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Compressive strength and cost-effectiveness of confined waste plastic bottle brick masonry walls

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ABSTRACT
Uganda faces a substantial housing deficit, and escalating construction costs resulting from unsustainable extraction of construction materials and inadequate management of plastic and sawdust waste. This study evaluates the compressive strength and cost effectiveness of Plastic Bottle Brick (PBB) masonry walls as a potential substitute for conventional concrete block walls in Mbale City, Uganda. The work specifically addresses the limited empirical evidence concerning the behaviour of vertically oriented confined PBB units incorporating uncompressed air (EB), sawdust (SD) and pit sand (PS). Compressive strength testing showed that PS walls achieved a strength of 0.6 ± 0.02 MPa, comparable to hollow concrete block (HCB) walls (0.6 ± 0.06 MPa). SD and EB walls exhibited lower strengths of 0.3 ± 0.05 MPa and 0.3 ± 0.03 MPa, respectively, below the strength of solid concrete block (SCB) walls (0.8 ± 0.03 MPa). All PBB walls demonstrated higher failure strains (1.8–2.0%) than concrete block walls (1.0–1.2%). The cost-benefit analysis considering materials, labour, time utilisation and carbon emissions costs found that EB blocks were the most economical (USD 3.22/UGX 11,694), while SCB were the least economical (USD 7.97). PBB production was commercially feasible, with casting time only 17% slower than conventional block production.

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Waste; plastic bottle; plastic bottle brick; masonry wall; compressive strength; cost-benefit analysis

1. Introduction

Globally, plastic waste has become a major environmental challenge because it persists in the environment and has low recycling rates. Plastic bottles, in particular, present a serious problem due to their extremely long decomposition period, which can exceed 1000 years, and the release of toxic chemicals during degradation. Although plastic bottles are recyclable, only about 9% are actually recycled worldwide, while the rest accumulate in landfills or the natural environment (OECD 2022). Waste generation is increasingly outpacing landfill capacity, driving a global shift towards sustainable recycling options, as traditional disposal methods become more costly, complex, and environmentally harmful (Sakr and AbouZeid 2025).

In Uganda, plastic waste poses a similarly serious challenge. The National Environment Management Authority (NEMA) reports that Uganda produces about 600 tonnes of plastic waste each day, but only around 40% is properly collected and disposed of. The remaining 60% pollutes the environment, clogs drainage systems, reduces soil fertility, and contributes to flooding, especially in urban areas (Buyondo 2022; Muganga 2022). As a result, innovative approaches to plastic waste management are attracting growing interest, especially those that incorporate waste materials into sustainable construction practices. One viable approach is the development of Plastic Bottle Bricks (PBBs), which are produced by combining waste plastic bottles filled with sand, aggregates, cement, stone dust, fly ash, or soil (Shrestha et al. 2023). Additionally, sawdust remains underutilised, evident by a Kampala City study which revealed that 69% of timber workshops discarded sawdust waste, 22% burned it, 6% sold it as fuel, and only 3% converted it into useful energy (Sseremba et al. 2011). Poor waste management and limited knowledge of potential uses contribute to environmental concerns (Udokpoh and Nnaji 2023).

In the context of sustainable masonry and low impact building materials (Jaafar, Abbas, and Allawi 2023), investigated the production of hollow concrete blocks incorporating recycled concrete, clay brick, and mosaic tile waste, reporting compressive strengths in the range of 6.25–7.95 MPa. Similarly, studies

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on solid masonry blocks manufactured using recycled concrete aggregates have demonstrated that replacement levels of up to 100% can be achieved, with compressive strengths ranging from 2.84 to 24.79 MPa depending on the mix proportions and aggregate quality (Dafedar et al. 2024). This study builds on this body of work by investigating confined waste plastic bottle brick masonry, which departs from conventional aggregate replacement and instead employs waste plastic as a structural core within a composite mortar framework.

A 'composite eco-brick' consisting of three sand filled PBBs embedded into cement mortar to form blocks of 230 × 100 × 70 mm; gave a 12–17% higher compressive strength in comparison to the selected common brick (5.85 MPa) (Priya, Nirmala, and Dhanalakshmi 2018). Additionally, a PBB block of dimensions 300 × 300 × 300 mm, consisting of eight PBBs per block, encased in cement mortar revealed a compressive strength of 0.6 MPa (Mansour, Mansour, and Ali 2015). Research by (Mansour, Mansour, and Ali 2015; Priya, Nirmala, and Dhanalakshmi 2018), and (Parab et al. 2021) confirmed that PBBs can achieve compressive strengths comparable to or greater than conventional clay bricks, with cost savings of up to 35%. In terms of materials and construction methods, significant variability exists in bottle geometry, filler materials (uncompressed air, sand, soil, or demolition waste), and binding agents used, resulting in inconsistent performance data. While some studies achieved high compressive strengths, the dependence on high grade cement mortar or concrete infill compromises the low-cost and eco-friendly intent of PBB technology. While PBBs can exceed the compressive strength of traditional bricks, plastics remain combustible and may release toxic fumes. However, dense packing and full mortar cover reduces this risk. Durability concerns persist because plastics can degrade under Ultraviolet light exposure, temperature extremes, and chemical attack, but protective mortar coatings and improved confinement provides mitigation. Chemical incompatibility of plastic bottles with alkaline cement has been reported, yet low pH binders and earthen mortars offer viable alternatives. Temperature sensitivity may soften or embrittle bottles, but can be overcome by mortar encasement, which limits exposure. Regulatory acceptance and public confidence in PBBs remains low due to limited long-term performance data (Li 2022; Yadav et al. 2024).

Uganda's growing housing deficit, estimated at about 1.6 million homes as of 2016 (MLHUD 2016), and the rising cost of construction materials, underscores the urgent need for alternative building solutions. The use of waste plastic bottles in masonry construction, particularly through Confined Waste Plastic Bottle Brick (PBB) walls, offers a practical way to address both the plastic waste problem and the housing shortage while enhancing environmental sustainability in Uganda's construction industry. However, there is a lack of scientific and contextual evidence on the structural performance, cost-effectiveness, and environmental benefits of Confined Waste Plastic Bottle Brick (PBB) masonry walls as a sustainable and affordable alternative to conventional masonry materials in Uganda.

2. Materials and methods

2.1. Materials

The materials used in this study and their key properties are summarised in Table 1.

The particle size distribution for saw dust, pit sand, river sand and stone dust used in this study are illustrated in Figure 1.

The PBB densities and the corresponding compaction thresholds are summarised in Table 2.

2.2. Methods

2.2.1. Sample preparation

2.2.1.1. Plastic bottle bricks (PBBs). Bottles were collected, washed, dried, and filled with either sand or sawdust, while others were left empty (Figure 2). Compaction was achieved using a steel rod and hammer in three layers (25 blows per layer), and later filled till no loose material was at the top of the bottle. This was done until the required compaction levels were consistently achieved (Figure 3). The minimum compaction levels were 80% (≥970 g) for sand and 53% (≥180 g) for sawdust. Each filled bottle was sealed and weighed for uniformity across samples. The bottles fulfilling the minimum thresholds are as shown in Figure 4.

Table 1. Material properties.

Material	Density/Weight	Key Characteristics	Observed Behaviour/Notes
Sawdust	~638 kg/m^3	Fibrous, lightweight, highly compressible	- Difficult to compact; high elasticity causes spring back.
Pit Sand	~2,274 kg/m^3	Fine, whitish-brown particles	- Highest compaction filler; cohesive; preferred for stability of wet blocks.
River Sand	~2,629 kg/m^3	Coarser particles, less fine material	- Lower workability; requires more water for cohesive wet blocks.
Stone Dust	~2,636 kg/m^3	Fine granular angled grey particles	- High density; commonly used in concrete block production.
Cement	~2,800–2,900 kg/m^3	Pozzolanic cement CEM IV B (P) 32.5N from Tororo Cement	- Frequently used cement for most concrete block making activities from field survey.
Water	~1000kg/m^3	Clear potable water	- Sourced from the National Water and Sewerage Corporation supply.
Sisal rope	4.5 g/m	Tensile strength of 222.9±15.9 MPa	- Stronger mortar bond than nylon ropes. - 2-3mm thick
Plastic bottle	10-15g	Cylindrical bottle with a narrow lower section and conical upper section	- 500 ml 'Elgon' water bottle, maintains shape when filled, smooth surface, 230mm height, 60mm diameter. - Internal volume of around 535ml. - Represents 65% of waste bottles sampled from a stockpile of 100 bottles.

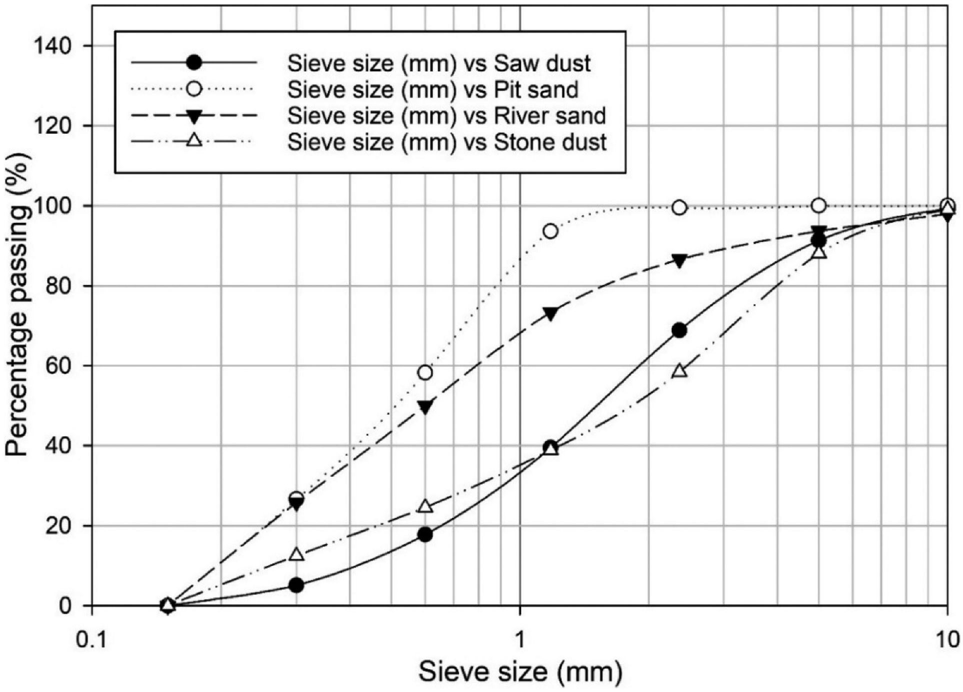

Figure 1. Particle distribution curves for materials used.

Table 2. PBBs weight and density.

Sample Description	Mass (g)	Filler density (kg/m^3)	Compaction (%)	PBB density (kg/m^3)
Empty bottle with cap	10	0	0	0
Saw dust filled bottle with cap	180	638.171	53	338.231
Pit sand filled bottle with cap	970	2273.930	80	1819.144

2.2.1.2. PBB masonry units. Bottles were arranged in three interlocking courses, tied with sisal rope, and cast into mortar blocks measuring 400 by 200 by 250 mm, using a 1:4 cement to sand mix by volume. The units were removed from the mould after 12–24 h and cured by spraying twice (7 am and 7 pm) for 28 days

Figure 2. Process for making PBBs.

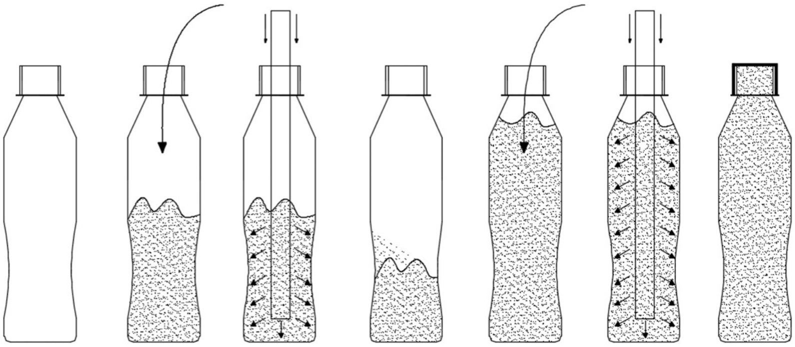

Figure 3. Filling of plastic bottles.

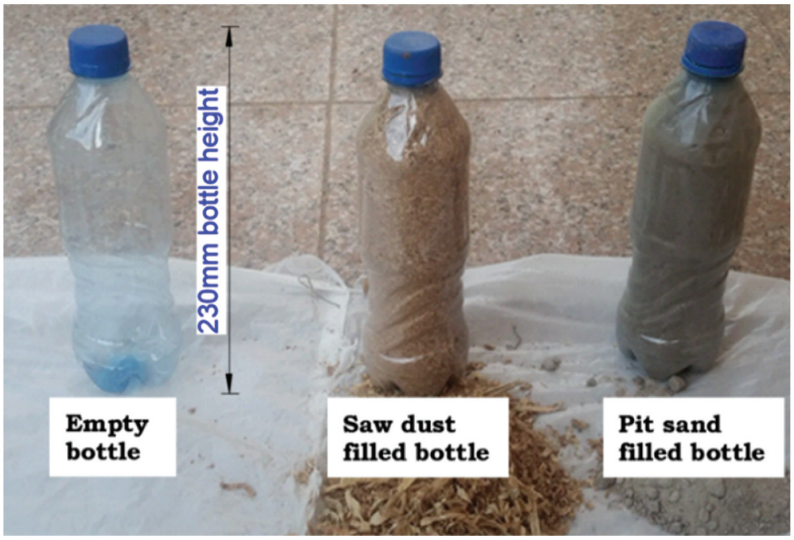

Figure 4. PBBs ready for confinement into PBB block cores.

(Figures 5–7). A 250 mm strip of damp proof membrane (this can be reused) was placed between the steel mould and the mortar to provide temporary lateral support, allowing the mould to be removed immediately after casting. This reduced demoulding time and enhanced the commercial feasibility of producing PBB units.

(a) Bottle tying (b) Mould preparation (c) Mortar casting (d) Mould removal (e) Curing of blocks

Figure 5. Process for preparing the PBB blocks.

Figure 6. Tying PBB masonry units.

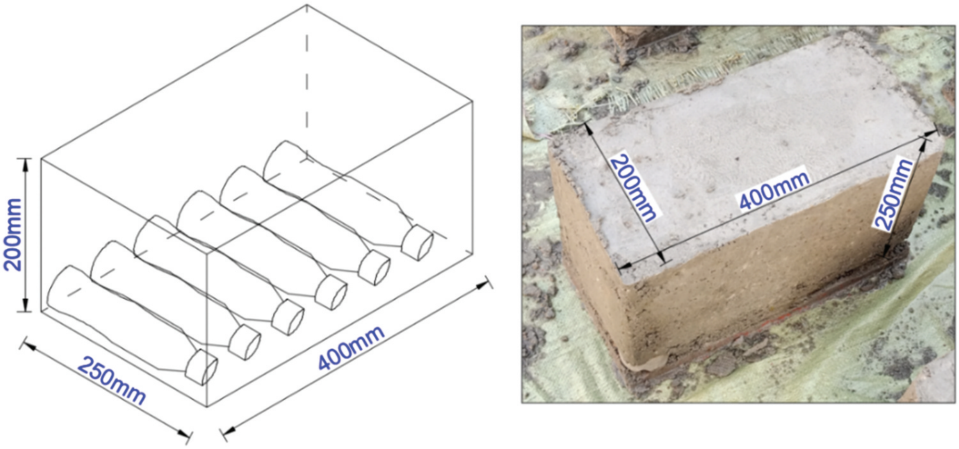

Figure 7. Typical geometry of PBB blocks.

2.2.1.3. Masonry walls. Wall specimens (1250 × 1100 × 200 mm) were built in compliance with EN 1052–1:1999, using vertical bottle orientation, four courses of blockwork, and 25 mm mortar joints with a 1:4 cement-river sand mix by volume (Figure 8).

2.2.1.4. Concrete blocks. Solid and hollow concrete blocks (Figure 9) were prepared using a 1:3:6 (cement:sand:stone dust) mix ratio, derived from dominant practices observed in the field survey. The concrete blocks commonly used in the field have a width of 200 mm and a length of 400 mm, with a typical height of 200 mm. For this study, the block height was increased to 250 mm to match the overall height of the PBB units, which is governed by the 230 mm bottle height and the

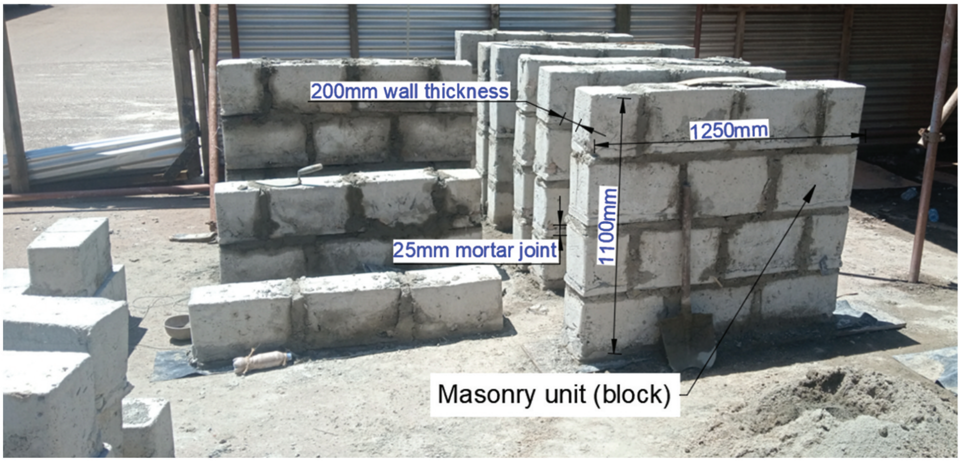

Figure 8. PBBM wall specimens.

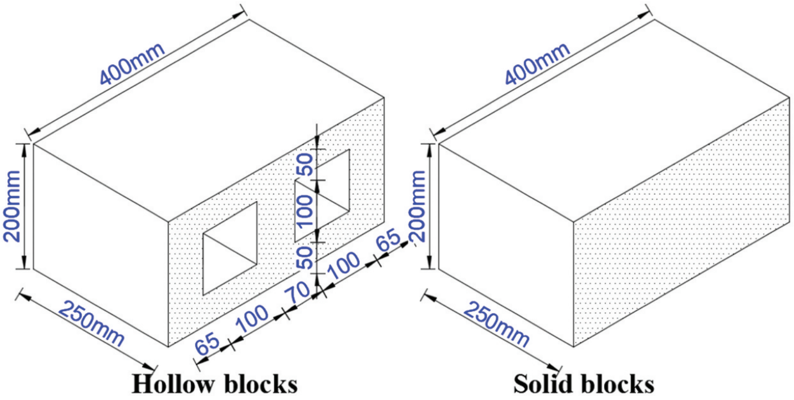

Figure 9. Typical geometry of concrete blocks used.

required mortar cover. The flange and web thicknesses of the 200 mm wide hollow concrete blocks were scaled proportionally to preserve the original geometric slenderness. This was done by maintaining the ratio between the height and thickness of the flange or web.

2.2.2. Data collection

Concrete block makers in Mbale City were surveyed to establish prevailing mix ratios, curing practices, and unit costs. A minimum sample of 96 respondents was determined using standard sample size estimation for unknown populations at a 95% confidence level and 1% margin of error. All respondents were aged 18 years or older, and informed consent for participation in the interviews was obtained verbally. Verbal consent was chosen to respect the respondents' convenience, as majority were engaged in block making activities at the time of data collection. Baseline information on concrete block properties, including geometry, mix ratios, density, and compressive strength, was further obtained from material testing laboratories. These data were used to benchmark the performance of PBB units and PBB masonry walls against commercially available solid and hollow concrete blocks.

2.2.3. Experimental program

A total of 63 compressive strength specimens and 15 water absorption specimens were tested across PBBs, PBB and concrete blocks, concrete and PBB walls, with a minimum of 3 samples per test (Table 3).

Table 3. Experimental program for the study.

Test Type	Applicable Standards	Testing Equipment and Loading Rate	Number of Specimens
PBB compressive strength	ASTM C39, EN 12,390–4	1500 kN compression machine at 2 kN/s	18 samples (6 per filler material; 3 vertical and 3 horizontal)
PBB and concrete blocks 28 days compressive strength	EN 12,390–4	1500 kN compression machine at 2 kN/s	30 samples (6 per block type; 3 vertical and 3 horizontal)
PBB and concrete block walls compression test	EN 1052–1:1999	Controls hydraulic jack (750 kN) at 1 mm/s	15 wall panels (3 per sample type)
Water absorption (PBB & concrete blocks	ASTM C140	Standard immersion and drying setup	15 specimens (3 per block type)

2.2.4. Cost–benefit analysis (CBA)

A CBA framework based on the Kaldor-Hicks efficiency criterion (Campbell and Brown 2023) was applied to compare PBB units with conventional concrete blocks. Costs considered included materials, labour, time utilisation, and carbon emissions cost. The following were considered for the cost-benefit analysis:

(a) **Materials**: quantified per unit based on Civil Engineering Standard Method of Measurement (CESMM4) guidelines.
(b) **Labour**: evaluated using productivity-based payment rates from local surveys.
(c) **Time utilisation**: was calculated from measured time in hours required to produce one masonry unit and average daily labour hours, reflecting differences in production speed between PBB blocks and conventional masonry units.
(d) **Carbon emissions**: estimated using emission factors from established literature and monetised using the mean global carbon tax reported by the World Bank Group (World Bank Group 2024) (as of 30th May, 2025).

Plastic bottles were valued at UGX 500 (USD 0.14) per kilogram, consistent with local waste plastic purchasing rates, while transportation costs were excluded due to their variability. Indirect benefits such as reduced pollution, improved waste management, and contributions to the Sustainable Development Goals were not monetised, following recommended practice for conservative CBA modelling (Pearce, Atkinson, and Mourato 2006). The following formulas were used to establish the materials, labour, time utilisation, carbon emissions cost and total cost per block/masonry unit:

$$\textbf{Materials cost} = \text{Market unit price of materials} \times \text{Quantity of materials used}$$

$$\textbf{Labour cost} = \frac{\text{Average daily labour fee}}{\text{Average quantity of tasks achieved}} \times \text{tasks permasonry unit}$$

$$\textbf{Time utilisation cost} = \frac{\text{Average daily labour fee}}{\text{Average daily work hours}} \times \text{tasks duration per masonry unit}$$

$$\begin{aligned}\textbf{Carbon emissions cost} = {} & \text{Quantity of materials used} \times \text{Carbon emissions per unit of material} \\ & \times \text{Carbon tax rate}\end{aligned}$$

$$\begin{aligned}\textbf{Total masonry unit cost} = {} & \text{Materials costs} + \text{Labour costs} + \text{Time utilisation costs} \\ & + \text{Carbon emissions costs}\end{aligned}$$

3. Results and discussion

3.1. Baseline survey findings

A semi-structured interview of 117 concrete block makers revealed 76.1% manufactured both hollow and solid blocks. 75% used a mix of cement, sand, and stone dust. About 50% preferred pit sand for its finer particles, which improved workability and stability of wet concrete blocks when combined with stone dust.

In contrast, river sand's coarser particles made it less desirable, often requiring more water to achieve the right consistency and cohesion for stable wet concrete blocks. 90% of block makers made blocks by hand, often on construction sites. Although the mean mix ratio was 1: (3.9) : (6.9), the data's skewness (1.33 for sand ratio and 1.28 for stone dust) indicated a positively skewed distribution, making the mode a more reliable indicator of central tendency. The mode yielded a ratio of 1: (2.7) : (5.6), which was rounded to 1:3:6 for practical measurement purposes. The water:cement ratio was observed to be between 0.7 and 0.9, and nearly all respondents (96.6%) used spraying and covering for curing.

3.2. Mass, density and water absorption of masonry units

The mass, density, and water absorption of the masonry units are summarised in Table 4.

According to the (NIOSH 2007) revised lifting equation, the recommended maximum weight for two-handed lifting over a substantial period (around 8 h per day) is 51 pounds (23.133 kg). Based on this guideline, only the EB and SD masonry units in Table 4 are ergonomically suitable for construction and can be considered lightweight in this context. The PS, HB, and SB units exceed the recommended limit by 61%, 45%, and 79%, respectively. The large difference in water absorption between 3% and 4% and 12–13% is likely due to voids between bottles that trap water when soaked. According to ASTM C90-22 (Table 3), EB, SD, and HB are classified as lightweight masonry units, PS as medium-weight, and SB as normal-weight units.

3.3. Compressive strength results

3.3.1. Plastic bottle bricks (PBBs)/Infilled plastic bottles

Compressive tests were carried out on the PBBs for varying filler materials (Figure 10), in the vertical and horizontal orientations, as summarised in Table 5.

Table 5 shows that PBBs in the horizontal orientation exhibited higher failure loads than in the vertical orientation. In the vertical orientation, the bottles behave as thin-walled cylindrical shells under axial compression, with a small contact area that concentrates load and promotes buckling, particularly at the neck and base (Young and Budynas 2002). The low second moment of area provides little resistance to

Table 4. Mass of various masonry units.

Sample ID	Sample Description	Mass (kg)	Volume (m^3)	Density (kg/m^3)	Water absorption (%)
EB	Empty plastic bottle block	21.683±0.839	0.02	1,084.15	12
SD	Saw dust filled PBB block	23.186±0.460	0.02	1,159.30	15
PS	Pit sand filled PBB block	37.214±0.677	0.02	1,860.70	4
HB	Hollow concrete block	33.600±0.982	0.02	1,680.00	4
SB	Solid concrete block	41.517±1.123	0.02	2,075.85	3

Figure 10. Buckling an empty plastic bottle in the vertical orientation (left), flattening of an empty plastic bottle in the horizontal orientation (right).

Table 5. Failure load of PBBs/infilled plastic bottles in compression.

ID	Sample description	Failure load (kN)	Strain (%)
EbV	Empty bottle in the vertical orientation	1.1±0.071	8.8
EbH	Empty bottle in the horizontal orientation	1.8±0.071	24.2
SdV	Saw dust filled bottle in the vertical orientation	1.3±0.000	8.8
SdH	Saw dust filled bottle in the horizontal orientation	5.4±1.202	42.2
PsV	Pit sand filled bottle in the vertical orientation	5.7±0.071	14.5
PsH	Pit sand filled bottle in the horizontal orientation	28.9±1.556	30.8

bending, especially for empty bottles, while filled bottles offer slightly more resistance, explaining the differences in strength. Additionally, imperfections at the neck and base further increase susceptibility to buckling. In contrast, bottles in the horizontal orientation are compressed along their cylindrical walls, which have a larger contact area and higher second moment of area. This configuration allows the load to be better distributed to the filler material, resulting in higher compressive strength. Horizontal tests also showed larger strains (24.2–42.2%) and more deformation, while vertical tests exhibited smaller strains (8.8–14.5%) and more stability despite lower strength.

The horizontally oriented PBBs exhibited higher compressive strength than vertically oriented bottles but also showed significantly larger deflections, indicating a greater susceptibility to excessive deformation. On the other hand, vertically oriented bottles, although of lower strength, demonstrated reduced deformation and more stable behaviour. In conventional construction where wall thicknesses of 200 mm or less are preferred, horizontally oriented bottles with wall thicknesses exceeding 200 mm (approximately 250 mm in this study), reduce the usable floor space. In contrast, the 65 mm diameter of vertically oriented bottles allows up to three courses of bottles to be accommodated within a conventional maximum wall thickness of 200 mm, while maintaining lower deformation. Therefore, vertically oriented PBBs are a more viable alternative for conventional masonry construction despite their lower compressive strength.

3.3.2. *Masonry units (blocks)*

Compressive tests were conducted on PBB masonry units with three filler types: air, sawdust, and pit sand. For each filler, the embedded bottles were tested in both vertical and horizontal orientations (Figure 11).

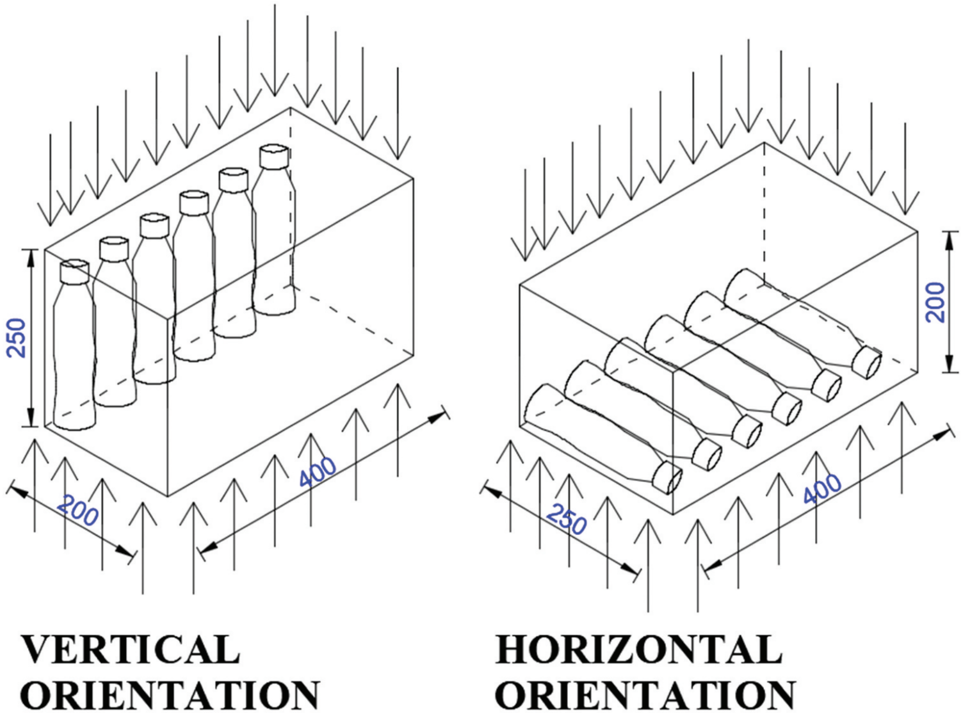

Figure 11. Loading of masonry unit samples using a compression testing machine.

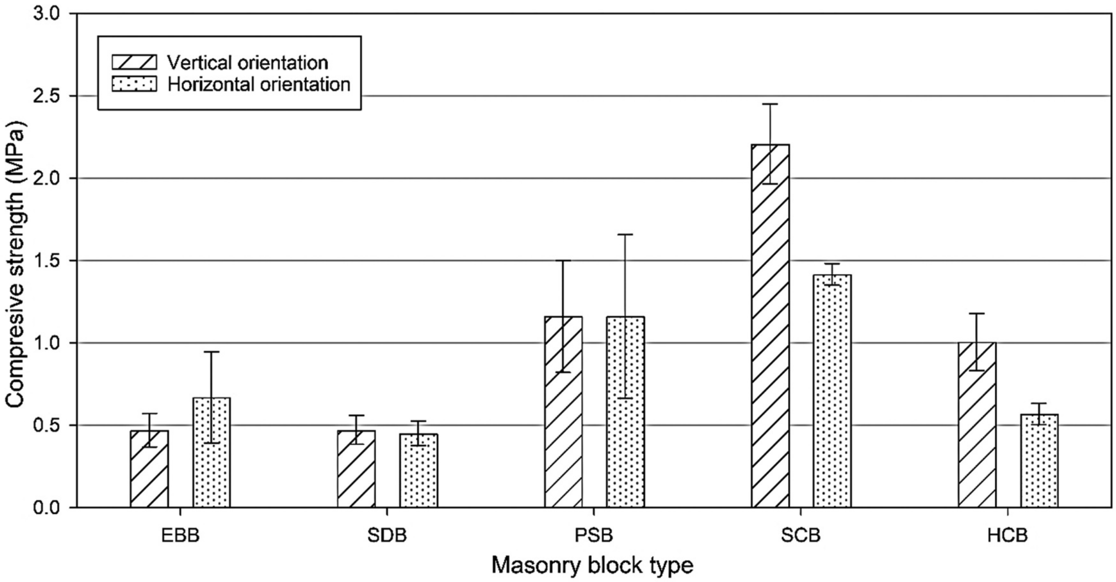

Figure 12. Compressive strength for PBB and concrete blocks.

The tested blocks included empty bottle blocks (EBB), sawdust-filled bottle blocks (SDB), pit sand-filled bottle blocks (PSB), solid concrete blocks (SCB), and hollow concrete blocks (HCB).

In the vertical orientation (Figure 12), SCBs exhibited the highest compressive strength due to their continuous and homogeneous load-bearing cross-section (Agunwamba, Ezeokonkwo, and Onyia 2016). In contrast, PBB units, with confined plastic bottles at their cores, are inherently weaker. However, pit sand-filled PBB units outperformed hollow concrete blocks because the compacted sand (80% density ≈1,860.7 kg/m^3) enhanced the structural contribution of the bottle cores, approaching the density of solid concrete (2,075.86 kg/m^3). Failure in SCBs occurred along diagonal shear planes, typical under uniaxial compression (Celano et al. 2021), while hollow concrete blocks failed along flanges and webs due to stress concentrations (Lü´ et al. 2012). PBB units failed at the mortar–bottle interface due to poor adhesion, followed by progressive buckling of the vertical bottles, which carried most of the axial load (Wonderlich 2014). The ductile nature of plastic caused a gradual, visibly deformed failure rather than sudden collapse.

In the horizontal orientation, SCBs again showed the highest average compressive strength, but pit sand-filled PBB units had overlapping standard deviation error bars, indicating comparable strength distribution. The reduction in concrete block strength was partly due to the reduced load-bearing depth from 250 mm to 200 mm, which decreased the moment of inertia and shear resistance. Hollow concrete blocks also showed overlapping error bars with empty and sawdust-filled PBB units, reflecting similar compressive strength; their lower strength was attributed to smaller load-bearing webs and elevated stress concentrations (Agunwamba, Ezeokonkwo, and Onyia 2016; Liu et al. 2018). Interestingly, empty bottle PBB units showed slightly higher mean strength than sawdust-filled units, possibly due to better damping under sustained loading. However, overlapping standard deviations indicate the difference is not statistically significant, and their compressive performance can be considered equivalent within experimental error.

Most conventional codes, including Eurocode 6 (EN 1996–1-1), BS 5628, and ACI 530 ASCE 5 TMS 402, do not clearly prescribe a minimum compressive strength for load bearing masonry units. However, some national provisions, such as the Danish National Annex to Eurocode 6 (DS/EN 1996–1-1 DK NA:2019), recommend a minimum compressive strength of 1.8 MPa for load bearing masonry units. Based on this criterion, only the SCB units qualify as load bearing masonry units. By comparison, a study by (Owino 2019) on masonry bricks used in Metropolitan Kampala, Uganda reported compressive strengths ranging from 1.08 to 14.38 MPa, with most of these units being used in load bearing walls. Using the lower boundary of 1.08 MPa as a practical reference, PSB and HCB units could also be considered suitable for load bearing

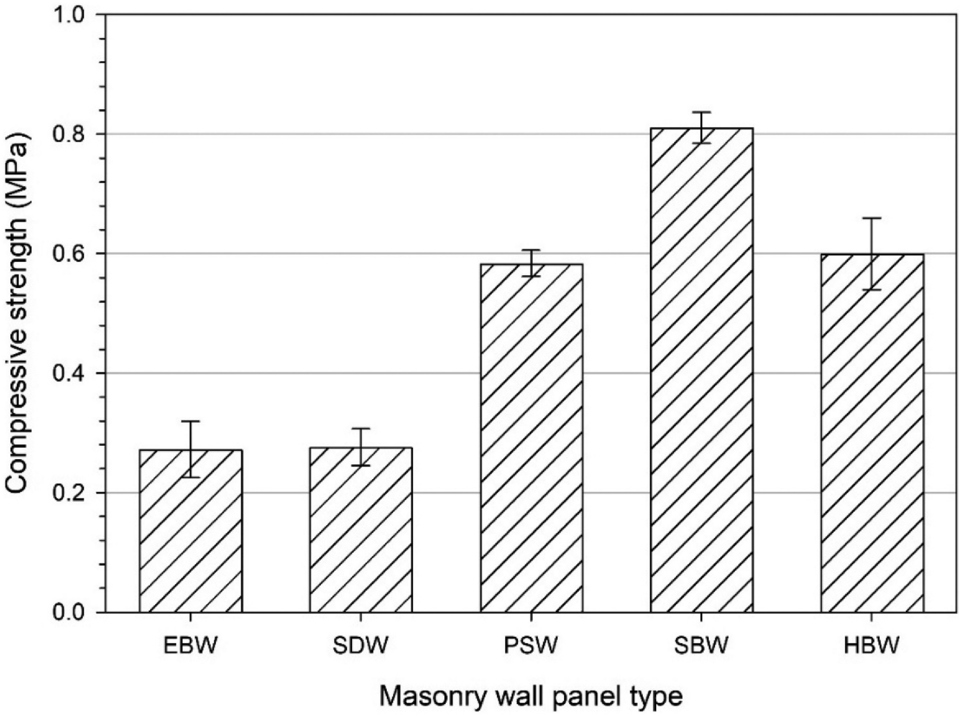

Figure 13. Compressive strength for PBB and concrete block walls.

applications. In contrast, EBB and SDB units are more appropriate for non-load bearing applications, such as partition walls in multi storey buildings, due to their lower strength and lightweight nature.

3.3.3. *Masonry wall tests*

The wall panels tested for compression included empty bottle block walls (EBW), sawdust PBB block walls (SDW), pit sand PBB block walls (PSW), solid concrete block walls (SBW), and hollow concrete block walls (HBW). These abbreviations are used consistently in all subsequent figures and tables.

Figure 13 presents the compressive strength results for all tested specimens, showing average values ranging from 0.3 MPa to 0.8 MPa with a standard deviation below 0.06 MPa, indicating consistent behaviour within each group of wall panels. Solid concrete blocks outperformed all PBB masonry panels by over 30% and also exceeded hollow concrete blocks, confirming their superior load-bearing capacity. Hollow concrete blocks exhibited similar strength to pit sand-filled PBB panels, highlighting the significant structural contribution of the sand filler. In contrast, unfilled (air-filled) and sawdust-filled PBB walls showed comparable strength, suggesting minimal structural benefit from sawdust.

Despite lower compressive strength, PBB panels demonstrated more gradual and ductile failure compared to the sudden, catastrophic failure of solid and hollow concrete walls (Rafi and Khan 2024). This ductility, reflected in higher strain values, provides an advantage in applications where energy absorption and warning before failure are important. The ability of PBB walls to deform without immediate collapse indicates their potential for low-load or non-load-bearing structures where resilience and post-peak performance are valued.

3.3.4. *Comparison of walls with masonry units*

The reduction in compressive strength from individual masonry units to full wall panels reflects the typical behaviour of masonry under axial load. Wall panels are weaker than their constituent units due to mortar joints, minor misalignments, and other discontinuities, consistent with BS 5628–1:2005, Clause 3.3, and Eurocode 6 (BS EN 1996–1-1:2005, Clause 5.2.2). For PBB walls, strength decreased by 40–50%, while concrete block walls showed reductions of 40–64%, stressing the effects of joint behaviour, unit heterogeneity, and wall geometry. Similar reductions between PBB and conventional masonry, in agreement with (Tokpomehoun et al. 2022), indicate a predictable correlation between unit and wall-level performance.

However, there's a need to account for wall-level effects in design rather than relying solely on unit compressive strengths, especially for non-uniform or alternative masonry units such as infilled bottles or PBBs.

3.4. Deformation values for masonry wall panels

The tested masonry panels measured approximately 1100 mm in height and 200 mm in thickness, giving a slenderness ratio of 5.5, classifying them as short walls unlikely to buckle according to Eurocode 6 (EN 1996–1-1). Consequently, strain measurements were based on vertical deflection. Vertical deformation was recorded on both the left and right sides of each panel, and the results are summarised in Table 6.

Plastic bottle brick (PBB) masonry walls exhibited higher strain values (1.8–2.0%) than concrete blocks (1.0–1.2%), indicating at least 57% greater ductility. PBB walls showed gradual, progressive cracking, while concrete walls failed suddenly and catastrophically. This enhanced ductility is due to the confinement provided by sisal-wrapped plastic bottles, allowing greater energy absorption, delayed crack propagation, and improved performance under dynamic or impact loads. Although their compressive strength may be lower, PBB walls are well-suited for low-risk or secondary applications, such as infill walls, where deformation is advantageous.

3.5. Failure patterns

3.5.1. PBB block failure patterns

3.5.1.1. Vertical orientation. Initially, the load was transmitted through the mortar and carried by the PBBs without visible damage. With further loading, cracks developed along the failure planes (Figure 14), with longer edges showing more damage. Failure was attributed to buckling of the bottles due to a low second moment of area and excessive deformation under heavy loads. After significant deflection and mortar

Table 6. Deflection and strain results for masonry walls at peak load.

Sample ID	Wall description	Strain (%)
EBW	Empty Plastic bottle walls	1.8±0.047
SDW	Saw dust filled bottle walls	1.9±0.031
PSW	Pit sand filled bottle walls	2.0±0.022
SBW	Solid concrete block walls	1.2±0.026
HBW	Hollow concrete block walls	1.0±0.060

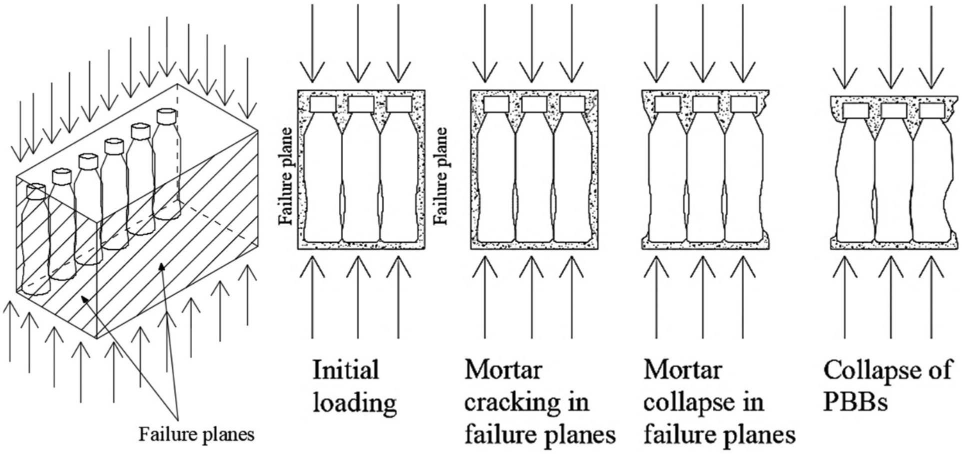

Figure 14. Typical failure patterns for PBB blocks in the vertical orientation.

Figure 15. EBB block failure (left), PSB block failure (centre), SDB block failure (right).

cracking, the PBBs continued to support the load until visible collapse or buckling occurred in some units (Figure 15).

3.5.1.2. Horizontal orientation loading. Initially, the load was carried by the mortar and PBBs without visible damage. With increased loading, cracks developed along the failure planes (Figure 16), particularly along the longer edges. After significant deflection and mortar cracking, the PBBs continued to support the load until some units collapsed (Figure 17).

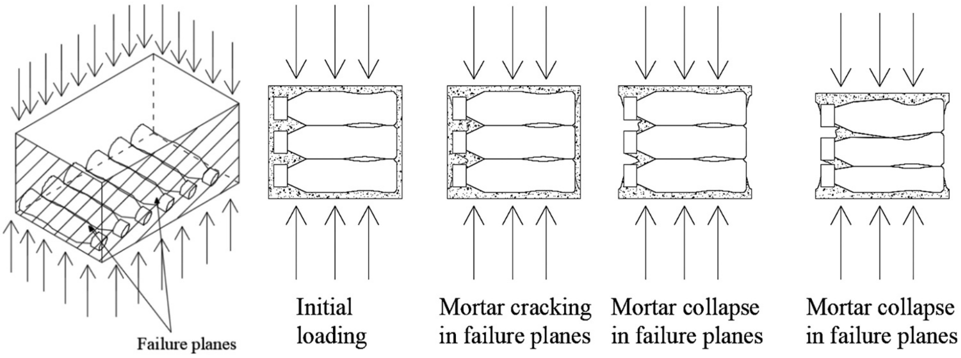

Figure 16. Typical failure patterns for PBB blocks in the horizontal orientation.

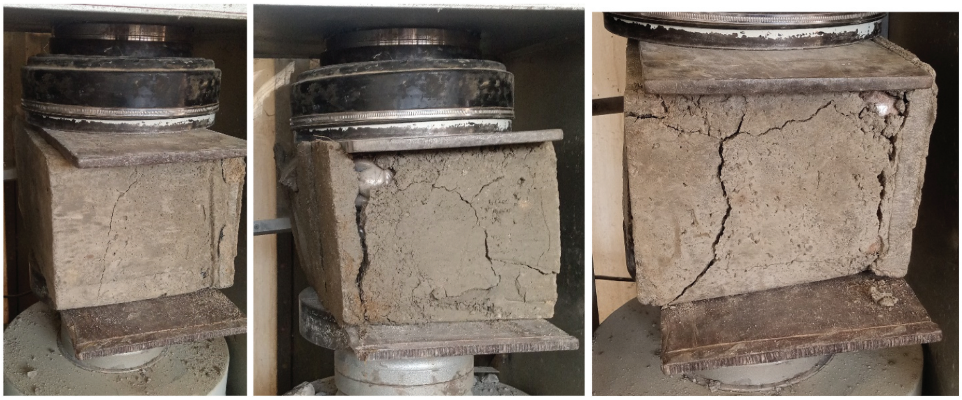

Figure 17. EBB block failure (left), PSB block failure (centre), SDB block failure (right).

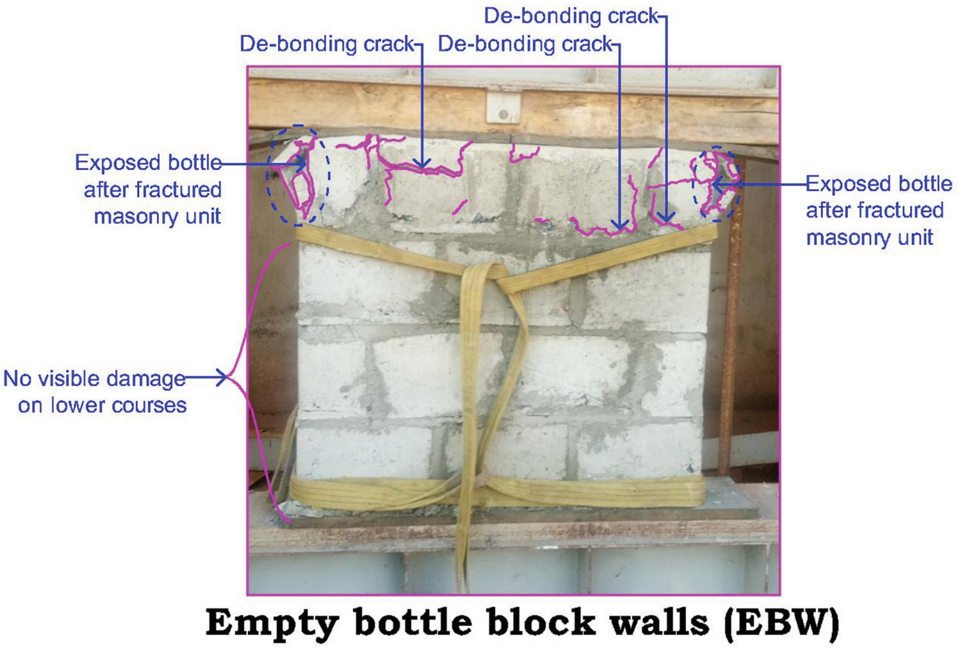

Figure 18. Failure patterns for walls constructed using empty bottle blocks.

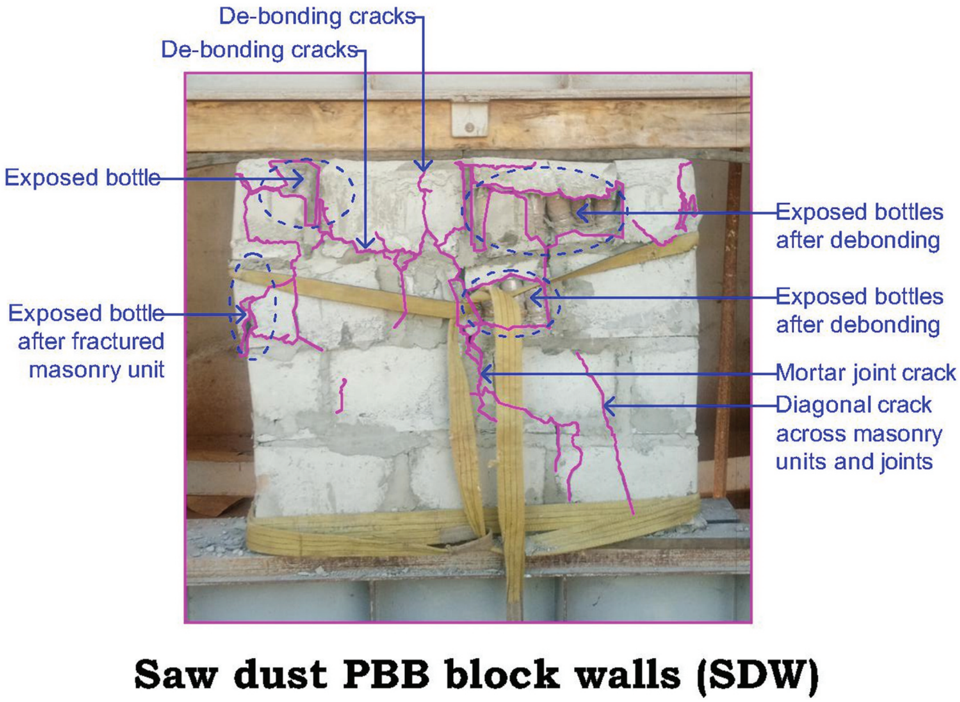

Figure 19. Failure patterns for walls constructed using Saw dust PBB blocks.

3.5.2. Masonry wall failure patterns

The failure patterns for PBB masonry wall samples were observed for each masonry walls specimen, and the failure patterns at peak load have been traced in Figures 18–20.

For the EBW specimens (Figure 18), cracks were mostly limited to the first course, likely due to buckling of the empty bottles and insufficient load transfer to lower courses. SDW specimens (Figure 19) showed similar peak loads, but the sawdust helped resist bottle buckling, allowing load distribution to lower courses. PSW specimens (Figure 20) exhibited more uniform crack patterns, reflecting the compacted sand's ability

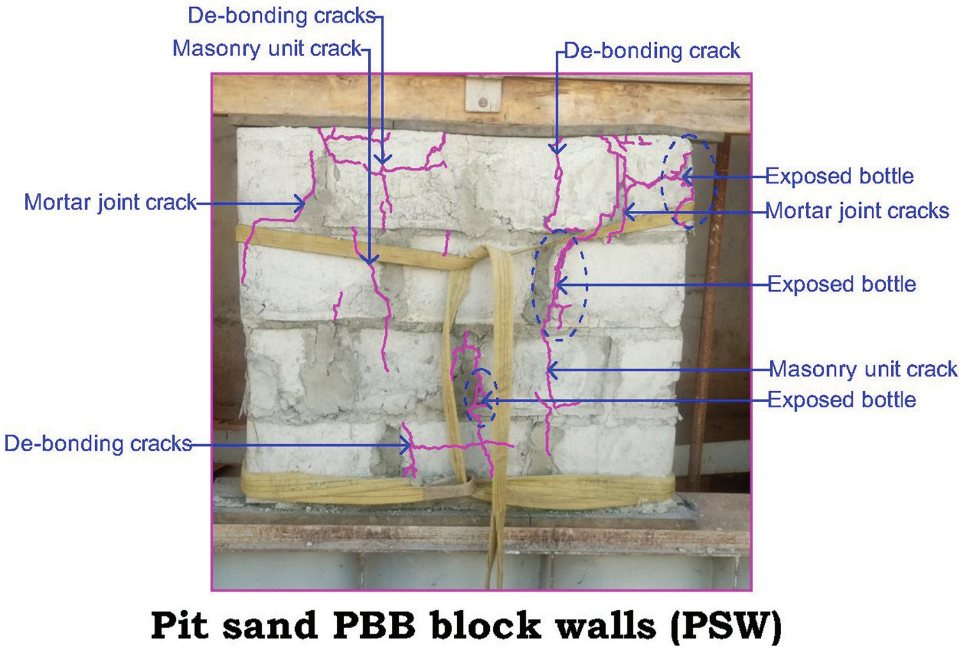

Figure 20. Failure patterns for walls constructed using pit sand PBB blocks.


Solid concrete block wall specimen **Hollow concrete block wall specimen**

Figure 21. Crack propagation for concrete block walls at peak load.

to prevent buckling and promote effective load transfer. Failure patterns for the concrete block walls are also shown in Figure 21.

Both concrete wall panels exhibited a sudden, brittle failure characterised by a dominant, nearly linear crack path that formed at peak load. This behaviour reflects the limited post-peak deformation capacity of conventional concrete masonry, which tends to fracture abruptly once its tensile capacity is exceeded.

3.6. Cost-benefit analysis

3.6.1. Materials costs

All materials used in the study were locally sourced, and their rates were established using a brief market survey as shown in Table 7.

Table 7. A summary of rates for locally purchased materials.

No.	Material Description	Unit	Rate (UGX)
1.	50kg Tororo Cement, CEM IV B (P) 32.5N – PC	Bag	31,000
2.	90m sisal rope	Rolls	5,000
3.	2 cubic meter trip of pit sand	Trip	60,000
4.	2 cubic meter trip of river sand	Trip	90,000
5.	2 cubic meter trip of stone dust	Trip	160,000
4.	Empty bottles with bottle tops	Item	20

The material rates for the PBB blocks were established using the formula below:

$$\text{Materials rate(Ugx.)} = \frac{\text{Material market price}}{\text{Standardised material quantity}}$$

17 plastic bottles, around 11.05 m of sisal rope, and approximately 0.01275 cubic metres of a 1:4 dry mortar mix by volume were used to produce each PBB masonry unit, and materials costs have been summarised in Table 8:

3.6.2. Labour costs

The labour rates were quantified based on outputs using the formula below.

$$\text{Labour rate} = \frac{\text{Daily labour rate for atask}}{\text{Quantity of task outputs}}$$

The labour costs for each masonry unit are quantified in Table 9.

3.6.3. Time utilisation cost

The duration per output was based on an approximated 10-hour work day, and hence the time taken to achieve each task was quantified using the formula below.

$$\text{Duration per output(hours/output)} = \frac{\text{Quantity of task outputs achieved daily}}{10}$$

Considering a weighted average labour cost of about Ugx. 15,000 was recorded, for a 10-hour working day, which gives an hourly rate of about Ugx. 1500 per hour. The quantification of time in monetary terms has been calculated in Table 10.

Table 8. Material costs per masonry block produced.

Material	Quantity utilised	Unit Cost (UGX)	Total Cost (UGX)
Cement	3.57 kg	620	2,213
Pit sand	0.0102 m^3	30,000	306
Sealed empty bottles	17 pieces	20	340
Sisal rope	11.05 m	55.6	614
Uncompressed air PBB block materials cost			**3,473**
Cement	3.57 kg	620	2,213
Pit sand	0.0102 m^3	30,000	306
Sealed empty bottles	17 pieces	20	340
Sisal rope	11.05 m	55.6	614
Saw dust	3.06 kg	28.6	88
Saw dust PBB block materials cost			**3,561**
Cement	3.57 kg	620	2,213
Pit sand	0.0193 m^3	30,000	579
Empty bottles with bottle tops	17 pieces	20	340
Sisal rope	11.05 m	55.6	614
Pit sand PBB block materials cost			**3,746**
Cement	3.758 kg	620	2,330
Pit sand	0.0081 m^3	30,000	243
Stone dust	0.0161 m^3	80,000	1,288
Solid concrete block materials cost			**3,861**
Cement	3.006 kg	620	1,864
Pit sand	0.0064 m^3	30,000	192
Stone dust	0.0129 m^3	80,000	1,032
Hollow concrete block materials cost			**3,088**

Table 9. Labour costs per masonry unit produced for masonry units.

Task description	Quantity of tasks	Unit Cost (UGX)	Total Cost (UGX)
Cleaning of plastic bottles	17 bottles	2.5	43
Tying of plastic bottles	1 block	500	500
Casting and Curing of blocks	1 block	1,031	1,031
Uncompressed air PBB block labour cost			**1,574**
Cleaning of plastic bottles	17 bottles	2.5	43
Filling of plastic bottle bricks	17 bottles	150	2,550
Tying of plastic bottle bricks	1 block	500	500
Casting and Curing of blocks	1 block	1,031	1,031
Saw dust PBB block labour cost			**4,124**
Cleaning of plastic bottles	17 bottles	2.5	43
Filling of plastic bottle bricks	17 bottles	100	1,700
Tying of plastic bottle bricks	1 block	500	500
Casting and Curing of blocks	1 block	1,031	1,031
Pit sand PBB block labour cost			**3,274**
Casting and Curing of blocks	1 block	1,717	1,717
Solid concrete block labour cost			**1,717**
Casting and Curing of blocks	1 block	1,717	1,717
Hollow concrete block labour cost			**1,717**

Table 10. Time utilisation cost in Ugandan shillings (Ugx.).

Task description	Task duration (hours)	Unit Cost (UGX)	Total Cost (UGX)
Tying of plastic bottles	0.25	1,500	375
Casting of masonry unit	0.357	1,500	536
Uncompressed air PBB block time utilisation cost			**911**
Filling of plastic bottle bricks	3.536	1,500	5,304
Tying of plastic bottle bricks	0.25	1,500	375
Casting of masonry unit	0.357	1,500	536
Saw dust PBB block time utilisation cost			**6,215**
Filling of plastic bottle bricks	3.536	1,500	5,304
Tying of plastic bottle bricks	0.25	1,500	375
Casting of masonry unit	0.357	1,500	536
Pit sand PBB block time utilisation cost			**6,215**
Casting of masonry unit	0.303	1,500	455
Solid concrete block time utilisation cost			**455**
Casting of masonry unit	0.303	1,500	455
Hollow concrete block time utilisation cost			**455**

3.6.4. Carbon emissions cost

Based on a literature review on carbon emissions used to process the materials used in this study, these figures were used to quantify carbon emissions for all materials as summarised in Table 11.

The estimated minimum (World Bank Group 2024) carbon tax worldwide was USD 0.46 (as of 30 May 2025) adopted for this quantification, which equals to about UGX 1668. The formula below was used to quantify the carbon emissions cost.

$$\begin{aligned}\text{Carbon emissions cost for amaterial} = {} & \text{Quantity of materials used} \\ & \times \text{Carbon emissions per unit of material} \times \text{Carbon tax rate}\end{aligned}$$

Based on the above inputs, the calculations are tabulated in Table 12 for each masonry unit type.

3.6.5. Cost comparison

The results from the costs were consolidated into a stacked column chart, as shown in Figure 22, to illustrate the cost trade-offs among the different masonry units.

Table 11. Carbon emissions from literature.

Material Description	Carbon emissions (kg of CO_2/ton)	Source
Cement	507.1	(IPCC 2006)
Pit sand	11.73	(Henderson, Atkinson, and Dawson 2024)
Plastic bottles	4,150	(Beverage Industry Environmental Roundtable 2012)
Sisal rope	0.00072	(CarbonCloud 2024)
Saw dust	1,566.98	(Ove Arup & Partners Limited, Embodied Carbon 2023)
Stone dust	8.1	(Meddah 2017)

Table 12. Embodied carbon emissions in each masonry unit.

Material	Quantity utilised	Carbon emissions (kg)	Carbon emissions tax (UGX)	Total Cost (UGX)
Cement	3.57 kg	1810.347	1,668	3,020
Pit sand	0.0102 m^3	217.65015	1,668	363
Sealed empty bottles	17 bottles	1411	1,668	2,354
Sisal rope	11.05 m	0.000036	1,668	0
Uncompressed air PBB block carbon emissions cost				**5,736**
Cement	3.57 kg	1810.347	1,668	3,020
Pit sand	0.0102 m^3	217.65015	1,668	363
Sealed empty bottles	17 bottles	1411	1,668	2,354
Sisal rope	11.05 m	0.000036	1,668	0
Saw dust	3.06 kg	4794.95268	1,668	7,998
Saw dust PBB block carbon emissions cost				**13,734**
Cement	3.57 kg	1810.347	1,668	3,020
Pit sand	0.0193 m^3	411.82857	1,668	687
Empty bottles with bottle tops	17 bottles	1411	1,668	2,354
Sisal rope	11.05 m	0.000036	1,668	0
Pit sand PBB block carbon emissions cost				**6,060**
Cement	3.758 kg	1905.6818	620	1,182
Pit sand	0.0081 m^3	172.84155	30,000	5,185
Stone dust	0.0161 m^3	275.0355	60,000	16,502
Solid concrete block carbon emissions cost				**22,869**
Cement	3.006 kg	1524.3426	620	945
Pit sand	0.0064 m^3	136.56066	30,000	4,097
Stone dust	0.0129 m^3	220.3686	60,000	13,222
Hollow concrete block carbon emissions cost				**18,264**

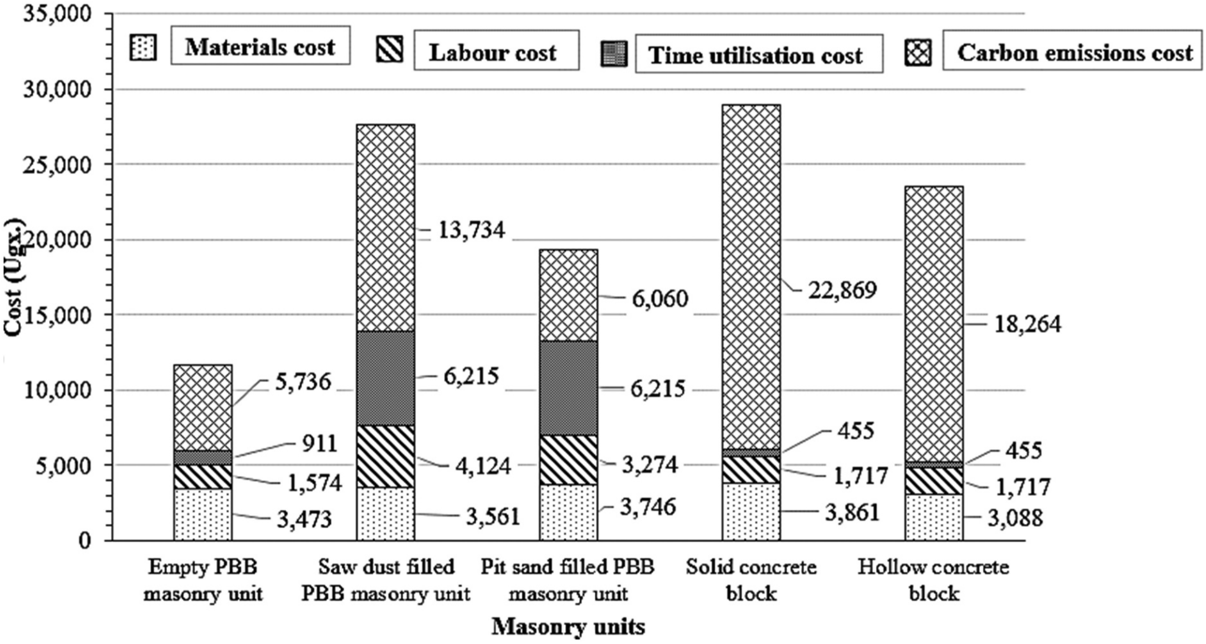

Figure 22. Cost-benefit assessment for masonry units.

All three PBB masonry units (empty bottle, sawdust-filled, and pit sand-filled) consistently have lower material costs than solid concrete blocks (SCB) due to the use of low-cost or waste materials like discarded plastic bottles. Hollow concrete blocks (HCB) have the lowest material costs because voids reduce the amount of cement and stone dust required. Labour costs for SCB and HCB are generally lower than for PBB units due to mechanisation, economies of scale, and simpler production methods. For PBB units, labour is highest for bottle filling, which accounts for over 50% of the effort for SDB and PSB and about 85% of production time per unit. Mechanising this process could significantly reduce both labour and time costs. PBB units excel in carbon cost, with EBB and PSB showing substantially lower emissions by repurposing plastic and reducing reliance on energy-intensive materials. While SDB has higher carbon emissions than

EBB and PSB, it remains far lower than SCB and HCB, highlighting the environmental advantage of PBB masonry in carbon-conscious construction despite higher labour and time requirements.

3.6.6. Cost-benefit comparison

The cost-benefit analysis was performed using Net Present Value (NPV) and Benefit-Cost Ratio (BCR), considering material and labour costs as expenses, and time savings and carbon reduction as benefits. Carbon reduction benefit was calculated as 22,869 minus the unit's carbon emissions, using the emissions cost of solid concrete blocks (Ugx 22,869) as a baseline. Time saving benefit was 455 minus the unit's time utilisation cost, with solid concrete blocks (Ugx 455) as the baseline. Total costs equalled material plus labour costs, total benefits equalled carbon reduction plus time saving benefits, net benefit was total benefits minus total costs, and BCR was total benefits divided by total costs. The Net benefits and Benefit-cost ratios for each block are summarised in Table 13.

The BCR for solid blocks is zero since their carbon and time costs were used as the baseline. Among the alternatives, sawdust-filled bottle blocks were the least cost-effective, with costs exceeding benefits by 56% due to high labour and carbon emissions. Empty bottle blocks achieved the highest net benefits and BCR, making them the most cost-effective, followed by pit sand-filled blocks. Hollow blocks performed better than solid blocks in BCR but were outperformed by both empty and pit sand-filled bottle blocks in overall benefits.

3.7. Comparisons with literature

Two main PET bottle construction methods have been reported: (1) replacing bricks with loose Plastic Bottle Bricks (PBBs) and (2) remoulding bottles into interlocking units. The first approach suffers from poor aesthetics and high mortar use, while the second, though visually appealing, is not cost effective due to the additional processing required (Pradeep et al. 2022). In contrast, the PBB masonry units developed in this study match conventional block geometry, require no additional skills, and use at least 4% less mortar than Method 1, making them more practical for field adoption. Interlocking bottles have been proposed for rapid shelter construction (Mansour and Mansour 2021), but they are not commercially available and would only be viable under large scale humanitarian deployment.

Previous studies have also employed confinement to enhance bottle stability (Premalatha et al. 2016). introduced steel mesh between PBB courses, increasing strength but raising costs, whereas sisal rope was a more economical alternative. Other studies used top or bottom tying methods (Jo 2024; Parab et al. 2021). The current study combined both top and bottom confinement to reduce instability associated with tying only one end.

Most literature reports compressive strength tests on 500 ml horizontally oriented PBBs, with similar bottle flattening observed. Pit sand filled PBBs in this study averaged 28.9 kN, higher than sand filled 500 ml bottles 11.25 kN, by (Muyen, Barna, and Hoque 2016) and fly ash filled bottles 18.1 kN, by (Premalatha et al. 2016) due to differences in bottle geometry and filler material properties. Several authors embedded PBBs in mortar or concrete to increase load capacity (Robleh, Koteng, and Kabubo 2021). achieved 9–20 MPa using concrete blocks with vertically oriented bottles and a bottle area of only 4.7% compared to this study's 60.1%, which hints at a greater compressive strength contribution of the confined bottle core rather than the mortar (Wonderlich 2014). reported 2.2–6.2 MPa using mortar covered, horizontally oriented bottles, with a high cement content (Tokpomehoun et al. 2022). recorded 1.8–2.8 MPa for bottles embedded in 1:3 mortar and confined with steel wire, and 0.8–1.4 MPa for corresponding wall panels both higher than this

Table 13. Net benefits and benefit-cost ratios for masonry units.

Masonry unit ID	Masonry unit description	Total costs (Ugx.)	Total benefit (Ugx.)	Net benefit (Ugx.)	BCR
EBB	Empty bottle block	5,047	16,677	11,630	3.30
SDB	Saw dust bottle block	7,685	3,375	−4,310	0.44
PSB	Pit sand bottle block	7,020	11,049	4,029	1.57
SCB	Solid concrete block	5,578	0	−5,578	0.00
HCB	Hollow concrete block	4,805	4,605	−200	0.96

study due to stronger mortar, steel confinement, and geometric differences. These approaches achieved higher strengths but at notably higher costs and lower environmental performance.

A major limitation across prior work is the heavy formwork demand for block production, often requiring 24 h before formwork was removed for each masonry unit. The present study addressed this by using reusable damp proof membrane strips to provide temporary support to the wet blocks, hence enabling immediate formwork removal similar to conventional concrete blocks and improving scalability. Overall, while many earlier PBB based units exhibited higher compressive strength largely because of substantial mortar or concrete content the PBB masonry units developed in this study offer improved cost effectiveness, reduced material demand, faster production, conventional aesthetics, and lower reskilling requirements, addressing several practical barriers that previously limited the viability of bottle-based construction.

4. Conclusion

This study was carried out to assess the compressive strength and cost effectiveness of confined waste plastic bottle brick masonry walls using experimental methods. The study revealed that among the PBB variants, the PSB units achieved a compressive strength of 1.2 ± 0.34 MPa, closely approaching the performance of HCB units (1.0 ± 0.17 MPa). In contrast, the SDB and EBB units recorded compressive strengths of 0.5 ± 0.10 MPa and 0.5 ± 0.09 MPa, respectively in the vertical orientation, all of which were significantly lower than SCB units (2.2 ± 0.24 MPa). Overall, PBB blocks are more suited for use as non-loadbearing infill walling materials.

In addition, the PSB walls attained a compressive strength of 0.6 ± 0.02 MPa, which was comparable to that of the HCB walls (0.6 ± 0.06 MPa). However, the SDB and EBB walls recorded lower mean strengths of 0.3 ± 0.05 MPa and 0.3 ± 0.03 MPa, respectively, which were well below the SCB walls (0.8 ± 0.03 MPa). Despite their lower peak strength, all PBB walls exhibited superior ductility and gradual failure patterns (1.8, 1.9, and 2.0%), contrasting with the brittle collapse observed in concrete block walls (1.2 and 1.0%). These results indicate that while PSB units possess adequate compressive capacity for small-scale or low-rise load-bearing applications, the EBB and SDB units are more suited for lightweight, non-load-bearing infill walls.

A cost-benefit analysis taking into account material, labour, time utilisation, and carbon emission costs showed that the EBB units were the most economical (UGX 11,694/USD 3.22), while the SCB units (UGX 28,902/USD 7.97) were the least economic. The SDB units, priced at UGX 27,634/USD 7.62, were the only PBB variant whose cost exceeded that of the HCB units (UGX 23,524/USD 6.49), primarily due to the carbon emissions cost for saw dust. The study also established a practical production methodology through which PBB masonry units could be fabricated at a casting speed only 17% slower than that of solid and hollow concrete blocks, making the process commercially viable and compatible with existing formwork systems used in the local construction industry.

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Author contributions

CRediT: **Emmison Eric Masaba:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Micheal Kyakula:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – review & editing; **Vicent Ssenyondo:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization.

Disclosure statement

The Authors declare no financial or non-financial conflicts of interest that would in any way influence the findings of this research.

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Commitment to provide data

The data supporting the findings of this study is available from the corresponding author upon reasonable request, provided that disclosure does not compromise privacy or confidentiality.

Data repository

The datasets generated and/or analysed during this study are available in the zenodo.org repository, at https://doi.org/10.5281/zenodo.17115207. (Masaba 2025).

Ethical approvals

Ethical Approvals were not attained for this study. This was because voluntary interviews were conducted, and respondents were assured anonymity. All respondents were aged 18 years or older, and informed consent for participation in the interviews was obtained verbally. Verbal consent was chosen to respect the respondents' convenience, as majority were engaged in block making activities at the time of data collection.

Generative artificial intelligence (AI)

The authors used OpenAI's ChatGPT (GPT-5) to enhance the literature search, improve wording and clarity. All ideas, methodologies, results, and conclusions are the authors' own.

Limitations and gaps in data provision

The Kireka Central Materials Laboratory (cmL) did not issue certificates for the water absorption and compressive strength tests of masonry walls. However, photos and videos of the procedures have been deposited in the repository to ensure transparency of the methods used.

Details of the bottle confinement/tying process could not be fully described in the methodology due to its complexity. Supplementary photos have been provided in the repository to illustrate the procedure.

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