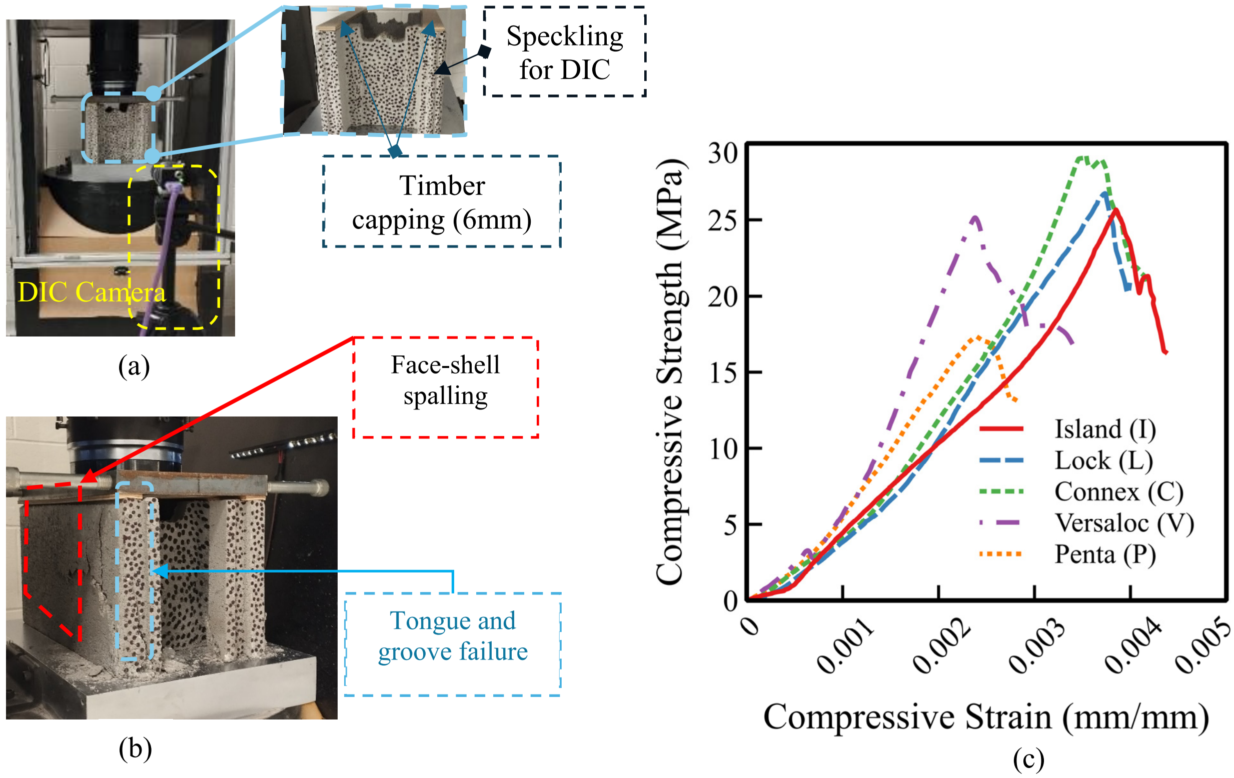

Figure 2: Interlocking blocks tests (a) testing set-up, (b) failure mechanism and (c) Stress-strain characteristics

Three different strength types of grouts were used in this study to construct the grouted dry-stack concrete masonry wallettes. The required mixes were obtained from a commercial supplier with a designated slump of 200 mm. The target compressive strengths of the grout mixes were 20 MPa (G20), 32 MPa (G32) and 40 MPa (G40). The compressive strength of supplied grouts was tested by casting and testing grout cylinders (100 mm diameter × 200 mm height) as per AS1012.9 [18]. The testing of the grout cylinders was carried out after 28 days of curing. The average compressive strengths of grouts were measured as 18.8 MPa (for G20), 32.5 MPa (for G32) and 40.3 MPa (for G40).

Experimental Campaign

The experimental campaign carried out in this study is shown in Fig. 3. The four to five courses high wallettes were constructed, which varied in size based on their geometry. The heights of the wallettes varied between 800-1000 mm, whereas the length was set at 600 mm, and the width was varied depending on the width of the blocks, as shown in Fig. 1. The construction procedure is shown in Fig. 4. The wallettes were stacked to create the running bond pattern by using full and half blocks to the required height. The formwork was set up at the vertical edges of wallettes to pour the grout without any leakages.

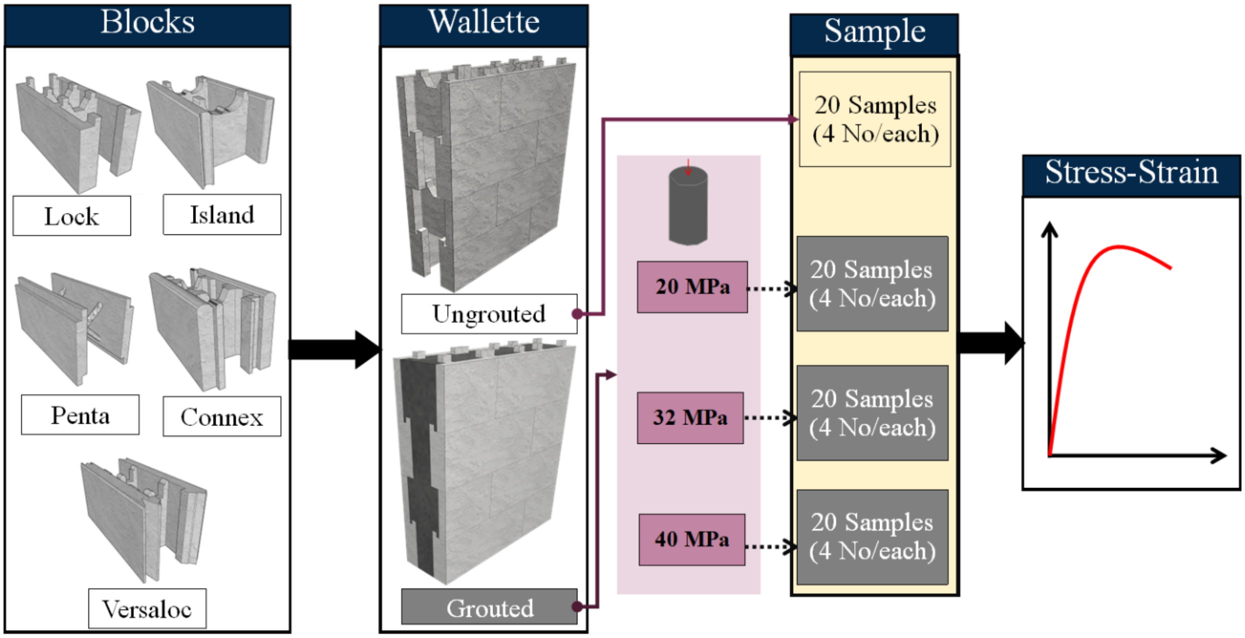

Figure 3: Experimental campaign of grouted and ungrouted wallettes

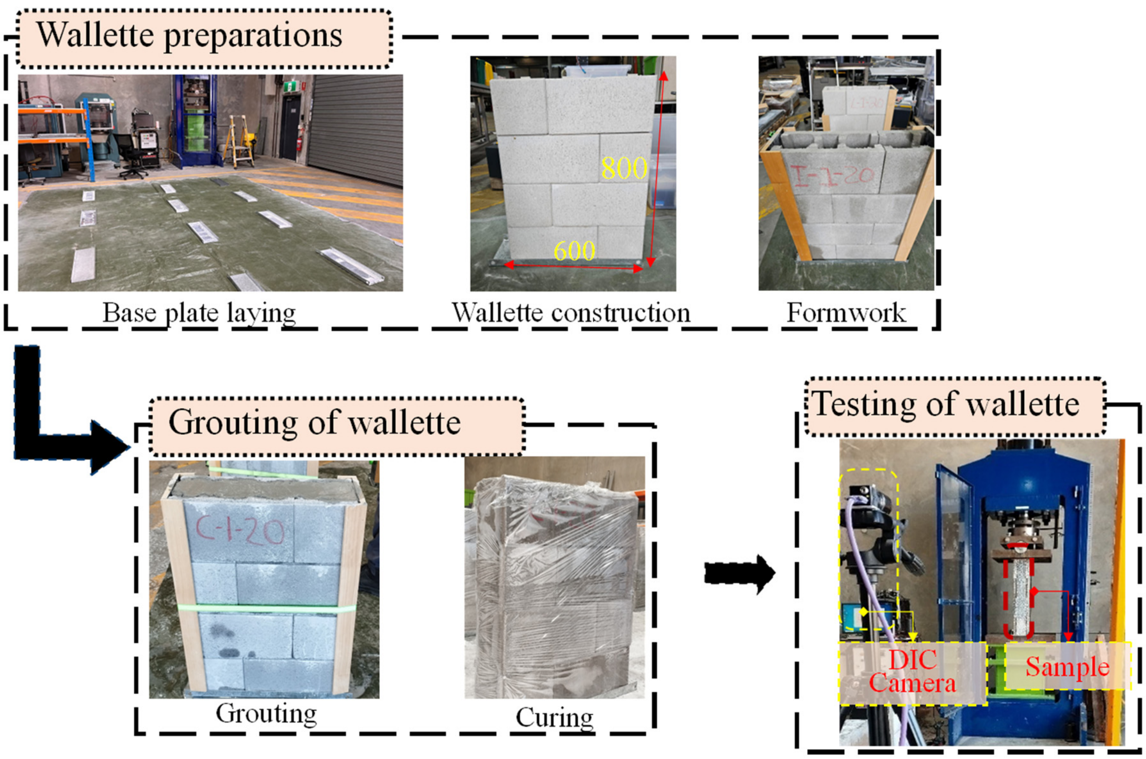

Figure 4: Construction and testing arrangements of dry-stack concrete masonry wallettes

The constructed wallettes were kept in the laboratory wrapped with cling sheet for 28 days and then tested under compression. The testing arrangement is shown in Fig. 4. For 80 tested wallettes, an alphanumeric nomenclature was used with the first letter showing the block type followed by the grout strength. For example, I-G20 represents the Island block wallettes with 20 MPa grout. The axial compression testing was carried out using a servo-controlled hydraulic actuator with a capacity of 4000 kN at a controlled displacement rate of 1 mm/min. Each wallette was set up properly to align with the loading platens to apply the concentric loading evenly with a 6 mm plywood capping on top of the wallettes as instructed in AS 3700 [10] and AS/NZS 4456.4 [16]. The DIC camera was used to obtain the deformation characteristics. This DIC technique has been commonly used in previous studies to measure the deformation of masonry under different loading effects [19, 20]. To capture the complete load-displacement behaviour of the wallettes, the testing was continued until the peak load dropped to at least 20% in the post-peak region during the loading.

RESULT AND DISCUSSION

The obtained characteristics of the tested wallettes under the axial compression loading, such as failure mechanisms, stress-strain characteristics and mechanical properties are presented in this section.

Failure Mechanism

The failure mechanism of the tested ungrouted dry-stack concrete masonry is shown in Fig. 5(a). The failure patterns of all the ungrouted wallettes exhibited splitting along the webs followed by the face-shell spalling at dry-stack joints. Notably, the failure mechanism of P-G0 (Penta block) only displayed the spalling of their face-shell, due to the absence of any conventional web-shells in the blocks, as can be seen in Fig. 5(a). Furthermore, the geometrical imperfections were visibly witnessed for the wallette constructed without grout. The similar failure mechanisms were reported in the ungrouted dry-stack prisms, where the initial settlement of the block, along with crack formation between the web and face-shell interactions, resulted in spalling of the face-shell [6, 8, 21].

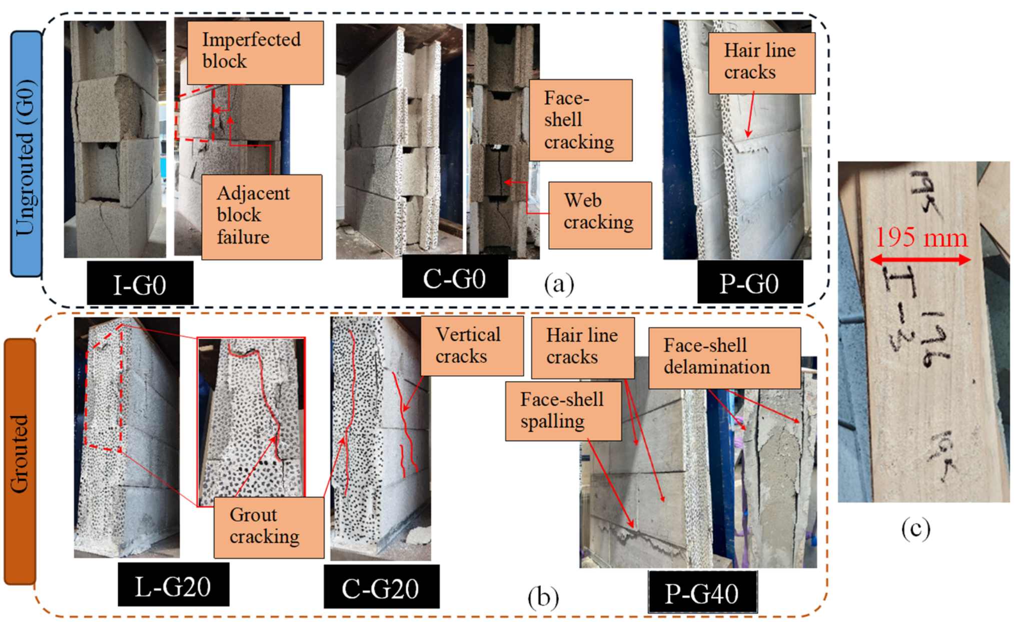

Figure 5: Typical failure mechanism of (a) ungrouted wallets (b) grouted dry-stack wallettes and (c) plywood placed on top of the wallette (depressed area calculation)

The grouted dry-stack concrete masonry wallettes showed completely distinct failure mechanisms as represented in Fig. 5(b). All the grouted wallettes exhibited similar failure patterns despite the different block types used in this study with face shell delamination and crushing of the grouted core. These failure patterns observed have been similar to the study performed by Drysdale and Gazzola [22]. The wallettes with low grout strength (G20), also displayed failure in grout with vertical splitting cracks. During the loading process, the hairline cracks were formed on the face-shell areas and the outward bulging was observed. Consequently, the dilation of grout enforced face-shell spalling in wallettes. This failure pattern is closely resembled to those of grouted concrete block mortared masonry wallettes, as the influence of the dry and imperfect block surfaces is not prominent, while the grout plays a significant role in resisting axial compression [23].

Stress-Strain Characteristics

The applied loads were obtained through the hydraulic actuator and strains measured using the DIC were post-processed to develop the stress-strain behaviour of the tested wallettes. The stress values were obtained using the net area on which the loading was applied. The net area of the grouted wallettes was the total top area of the wallettes, whereas for the ungrouted wallettes only the face-shell area was loaded. The strain values were obtained by performing post-analysis of the DIC image data with the displacement measurements corresponding to gauge lengths. The gauge length was varied between 650 and 750 mm. The average stress-strain curves of each typology are shown in Fig. 6.

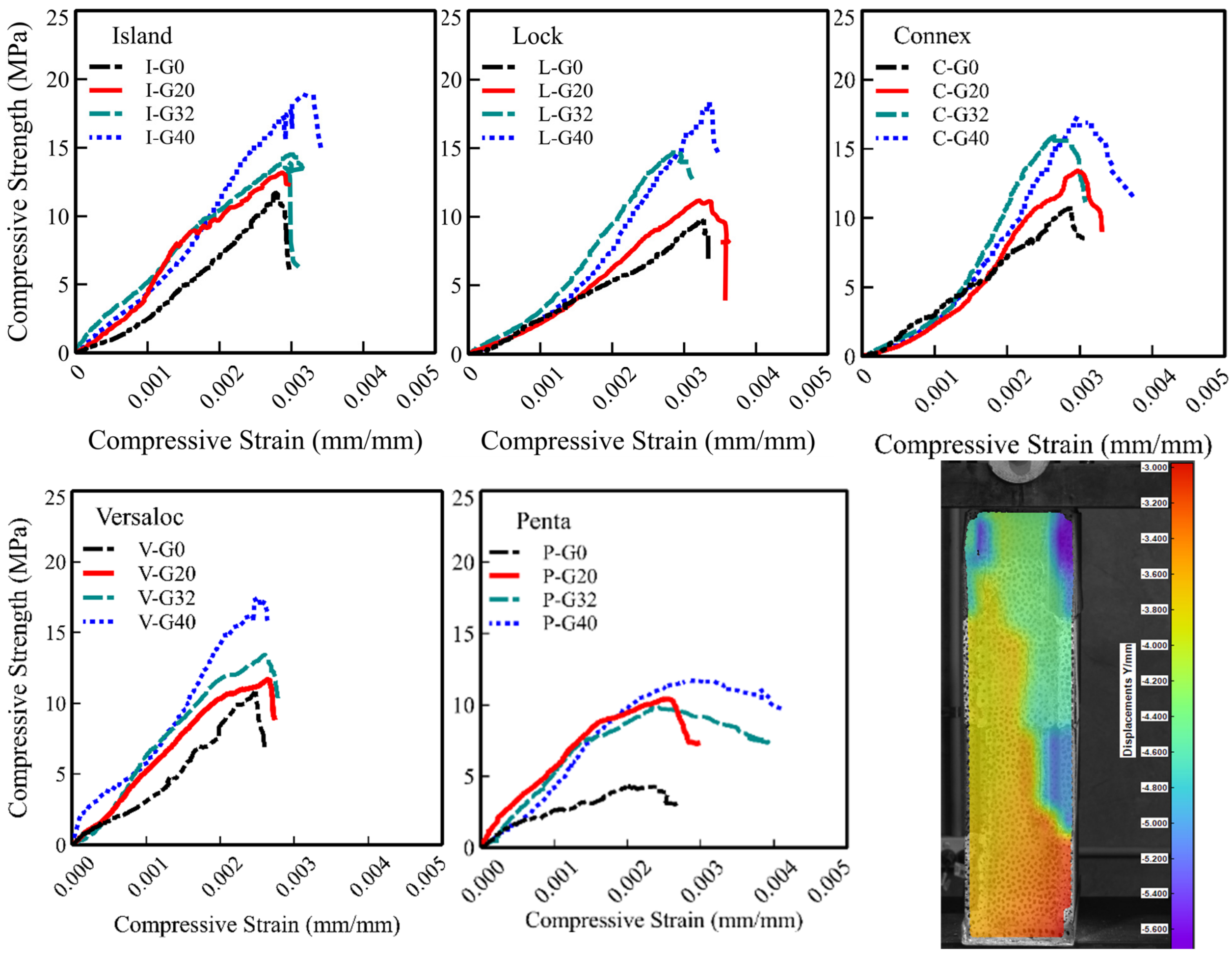

Figure 6: Stress-strain relationship of grouted/ungrouted dry-stack concrete masonry wallettes

Ungrouted wallettes depicted a distinct behaviour, where initial settlement in the dry-stack joints was observed, which resulted in lower initial slope or elastic modulus. This could be due to the surface unevenness of the blocks used. A similar behaviour was reported in the study conducted by Zahra et al. [5] and in TMS 1430-21 [15]. Due to this effect, the ungrouted wallettes gained increased stiffness once the full settlement behaviour of dry-stack joints was reached. However, previous studies indicated that it can be addressed by grinding the surface of the block or using adhesive between blocks [13, 24]. At the peak load, the ungrouted wallettes failed mostly in brittle manner. The deformation characteristics of the grouted wallettes showed failure trends similar to conventional grouted wallettes with a consistent initial slope until peak stress was reached. A decline in strength occurred after the peak, which was caused by the crushing/cracking or complete failure of the grouted wallettes under axial compression.

Mechanical Properties

The mechanical properties of tested dry-stack concrete masonry wallettes were derived in terms of peak compressive strength and elastic modulus from the stress-strain graphs. The peak stress was calculated for the net loaded area as mentioned in the previous section. The net area was considered as the depressed area of the plywood, as stated in Fig 5 (c). The applied load was divided by the net area, and the peak stress was computed. The acquired mechanical properties are detailed in Fig 7. The initial linear portions of the stress-strain curves (ungrouted and grouted panels) were used to compute the elastic stress and corresponding strain values that were used to compute the elastic modulus of the wallettes. To determine the elastic modulus for grouted wallettes, the elastic range was defined as the slope of the stress-strain curve up to 40% of the peak stress [8]. For ungrouted wallettes, the elastic modulus was computed from the second branch of stress-strain curves, after initial settlement of joints, as stated in TMS 1430-21 [15].

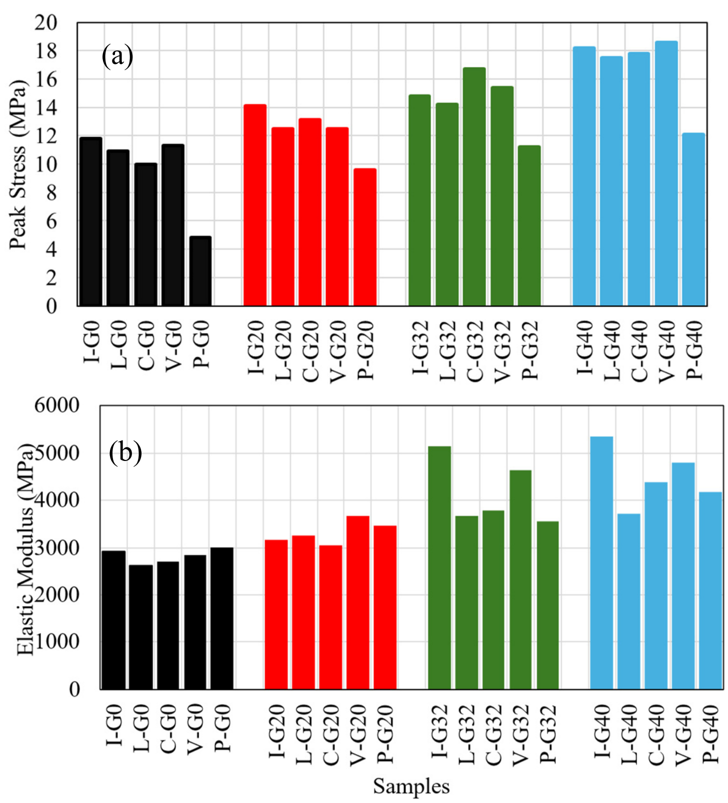

Figure 7: Mechanical properties of dry-stack concrete masonry wallettes (a) peak stress and (b) elastic modulus

The axial compressive strength of the grouted wallettes indicated higher compressive strength than the ungrouted wallettes. It is obvious from the graphs that the axial compressive strength of the dry-stack concrete masonry wallettes are significantly influenced by the internal grouting. Generally, the grouted wallettes depicted a similar range of compressive strengths regardless of the different block types used except for Penta blocks. A marginal increase in the strength of Penta blocks wallettes was observed as compared to other wallettes, which was mainly due to their geometric design and imperfections in the blocks. The elastic moduli of dry-stack wallettes were also increased when the grout strength was increased from 0 to 40 MPa. This indicates that the grout plays a significant role in contributing to the axial compressive strength and stiffness of grouted dry-stack concrete masonry. A similar observation was made in the previous studies reported on the grouted concrete masonry wallettes tested under axial compression [25]. In addition, the peak stress value of the dry-stack concrete masonry was lower than the interlocking block strength used in this study, which is also consistent with the past studies [26].

The elastic modulus measured for the tested wallettes ranged from 2623 to 5356 MPa, that are 212 to 361 times the measured compressive strengths correspondingly for ungrouted to grouted wallettes with increasing grout strengths. The elastic modulus obtained for ungrouted dry-stack wallettes matched closely with the TMS 1430-21 [15] recommended value of 2870 MPa.

CONCLUSIONS

An experimental campaign was conducted to assess the axial compression behaviour of dry-stack concrete masonry. Five types of blocks sourced from various manufacturers were selected for this purpose across Australia. A total of 80 wallettes were built with the height varying from 800 to 1000 mm, width being 600 mm, and thickness being either 150 or 200 mm. Three different grout strengths of 20 MPa, 32 MPa, or 40 MPa were used. The study assessed the failure mechanism, stress-strain behaviour, and mechanical properties. The following conclusion can be drawn from the study:

- Results indicate that the grouting is critical for achieving effective axial load transmission in dry stack masonry walls. Without grouting, the axial compression behaviour of dry-stack concrete masonry wallettes relies predominantly on face-shell load transfer, which is adversely affected by the imperfections on the contact surfaces of the blocks. Grouting provides stability, increases stiffness and strength of dry-stack masonry.
- The failure and stress-strain behaviour of wallettes made of double webbed concrete blocks was quite similar with minor variations for different blocks, except for Penta blocks in which cross-steel ties were present instead of concrete web shells. This configuration along with imperfection in their interlocking designs caused reduced strength in these wallettes.
- An increase in grout strength positively influenced the behaviour of dry-stack masonry by enhancing its compressive strength, deformation characteristics and elastic moduli progressively improving as the grout strength increased from 20 MPa to 40 MPa.

This study summarises the impact of incorporating the grouts in the dry-stack concrete masonry systems through experimental testing. Analytical formulations will be developed in future based on these results obtained to facilitate their inclusion in Australian Masonry Standards for predicting the compressive strength of grouted dry-stack concrete masonry.

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Acknowledgements

The PhD scholarship to the first author was sponsored by Concrete Masonry Association of Australia (CMAA). The contribution of Adbri Masonry, Baines Masonry, Lutum Masonry and Island Block & Paving for their sponsorship of the interlocking concrete blocks is acknowledged. The technical support provided by the QUT materials lab and Pilot Project Precinct (Banyo) is also acknowledged.

References

[1] K. Ramamurthy and E. K. K. Nambiar, "Accelerated masonry construction review and future prospects," *Progress in Structural Engineering and Materials,* vol. 6, no. 1, pp. 1-9, 2004, doi: 10.1002/pse.162.

[2] J. A. Thamboo, T. Zahra, and R. Dhanasekar, "Development of design methodology for mortarless masonry system: Case study – a resettlement housing colony," *Journal of Building Engineering,* vol. 27, p. 100973, 2020, doi: 10.1016/j.jobe.2019.100973.

[3] M. S. Jaafar, A. H. Alwathaf, W. A. Thanoon, J. Noorzaei, and M. R. Abdulkadir, "Behaviour of interlocking mortarless block masonry," *Proceedings of the Institution of Civil Engineers - Construction Materials,* vol. 159, no. 3, pp. 111-117, 2006, doi: 10.1680/coma.2006.159.3.111.

[4] A. Gul, B. Alam, and K. Shahzada, "Seismic performance evaluation of unconfined dry stacked block masonry structure," *Engineering Structures,* vol. 265, p. 114529, 2022, doi: 10.1016/j.engstruct.2022.114529.

[5] T. Zahra and M. Dhanasekar, "Characterisation and strategies for mitigation of the contact surface unevenness in dry-stack masonry," *Construction and Building Materials,* vol. 169, pp. 612-628, 2018, doi: 10.1016/j.conbuildmat.2018.03.002.

[6] K.-H. Oh, H. G. Harris, and A. A. Hamid, "Behaviour of Interlocking Mortarless Masonry Under Compressive Loads," presented at the Seventh Canadian Masonry Symposium, McMaster University, Hamilton, Ontario, June 4-7, 1995.

[7] M. A. Hossain, Y. Z. Totoev, M. J. Masia, and M. Friend, "In-plane cyclic behavior of semi interlocking masonry panel under large drift," presented at the 13th Canadian masonry symposium, Halifax, Canada, June 4th – June 7th 2017, 2017.

[8] T. Zahra *et al.*, "Behaviour of reinforced mortarless concrete masonry panels under axial compression: An experimental and analytical study," *Construction and Building Materials,* vol. 377, 2023, doi: 10.1016/j.conbuildmat.2023.131097.

[9] A. W. Hendry, *Structural masonry*. Bloomsbury Publishing, 1998.

[10] *AS 3700: Masonry Structures*, 978 0 7337 9936 5, Standards Australia, Sydney, Australia, 2018.

[11] *CSA S304-14 (R2019): Design of Masonry Structures*, Canadian Standards Association, Mississauga, ON, Canada, 2014. [Online]. Available: https://www.csagroup.org/store/product/S304.1-04/

[12] *TMS 402/602-16: Building Code Requirements for Masonry Structures*, The Masonry Society, Longmont, CO, USA, 2016.

[13] S. Atamturktur, B. E. Ross, J. Thompson, and D. Biggs, "Compressive Strength of Dry-Stacked Concrete Masonry Unit Assemblies," *Journal of Materials in Civil Engineering,* vol. 29, no. 2, p. 06016020, 2017, doi: 10.1061/(asce)mt.1943-5533.0001693.

[14] A. Al-Fakih, M. M. A. Wahab, B. S. Mohammed, M. S. Liew, N. A. Wan Abdullah Zawawi, and S. As'Ad, "Experimental study on axial compressive behavior of rubberized interlocking masonry walls," *Journal of Building Engineering,* vol. 29, 2020, doi: 10.1016/j.jobe.2019.101107.

[15] *TMS 1430: Design and Construction Guidelines for Dry-stack Concrete Masonry.*, The Masonry Society, Longmont, CO USA, 2021.

[16] *AS/NZS 4456.4 (2003): Masonry units, segmental pavers and flags—Methods of test Determining compressive strength of masonry units*, Standards Australia, Sydney, Australia, 2009.

[17] M. Sathurshan, H. Derakhshan, J. Thamboo, J. Gill, C. Inglis, and T. Zahra, "Compressive Strength in Grouted Dry-Stack Concrete Block Masonry: Experimental and Analytical predictions," *Construction and Building Materials,* vol. 467, p. 140411, 2025.

[18] *AS 1012.9: Methods of testing concrete Compressive strength tests - Concrete, mortar and grout specimens*, Standards Australia, Sydney, Australia, 2014.

[19] J.A. Thamboo, M. Dhanasekar, and C. Yan, "Effects of joint thickness, adhesion and web shells to the face shell bedded concrete masonry loaded in compression," *Australian Journal of Structural Engineering,* vol. 14, no. 3, p. 12, 2013, doi: 10.7158/13287982.2013.11465139.

[20] T. Zahra, J. Thamboo, and M. Asad, "Compressive strength and deformation characteristics of concrete block masonry made with different mortars, blocks and mortar beddings types," *Journal of Building Engineering,* vol. 38, p. 102213, 2021, doi: 10.1016/j.jobe.2021.102213.

[21] G. Marzahn, "Investigation on the initial settlement of dry-stacked masonry under compression," *Leipzig Annual Civil Engineering Report,* vol. 3, pp. 247-261, 1999.

[22] R. Drysdale and E. Gazzola, "Strength and deformation properties of a grouted, dry- stacked, interlocking, concrete block system," *Brick and Block Masonry,* vol. 1, pp. 164-171, 1991.

[23] B. Abdelrahman and K. Galal, "Influence of pre-wetting, non-shrink grout, and scaling on the compressive strength of grouted concrete masonry prisms," *Construction and Building Materials,* vol. 241, p. 117985, 2020, doi: 10.1016/j.conbuildmat.2019.117985.

[24] G. G. Chewe Ngapeya and D. Waldmann, "Experimental and analytical analysis of the load-bearing capacity Pu of improved dry-stacked masonry," *Journal of Building Engineering,* vol. 27, p. 100927, 2020, doi: 10.1016/j.jobe.2019.100927.

[25] M. S. Jaafar, W. A. Thanoon, A. M. S. Najm, M. R. Abdulkadir, and A. A. Abang Ali, "Strength correlation between individual block, prism and basic wall panel for load bearing interlocking mortarless hollow block masonry," *Construction and Building Materials,* vol. 20, no. 7, pp. 492-498, 2006, doi: 10.1016/j.conbuildmat.2005.01.046.

[26] R. G. Drysdale and A. A. Hamid, "Behavior of Concrete Block Masonry Under Axial Compression," *Journal of the American Concrete Institute,* vol. 76, no. 6, pp. 707-721, 1979, doi: 10.14359/6965.