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Article

Mechanical Performance and Compressive Behaviour of Plastic Waste–Based Brick under Horizontal and Vertical Loading Orientations

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Abstract: Plastic waste–based bricks (PW-Bricks) offer a promising pathway for plastic waste valorisation in the construction sector; however, their mechanical performance is commonly evaluated using a single compressive strength metric that does not reflect actual masonry loading conditions. This study investigates the compressive behaviour of PW-Bricks under horizontal and vertical loading and proposes an orientation-sensitive evaluation framework for mix optimization. PW-Bricks incorporating 20–50% plastic waste were fabricated alongside conventional cement–sand bricks as control specimens and tested at curing ages of 3, 7, and 10 days following ASTM C109/C109M-21. The results demonstrate a pronounced orientation-dependent response. Under horizontal loading, compressive strength increased with plastic waste content and curing age, reaching 30.15 MPa for PW-Bricks containing 50% plastic waste at 10 days, compared with 22.74 MPa for conventional bricks. In contrast, under vertical loading, PW-Bricks exhibited relatively low and nearly constant compressive strengths ranging from 1.08 to 1.22 MPa, whereas conventional bricks achieved 2.48 MPa at 10 days. To evaluate this trade-off, normalized horizontal and vertical strength indices were integrated into a composite performance index balancing enhanced horizontal resistance with minimum vertical stability requirements. Based on this evaluation, PW-Bricks containing 40% plastic waste were identified as the optimal mix, providing the most favourable balance between mechanical performance, material homogeneity, and sustainability. The proposed framework offers a transferable methodology for evaluating heterogeneous waste-based masonry materials and supports application-oriented mix design for non-load-bearing and semi-structural masonry systems.

Keywords: Plastic waste–based bricks; Orientation-dependent compressive behaviour; Horizontal and vertical loading; Composite performance index; Sustainable masonry materials

1. Introduction

Plastic waste accumulation in Indonesia poses a growing environmental challenge due to the persistence of non-biodegradable polymers and limited recycling capacity (Das et al., 2025; Kelaniyagama et al., 2024; Nguyen, 2024; Shamsuddin et al., 2025). In parallel, the construction sector continues to rely heavily on resource-intensive conventional masonry materials (Ahmed, 2021; Georgiou et al., 2025; Rupal & Tank, 2025). These converging pressures have stimulated increasing interest in alternative masonry units that simultaneously enable plastic waste valorisation and deliver adequate mechanical performance (Athithan & Natarajan, 2023; Díaz et al., 2025; Ikechukwu & Naghizadeh, 2022).

Among these alternatives, plastic waste–based bricks (PW-Bricks) have emerged as a promising solution for integrating plastic waste into sustainable construction materials (Edike et al., 2023; El-Metwally et al., 2023; Kumar et al., 2021; Singh et al., 2023; Uvarajan et al., 2022). Recent studies have further demonstrated that incorporating recycled HDPE, LDPE, PP, and mixed plastic waste into masonry units can improve compressive performance, thermal insulation, and environmental sustainability (Díaz et al., 2025; Ong et al., 2023; Sarwar et al., 2023; Solomon et al., 2023). However, most existing studies still evaluate PW-Bricks using a single, orientation-agnostic compressive strength parameter (Kulkarni et al., 2022; Sahani et al., 2022), despite the fact that masonry elements in practical applications are subjected not only to axial loads but also to horizontal and combined loading conditions (Bazri et al., 2025). For heterogeneous materials incorporating plastic waste, mechanical responses may vary significantly with loading orientation due to anisotropic stress transfer and heterogeneous composite behaviour (Dowling et al., 1999; Suksiripattanapong et al., 2022; Thomason, 2002). As a result, reliance on a single compressive strength value can obscure critical trade-offs between vertical load-bearing capacity and horizontal resistance.

From a material behavior perspective, increasing plastic content may enhance ductility and horizontal resistance by improving stress redistribution and delaying brittle crack propagation within the composite matrix, while potentially reducing stiffness and vertical compressive strength (Valiev et al., 2002). In heterogeneous plastic–mineral composites, higher plastic incorporation may also weaken interfacial bonding and reduce the efficiency of axial stress transfer under vertical loading. Consequently, defining an optimal PW-Bricks mix ratio requires an evaluation framework that explicitly considers orientation-dependent mechanical behavior rather than relying solely on a single compressive strength value (Bhushaiah et al., 2019; Wahid et al., 2015). Despite its practical relevance, orientation-sensitive performance assessment remains insufficiently explored in current PW-Bricks research. Accordingly, this study treats loading orientation as an analytical variable and integrates orientation-sensitive responses into a unified performance-based evaluation framework for mix optimization

Unlike previous PW-Bricks studies that primarily report single compressive strength values, the present study explicitly treats loading orientation as an analytical variable and integrates orientation-sensitive responses into a unified performance-based evaluation framework for mix optimization.

Against this background, the present study proposes an orientation-sensitive evaluation framework to assess the mechanical behavior of PW-Bricks under both horizontal and vertical compressive loading conditions. The objectives of this research are to: (i) quantify the compressive strength of PW-Bricks under horizontal and vertical loading at different curing ages; (ii) examine the influence of plastic waste content on orientation-dependent mechanical performance; and (iii) identify an optimal PW-Bricks mix ratio that balances horizontal resistance, minimum vertical stability, and sustainability considerations. The developed PW-Bricks are primarily intended for non-load-bearing and semi-structural masonry applications, where horizontal resistance, deformation tolerance, and material sustainability are prioritized over primary axial load-bearing capacity.

This study is guided by the hypothesis that increasing plastic waste content enhances horizontal compressive resistance while reducing vertical load-bearing capacity, leading to a trade-off that governs the optimal mix proportion for practical applications. Accordingly, the following research questions are addressed: how does plastic waste content influence compressive strength under different loading orientations; to what extent does orientation-dependent behavior control PW-Bricks performance; and which plastic waste proportion provides the most favorable balance between mechanical performance and material sustainability.

By addressing these questions, this research advances the understanding of orientation-dependent behavior in plastic-modified masonry materials and provides a rational basis for defining optimal PW-Bricks mix ratios. Beyond its technical contributions, the findings support sustainable construction practices by linking plastic waste valorization with application-specific material design, particularly for non-load-bearing and modular masonry systems. Unlike previous studies that report compressive strength as a single scalar value, this study explicitly integrates loading orientation into a composite, performance-based evaluation framework.

2. Materials and Methods

This study builds on previous investigations of plastic waste–based construction materials conducted with different research objects and material configurations. Unlike earlier studies (Bhushaiah et al., 2019; Shrestha et al., 2023), this research explicitly examines loading orientation as an intervening factor and employs a conventional cement–sand brick as a control to isolate the mechanical effects of plastic waste incorporation. The subsequent methodology and analytical structure are detailed in Section 2.1 (Conceptual Framework), Section 2.2 (Materials and Specimen Preparation), Section 2.3 (Experimental Design and Testing), and Section 2.4 (Performance Evaluation and Analysis).

2.1. Conceptual Framework

This study employs a conceptual framework (Plamonia, 2020; Plamonia et al., 2024, 2026; Verschuren, 2003; Verschuren et al., 2010) . Conceptual Framework as an analytical structure for evaluating the orientation-dependent mechanical behavior of PW-Bricks. The framework consists of three core variables (See Figure 1): an independent variable, an intervening variable, and a dependent variable (MacKinnon et al., 2002), to evaluate the mechanical performance of PW-Bricks. Plastic waste content is defined as the independent variable governing the composite material composition and internal mechanical characteristics (X). Loading orientation functions as an intervening variable that conditions stress transfer mechanisms and failure modes within the heterogeneous plastic–mineral composite (Z). The dependent variable is represented by orientation-specific compressive performance and integrated performance outcomes (Y).

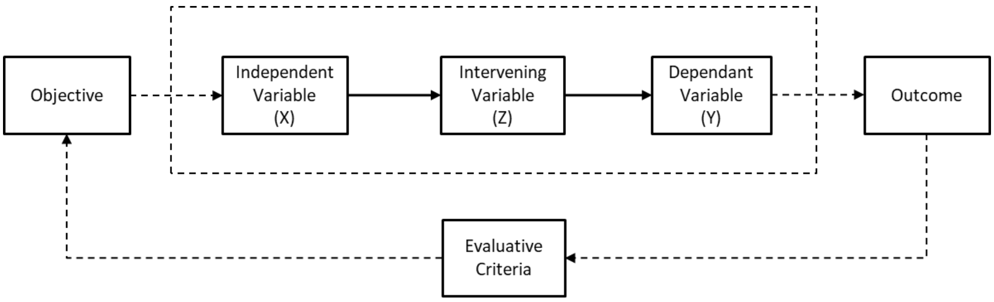


Figure 1. Conceptual Framework

2.1.1. Variable Operationalization within the Conceptual Framework

As illustrated in Figure 1, the framework is structured into three variables to enable observable relationships among them, and the operational definitions of each variable are presented in Table 1.

Table 1. Operationalization of variables within the conceptual framework

Variable Type	Indicator	Operational Definition	Unit	Data Source
Independent (X)	Plastic waste content	Mass fraction of plastic waste in the plastic–mineral composite	%	Experimental mix design
Intervening (Z)	Horizontal loading	Compression applied perpendicular to the bedding plane	Categorical	Laboratory test configuration
	Vertical loading	Compression applied parallel to the bedding plane	Categorical	Laboratory test configuration
Dependent (Y)	Horizontal compressive strength	Average compressive strength under horizontal loading	MPa	Laboratory compressive strength tests
	Vertical compressive strength	Average compressive strength under vertical loading	MPa	Laboratory compressive strength tests
	Composite performance index	Integrated index combining normalized horizontal and vertical performance	MPa	Derived from experimental results

Plastic waste content (X) governs the degree of material modification by altering composite microstructure, ductility, stiffness, and internal stress redistribution (Ghayoor et al., 2018; Jin et al., 2008). Higher values of X indicate increased plastic incorporation, which tends to enhance deformation tolerance under horizontal loading while potentially reducing axial stiffness (Hübel & Vollrath, 2021).

Loading orientation (Z) intervenes in the relationship between material composition and mechanical response by conditioning stress-transfer mechanisms and failure behaviour (Anagnostopoulos et al., 2005; Colombi & D'Antino, 2019; Wang et al., 2023) . As a result, identical material compositions exhibit fundamentally different compressive responses under horizontal and vertical loading.

Mechanical performance outcomes (Y) are evaluated using orientation-specific compressive strengths and an integrated composite performance index. Horizontal compressive strength reflects horizontal resistance and deformation tolerance (Dai & Shaw, 2008) , vertical compressive strength represents axial load-bearing capacity and serves as a minimum stability constraint (Debski et al., 2021), and the composite performance index provides a unified outcome indicator for comparing PW-Bricks mixtures and identifying an optimal mix ratio that balances mechanical performance with plastic waste utilization.

Rather than serving as a purely theoretical model, the conceptual framework provides a structured basis for interpreting the experimental results by linking material composition, loading orientation, and mechanical response within a single analytical scheme. The framework guides the experimental design by defining plastic waste content as the governing material variable, loading orientation as the conditioning factor influencing stress-transfer behavior, and compressive strength as the measurable performance outcome. This structure enables systematic comparison between horizontal and vertical loading responses and supports the development of the composite performance index used for mix optimization. Consequently, the framework functions as an analytical tool for interpreting orientation-dependent mechanical behavior rather than as an abstract theoretical construct.

2.1.2. Evaluative criteria and outcome indicators

The evaluative criteria and outcome indicators are derived directly from the research objectives and questions, translating the conceptual relationships among research variables into measurable analytical metrics (Ofem & Akaawase Alexander, 2023) . Each criterion defines how variations in plastic waste content and loading orientation are systematically assessed, while the corresponding outcome indicators provide observable and comparable measures of mechanical performance, enabling objective evaluation and mix optimization as summarized in Table 2.

Table 2. Evaluative criteria and outcome indicators

Objective	Variable	Evaluation Criterion	Indicator	Outcome
Objective 1: Quantify the compressive strength of PW-Bricks under horizontal and vertical loading orientations at different curing ages	X, Z	Orientation-specific strength performance	Horizontal and vertical compressive strength measured at different curing ages	Quantified compressive strength profiles under horizontal and vertical loading
Objective 2: Examine how increasing plastic waste content influences orientation-dependent mechanical performance	X, Z	Orientation-dependent mechanical response	Comparative trends between horizontal and vertical compressive strength across plastic waste contents	Identification of orientation-sensitive mechanical behaviour
Objective 3: Identify an optimal PW-Bricks mix ratio that balances horizontal resistance, minimum vertical stability, and sustainability considerations	X, Y	Overall mechanical suitability	Composite performance index integrating horizontal resistance, vertical stability, and plastic waste utilization	Optimal PW-Bricks mix ratio selection

2.2. Materials and Specimen Preparation

The materials used in this study consisted of plastic waste, ordinary Portland cement, natural fine aggregate (sand), and quarry dust. Plastic waste comprised high-density polyethylene (HDPE) (Sarwar et al., 2023; Silviyati et al., 2020), low-density polyethylene (LDPE) (Daoudi et al., 2024; Solomon et al., 2023), and polypropylene (PP) (Islam & Shahjalal, 2021; Zachariah et al., 2018), selected for their thermoplastic properties that enable remelting and homogeneous blending within the composite matrix (Hamzah & Ahmad, 2022)

Conventional control bricks were produced using only ordinary Portland cement and natural sand, without plastic waste or quarry dust. For all mixtures, the cement–sand ratio was fixed at 1:3 by mass to ensure consistent binder characteristics and to isolate the mechanical effects attributable solely to plastic waste incorporation (See Table 3).

Table 3. Physical characteristics of raw materials

Material	Type / Source	Physical Characteristics	Preparation / Function
Plastic waste (PW)	HDPE, LDPE, PP	Particle size < 3 cm^2	Washed and sun-dried prior to use
Cement	Ordinary Portland Cement	Standard consistency	Primary binder material
Sand	Natural fine aggregate	Clean and dry	Mixed with cement (1:3)
Quarry dust (QD)	Crushed stone residue	Fine mineral filler	Blended with molten plastic

Subsequently, Section 2.2.1 describes the conventional cement–sand bricks used as control specimens, while Section 2.2.2 details the preparation, manufacturing, and mix design of PW-Bricks as experimental specimens.

2.2.1. Conventional Brick as Control Specimen

Control specimens (PW-0) consisted of solid cement–sand bricks without plastic waste (0%), representing conventional masonry units commonly used in practice. A cement-to-sand ratio of 1:3 by mass was adopted in accordance with established brick-making practice (Arulmoly et al., 2021; Hasan et al., 2025; Tat et al., 2022). All specimens were moulded to standard brick dimensions (230 × 110 × 50 mm), enabling direct comparison between control specimens and PW-Bricks (see Figure 2 and Table 4).

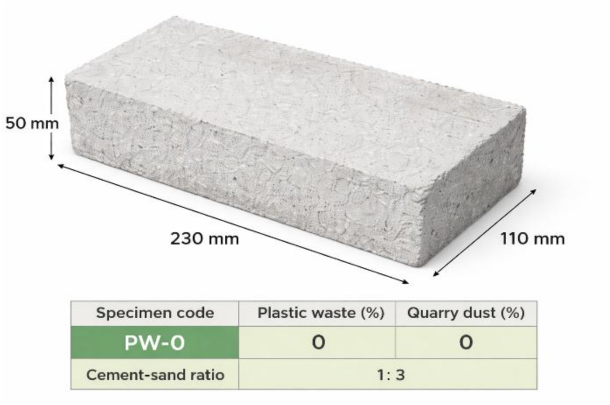


Figure 2. Geometry of control specimens

Table 4. Material Properties of Control Specimens

Parameter	Control Cement–Sand Brick
Brick type	Solid cement–sand brick
Function	Control / reference specimen
Length (mm)	230
Width (mm)	110
Height (mm)	50
Mix composition	Cement + sand
Cement: sand ratio	1: 3 (by mass) or 5: 15
Plastic waste content	0%
Brick structure	Solid (non-hollow)
Production method	Press moulding (manual or mechanical)
Curing condition	Laboratory curing
Testing orientation	Horizontal and vertical

This reference mix was used to isolate the effect of plastic waste incorporation on the mechanical performance of PW-Bricks. The control specimens served as the baseline for all comparative analyses.

2.2.2. PW-Bricks as Experimental Specimens

Section 2.2.2 outlines the PW-Bricks as experimental specimens, covering material preparation (Section 2.2.2.1), manufacturing procedures (Section 2.2.2.2), mix design strategy (Section 2.2.2.3), and specimen geometry with testing configuration (Section 2.2.2.4). This structure ensures consistency and direct comparability for evaluating compressive behaviour under horizontal and vertical loading.

2.2.2.1. Preparation

Plastic waste was manually sorted to separate HDPE, LDPE, and PP. Contaminants were removed through washing, followed by sun drying for approximately 5 hours. The cleaned plastics were shredded into fragments smaller than 3 cm² to facilitate uniform melting and mixing. The shredded plastic was subsequently heated to approximately 175 °C until a homogeneous molten state was achieved, ensuring material consistency and reproducibility (See Table 5).

Table 5. Plastic waste preprocessing procedure

No	Process	Description
1	Sorting	Manual separation of HDPE, LDPE, PP
2	Washing	Removal of dirt and contaminants
3	Drying	Sun drying for ±5 hours
4	Shredding	Plastic cut into < 3 cm² fragments
5	Heating	Melted at ~175 °C until homogeneous

2.2.2.2. Manufacturing

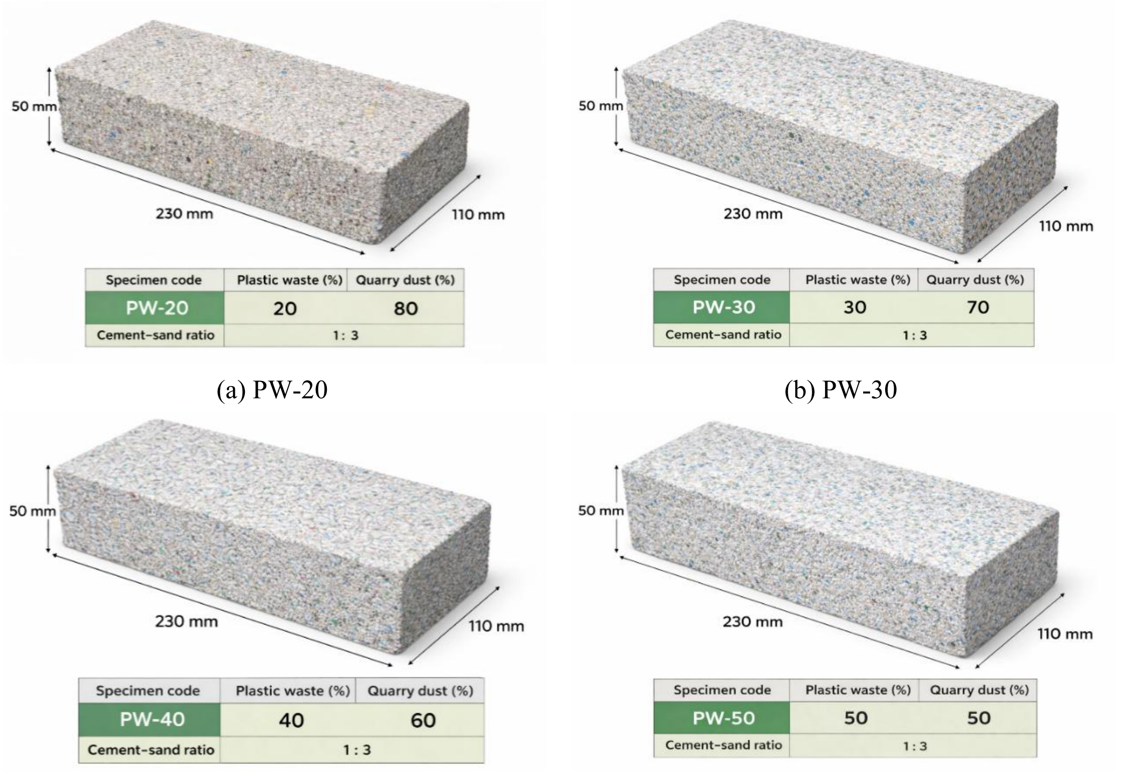
Plastic waste was heated in a controlled vessel at approximately 175 °C with continuous manual stirring to ensure complete melting and to prevent the formation of unmelted plastic fragments (Lange, 2021) . The selected processing temperature (~175 °C) was intended to ensure sufficient melting of HDPE, LDPE, and PP while minimizing excessive thermal degradation of the polymer phases. Within this temperature range, the thermoplastic materials achieve adequate flowability to improve dispersion and bonding within the plastic–mineral composite matrix without reaching severe decomposition conditions associated with significant polymer chain degradation. All procedures were conducted in a closed workshop environment using appropriate personal protective equipment to mitigate health and environmental risks associated with plastic melting (Cudzik & Kropisz, 2024) . Once a stable molten phase was achieved, quarry dust was gradually incorporated to form a homogeneous plastic–mineral composite (Ngugi et al., 2024; Shagwira et al., 2024) . This composite was then blended with cement–sand mortar to produce a uniform mixture suitable for moulding (Y. O. Babatunde et al., 2022; Saikia & De Brito, 2012) . The mixture was placed into brick moulds and cured for 3, 7 , and 10 days under controlled laboratory conditions (Abdel Tawab et al., 2020) (See Tabel 6).

Table 6. PW-Bricks production stages

Stage	Process Description
Melting	Plastic heated to molten state (175 °C)
Mixing	Molten plastic mixed with QD and cement–sand
Moulding	Mixture placed into brick mould
Curing	Specimens cured for 3, 7, and 10 days

2.2.2.3. Mix Design Strategy

PW-Bricks were designed as experimental specimens incorporating varying proportions of plastic waste to evaluate the effect of material modification on orientation-dependent compressive performance. Four PW-Bricks mixtures were prepared with plastic waste contents of 20%, 30%, 40%, and 50% by mass of the plastic–mineral composite (Ikechukwu & Naghizadeh, 2022) (See Figure 3).



(a) PW-20

(b) PW-30

(c) PW-40

(d) PW-50

Figure 3. Visual comparison of PW-Brick specimens with different plastic waste contents: (a) PW-20, (b) PW-30, (c) PW-40, and (d) PW-50. Increasing plastic content results in more pronounced plastic inclusions and reduced mineral matrix continuity, indicating changes in material homogeneity that are consistent with the observed orientation-dependent mechanical behavior.

For all PW-Bricks mixtures, plastic waste partially replaced quarry dust within the plastic–mineral composite fraction (Ikechukwu & Naghizadeh, 2022) while the cement–sand ratio was maintained at a constant value of 1:3 by mass. This design strategy ensured that the binder composition and specimen geometry remained unchanged, allowing the isolated evaluation of plastic waste content on mechanical behaviour (Y. Babatunde et al., 2022; Martinho et al., 2022; Thiam & Fall, 2021) . Detailed mix proportions and batch masses for each PW-Bricks mixture are summarized in Tables 7 and 8.

Table 7. PW-Bricks mix design variations

Specimen code	Plastic waste (%)	Quarry dust (%)	Cement–sand ratio
PW-20	20	80	1: 3
PW-30	30	70	1: 3
PW-40	40	60	1: 3
PW-50	50	50	1: 3

Table 8. Mix design of PW-Bricks with varying plastic waste contents

Mix ID	Plastic waste (%)	Quarry dust (%)	Plastic waste (kg)	Quarry dust (kg)	Cement (kg)	Sand (kg)
PW-20	20	80	3.0	12.0	5.0	15.0
PW-30	30	70	4.5	10.5	5.0	15.0
PW-40	40	60	6.0	9.0	5.0	15.0
PW-50	50	50	7.5	7.5	5.0	15.0

Notes: (1) Plastic waste and quarry dust contents are defined as mass percentages of the plastic–mineral composite fraction, in which plastic waste progressively replaces the mineral filler (quarry dust); (2) The cement–sand matrix was fixed at a ratio of 1:3 by mass for all mixtures to ensure consistent binder characteristics and isolate the mechanical effects attributable solely to plastic waste incorporation; (3) The total mass of the cement–sand phase was kept constant across all batches, such that variations in mechanical performance can be directly attributed to changes in plastic waste content rather than differences in binder quantity; (4) Mix identifiers PW-20, PW-30, PW-40, and PW-50 correspond to plastic waste contents of 20%, 30%, 40%, and 50%, respectively; (5) All mixtures were produced using identical molding, compaction, and curing procedures to minimize experimental variability and ensure direct comparability.

2.2.2.4. Specimen Geometry and Testing Configuration

In order to ensure direct geometric and mechanical comparability, PW-Bricks specimens were moulded to identical dimensions to the control brick. All specimens were cured under identical laboratory conditions and tested under horizontal and vertical loading orientations to evaluate orientation-dependent compressive behaviour (see Table 9).

Table 9. Geometry, material composition, and testing configuration of control and PW-Brick specimens

Parameter	Control cement–sand brick	PW-Bricks
Brick type	Solid cement–sand brick	Plastic waste–modified brick
Specimen role	Control / reference	Experimental specimen
Length (mm)	230	230
Width (mm)	110	110
Height (mm)	50	50
Mix composition	Cement + sand	Cement + sand + plastic waste
Cement: sand ratio	1: 3 (by mass)	1: 3 (by mass) *
Plastic waste content	0%	20–50%
Brick structure	Solid (non-hollow)	Solid (non-hollow)
Curing condition	Laboratory curing	Laboratory curing
Testing orientation	Horizontal and vertical	Horizontal and vertical

** In PW-Bricks, plastic waste partially replaces the mineral filler (quarry dust) within the composite fraction on a mass basis.*

2.3. Experimental Design and Testing

Section 2.3 describes the experimental framework used to evaluate PW-Bricks, including the definition of experimental variables and test matrix (Section 2.3.1), the number and distribution of test specimens (Section 2.3.2), and the compressive strength testing procedure (Section 2.3.3). This structure ensures systematic assessment of the effects of plastic waste content, curing age, and loading orientation on compressive performance.

2.3.1. Variables and Matrix

The experimental program was designed to systematically investigate the coupled effects of plastic waste content, curing age, and loading orientation on the compressive behaviour of PW-Bricks. The primary experimental variables included plastic waste content (0–50%), curing age (3, 7, and 10 days), and loading orientation (horizontal and vertical).

Early curing ages were intentionally selected to capture the initial development of orientation-dependent mechanical behavior during the critical hardening stage in which stiffness evolution, stress redistribution, and plastic–mineral interactions become established within the heterogeneous composite matrix (Gibson & Ashby, 1997; Neville, 1995). Unlike conventional structural masonry studies that emphasize ultimate 28-day compressive strength, the present study focuses on comparative orientation-sensitive behavior relevant to prefabricated, modular, and non-load-bearing masonry applications. Previous studies on cementitious and composite materials have shown that early-age curing stages provide meaningful insight into deformation tolerance and subsequent mechanical performance development (Hübel & Vollrath, 2021; Neville, 1995). Therefore, the selected curing periods were considered sufficient for evaluating the relative influence of plastic waste content and loading orientation on compressive response. Nevertheless, standard 28-day performance and long-term durability behaviour remain important subjects for future investigation. The resulting experimental matrix is summarized in Table 10.

Table 10. Experimental matrix

Variable	Levels
Plastic waste content (%)	0, 20, 30, 40, 50
Curing age (days)	3, 7, 10
Loading orientation	Horizontal, Vertical
Test standard	ASTM C109/C109M-21

2.3.2. Number of Specimens

For each mix design, a minimum of three specimens was tested for every combination of curing age and loading orientation to ensure statistical adequacy and result reliability. The specimen distribution is summarized in Table 11.

Table 11. Number of test specimens

Specimen type	Orientation	Curing age (days)	Number of specimens
Control brick	Horizontal	3, 7, 10	≥3
PW-Bricks (20–50%)	Horizontal	3, 7, 10	≥3
Control brick	Vertical	3, 7, 10	≥3
PW-Bricks (20–50%)	Vertical	3, 7, 10	≥3

2.3.3. Compressive Strength Test

Compressive strength tests were performed after curing periods of 3, 7, and 10 days using an Autocon 2000 compression testing machine (Momotaz et al., 2023, 2024). Specimens were loaded monotonically until failure. Compressive strength was calculated as:

$$f_c = \frac{F}{A} \tag{1}$$

where f_c is the compressive strength (MPa), F is the maximum applied load (N), and A is the loaded cross-sectional area (mm²).The testing protocol present in Table 12. Although ASTM C109/C109M-21 was originally developed for cement mortar specimens, the procedure was adopted in this study as a controlled comparative compression protocol for evaluating relative orientation-dependent behavior among mixtures with identical geometry and loading conditions. The standard was therefore used as a consistent experimental reference rather than as a direct certification procedure for structural masonry units.

Table 12. Compressive strength testing protocol (Daza et al., 2022, 2023; Quiatchon et al., 2021)

Parameter	Description
Parameter	Description
Standard	ASTM C109/C109M-21
Equipment	Autocon 2000
Loading mode	Monotonic compression
Strength formula	$f_c = F/A$
Unit	MPa (N/mm²)

All reported compressive strength values represent the mean ± standard deviation of at least three specimens per condition. Standard deviation values were calculated from repeated measurements obtained from at least three specimens for each testing condition. Standard deviation was used to evaluate the variability, repeatability, and consistency of the experimental measurements in accordance with common practice for cementitious and composite material testing (ASTM, 2013) . Variability among specimens was generally limited, indicating relatively stable material behavior and reproducible compressive response across repeated tests (Daza et al., 2022, 2023; Quiatchon et al., 2021).

The observed mechanical trends remained consistent for all curing ages, plastic waste contents, and loading orientations.

2.4. Performance Evaluation

To enable objective comparison among PW-Bricks mixtures and to decouple performance trends from absolute strength magnitudes, an orientation-sensitive normalized evaluation framework was adopted. Compressive strength results were evaluated separately for horizontal and vertical loading orientations, reflecting their distinct structural roles in masonry systems (Hendry, 1998; Lourenço, 2002; Rots, 1997). The normalized horizontal and vertical strength indices are defined in Sections 2.4.1, 2.4.2, and 2.4.3 respectively.

2.4.1. Normalized Horizontal Compressive Strength

The normalized horizontal compressive strength index quantifies the relative resistance of each PW-Bricks mixture to horizontal or non-axial loading conditions, which are critical in masonry systems subjected to shear transfer, confinement effects, or in-plane stress redistribution, See Equation 2 (Lourenço, 2002; Rots, 1997).

$$H_i = \frac{f_{c,h,i}}{f_{c,h,max}} \tag{2}$$

where: (1) normalized horizontal compressive strength index of mixture i (–); (2) $f_{c,h,i}$ = measured horizontal compressive strength of mixture i (MPa); (3) $f_{c,h,max}$ = maximum horizontal compressive strength observed among all tested mixtures (MPa).

2.4.2. Normalized Vertical Compressive Strength

The normalized vertical compressive strength index represents axial load-bearing capacity and serves as a minimum stability constraint, ensuring that PW-Bricks maintain adequate compressive performance under gravity-dominated loading conditions (Gibson et al., 2010; Lourenço, 2002).

$$V_i = \frac{f_{c,v,i}}{f_{c,v,max}} \tag{3}$$

where: (1) V_i = normalized vertical compressive strength index of mixture i (–); (2) $f_{c,v,i}$ = measured vertical compressive strength of mixture i (MPa); (3) $f_{c,v,max}$ = maximum vertical compressive strength observed among all tested mixtures (MPa).

2.4.3. Composite Performance Index

To integrate horizontal resistance and vertical stability into a single evaluative metric, a composite performance index was defined (Belton & Stewart, 2012) as:

$$P_i = \alpha H_i + \beta V_i \tag{4}$$

where: (1) P = composite performance index of mixture i (–); (2) α = weighting coefficient for horizontal performance; (3) β = weighting coefficient for vertical performance. The weighting coefficients were assigned as follows: (1) α = 0.7, emphasizing horizontal performance dominance; (2) β = 0.3, representing the minimum vertical stability requirement, consistent with performance-based masonry design principles.

This weighting coefficients reflect application-driven priorities rather than universal material constants and may be adjusted for alternative structural or functional requirements. The weighting scheme was intentionally selected to reflect the intended application of PW-Bricks in non-load-bearing and horizontal ly governed masonry systems, where horizontal resistance, deformation tolerance, and crack control are considered more critical than primary axial load-bearing capacity. Accordingly, greater emphasis was assigned to horizontal performance (0.7), while vertical compressive strength (0.3) was retained as a minimum structural stability requirement rather than the dominant design criterion. Accordingly, the adopted weighting scheme should be interpreted as application-specific rather than as a universally applicable design constant for all masonry systems.

The composite performance index provides a rational basis for identifying an optimal PW-Bricks mix by balancing enhanced horizontal resistance with the requirement for sufficient vertical compressive capacity. The adopted weighting scheme reflects intended applications in non-load-bearing or horizontal ly governed masonry systems, where horizontal performance is critical while vertical strength functions as a minimum stability constraint. Importantly, the proposed orientation-sensitive evaluation framework is independent of absolute strength values and is therefore transferable to other waste-based masonry materials and heterogeneous mix designs.

3. Results and Discussion

In accordance with the experimental framework described in Section 2. Section 3.1 reports the results, while Section 3.2 discusses the mechanical implications, performance trade-offs, and optimal mix ratio determination.

3.1. Results

3.1.1. Horizontal Compressive Strength

Horizontal compressive strength results are summarized in Table 13. Horizontal loading represents resistance to horizontal stresses and shear-related actions, which are relevant for non-axial masonry applications.

Table 13. Average horizontal compressive strength values (mean ± SD)

Curing Age	Normal Brick (MPa)	PW-Bricks 20% (MPa)	PW-Bricks 30% (MPa)	PW-Bricks 40% (MPa)	PW-Bricks 50% (MPa)
3 days	5.85 ± 0.18	10.90 ± 0.31	12.88 ± 0.39	11.18 ± 0.35	14.47 ± 0.42
7 days	12.45 ± 0.36	24.25 ± 0.55	20.17 ± 0.47	21.27 ± 0.50	25.13 ± 0.59
10 days	22.74 ± 0.49	24.61 ± 0.57	21.77 ± 0.52	24.13 ± 0.55	30.15 ± 0.68

Notes: Values represent mean compressive strength ± standard deviation (MPa) measured under horizontal loading at curing ages of 3, 7, and 10 days based on at least three specimens per condition. Relatively low standard deviation values indicate good repeatability and consistent specimen behavior during testing.

All values represent the mean ± standard deviation of at least three specimens. Standard deviations were relatively low for all mixtures, indicating good repeatability and limited variability among specimens. Horizontal compressive strength increased with curing age for all mixtures, with PW-Bricks consistently outperforming conventional bricks and exhibiting greater strength gains at higher plastic waste contents.

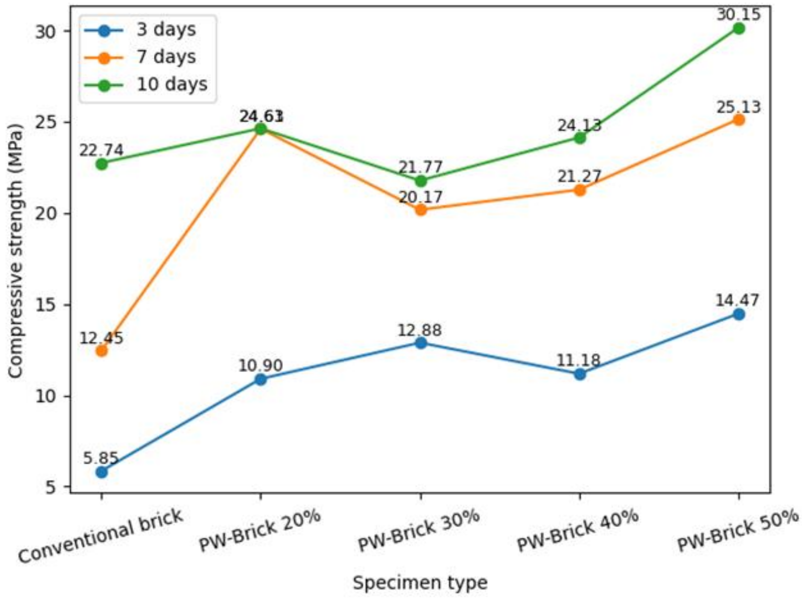


Figure 4. Horizontal compressive strength of conventional bricks and PW-Bricks at curing ages of 3, 7, and 10 days. Error bars represent ±1 standard deviation based on at least three specimens per condition, indicating the variability and repeatability of the compressive strength measurements.

Figure 4 demonstrates that compressive strength increases with curing age for all specimens under horizontal loading. PW-Bricks consistently exhibit higher compressive strength than conventional bricks, indicating that the incorporation of plastic waste enhances mechanical performance. The highest compressive strength was recorded for PW-Bricks containing 50% plastic waste at 10 days, reaching 30.15 MPa, whereas the lowest value was observed for conventional bricks at 3 days, with a compressive strength of 5.85 MPa. These results confirm that plastic waste contributes positively to strength development, particularly at longer curing ages. The improved horizontal compressive performance may be attributed to the increased ductility of the plastic phase, which enhances stress redistribution and delays localized brittle cracking within the heterogeneous composite matrix. In addition, the thermoplastic component may act as a flexible binding medium that improves deformation tolerance under horizontal loading conditions.

3.1.2. Vertical Compressive Strength

Vertical compressive strength results are presented in Table 14. Vertical loading represents axial load-bearing capacity, which governs the suitability of masonry units for structural applications.

Table 14*.* Average vertical compressive strength values (mean ± SD)

Curing Age	Normal Brick (MPa)	PW-Bricks 20% (MPa)	PW-Bricks 30% (MPa)	PW-Bricks 40% (MPa)	PW-Bricks 50% (MPa)
3 days	1.51 ± 0.04	1.11 ± 0.03	1.15 ± 0.03	1.08 ± 0.02	1.12 ± 0.03
7 days	2.16 ± 0.06	1.15 ± 0.03	1.16 ± 0.03	1.21 ± 0.03	1.15 ± 0.03
10 days	2.48 ± 0.07	1.20 ± 0.03	1.19 ± 0.03	1.22 ± 0.04	1.19 ± 0.03

Notes: Values represent mean compressive strength ± standard deviation (MPa) measured under vertical loading at curing ages of 3, 7, and 10 days based on at least three specimens per condition. The relatively small variability confirms the consistency of the observed orientation-dependent mechanical behavior.

Testing conditions, curing regime, and specimen dimensions were identical to those used in horizontal testing (Section 2.4.1), with only the loading orientation altered. This ensures that observed differences are attributable primarily to orientation-dependent material behavior rather than procedural variation. Standard deviation values remained relatively low across all mixtures, confirming the repeatability and consistency of the vertical compressive strength measurements.

Conventional bricks exhibit a clear increase in vertical compressive strength with curing age. In contrast, PW-Bricks display relatively constant and lower vertical strength values across all plastic contents and curing ages.

Under vertical loading, conventional bricks show increasing compressive strength with curing age, reaching 2.48 MPa at 10 days, whereas PW-Bricks exhibit lower and relatively stable strengths of approximately 1.1–1.2 MPa across all plastic contents. This indicates that plastic incorporation does not significantly improve axial load-bearing capacity under vertical compression.

To assess the vertical load-bearing performance of the specimens, compressive strength tests were conducted under vertical loading at curing ages of 3, 7, and 10 days. Vertical orientation represents the critical loading condition for masonry elements subjected to axial stresses. The variation in vertical compressive strength for conventional bricks and PW-Bricks with different plastic contents is illustrated in Figure 5

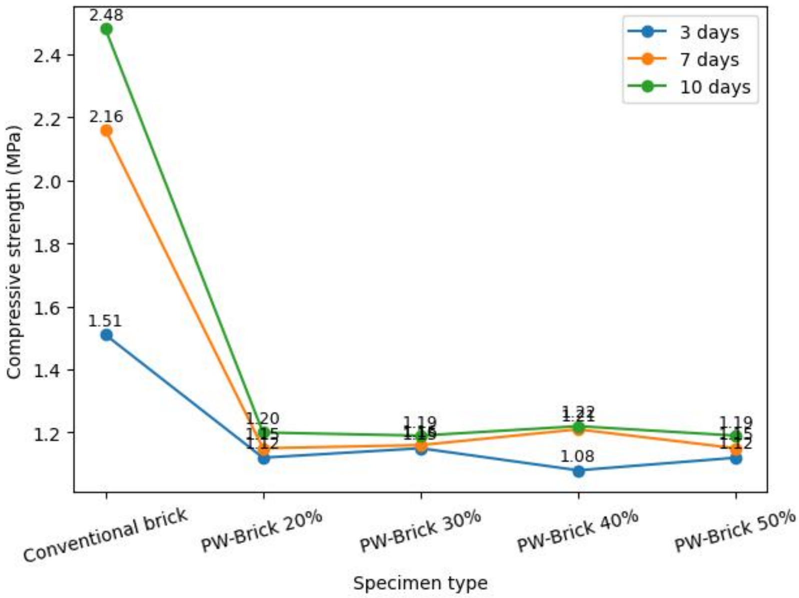


Figure 5. Vertical compressive strength of conventional bricks and PW-Bricks at curing ages of 3, 7, and 10 days. Error bars represent ±1 standard deviation based on at least three specimens per condition, indicating the variability and repeatability of the compressive strength measurements.

As shown in Figure 5, conventional bricks exhibit a clear increase in vertical compressive strength with curing age, reaching a maximum value of 2.48 MPa at 10 days. In contrast, PW-Bricks display relatively low and nearly constant vertical compressive strength values, ranging from approximately 1.08 to 1.22 MPa across all curing ages and plastic contents. This indicates that, unlike horizontal loading, the incorporation of plastic waste does not enhance vertical load-bearing capacity, likely due to reduced stiffness and heterogeneous stress transfer within the plastic–mineral composite. Consequently, PW-Bricks are more suitable for non-load-bearing or horizontally loaded applications rather than primary vertical load-bearing masonry.

The relatively low vertical compressive strength of PW-Bricks indicates that their application in primary load-bearing masonry systems may be limited, particularly in structures dominated by axial compressive loads. Nevertheless, the observed mechanical behavior remains suitable for non-load-bearing and semi-structural applications such as partition walls, infill panels, lightweight modular units, and horizontally governed masonry systems, where deformation tolerance and material sustainability are prioritized over high axial load-bearing capacity.

3.1.3. Composite Performance Index

To synthesize the mechanical responses observed under horizontal and vertical loading into a single evaluative metric, a composite performance index (P_i) was calculated for each mixture in accordance with Equation (4) defined in the methodology section. The index integrates the normalized horizontal compressive strength (H_i) and normalized vertical compressive strength (V_i) using weighting coefficients α = 0.7 and β = 0.3, respectively (See Table 15).

Normalized indices H_i and V were computed using the maximum observed strengths under horizontal and vertical loading as reference values, allowing direct comparison among mixtures with different plastic waste contents. The composite index $P_i$thus represents the overall mechanical suitability of each mixture for non-load-bearing and horizontally loaded masonry applications.

Table 15. Normalized strength indices and composite performance index

Specimen	($f_{c,h}$) (MPa)*	(H_i) (–)	($f_{c,v}$) (MPa)*	(V_i) (–)	(P_i) (–)
Normal brick	22.74	0.75	2.48	1.00	0.83
PW-Bricks 20%	24.61	0.82	1.20	0.48	0.72
PW-Bricks 30%	21.77	0.72	1.19	0.48	0.65
PW-Bricks 40%	24.13	0.80	1.22	0.49	0.71
PW-Bricks 50%	**30.15**	**1.00**	**1.19**	**0.48**	**0.86**

*Compressive strength values correspond to 10-day curing age, at which maximum performance was recorded for all specimens. Notes: (1) $H_i = \frac{f_{c,h,i}}{f_{c,h,max}}$, where $f_{c,h,max}$ = 30.15 (PW-Bricks 50); (2) $V_i = \frac{f_{c,v,i}}{f_{c,v,max}}$, where $f_{c,v,max}$ = 2.48 MPa (normal brick); (3) P_i = 0.7 H_i + 0.3 V_i as defined in Equation (4); (4) All indices are dimensionless.

Table 15 demonstrates that while conventional bricks retain the highest normalized vertical strength (V_i = 1.00), their horizontal performance is substantially lower than that of PW-Bricks with higher plastic waste content. In contrast, PW-Bricks —particularly PW-Bricks 50—achieve the highest normalized horizontal strength (H_i = 1.00), reflecting enhanced resistance to horizontal loading.

The composite performance index confirms that PW-Bricks 50 exhibits the highest overall performance (P_i = 0.86), driven primarily by gains in horizontal resistance while maintaining adequate vertical stability. PW-Bricks 40 yields a comparable composite index, indicating diminishing marginal returns beyond 40% plastic waste content when vertical stability constraints are considered.

Overall, the composite index provides quantitative support for identifying an optimal PW-Bricks mix by explicitly balancing horizontal performance enhancement against minimum vertical compressive requirements, consistent with the intended non-load-bearing application of the developed PW-Bricks.

3.2. Discussion

This section discusses the experimental results in relation to masonry mechanics, composite material behaviour, and performance-based evaluation principles. Moreover, this section connects the experimental findings with the conceptual framework and the orientation-sensitive performance evaluation approach proposed in Section 2. Particular attention is given to the orientation-dependent compressive response of PW-Bricks, as compressive strength in masonry materials is governed by distinct stress-transfer mechanisms under axial and horizontal loading (Hendry, 1998; Lourenço, 2002). The discussion further examines the mechanical trade-offs introduced by plastic waste incorporation, highlighting how improvements in horizontal resistance may coexist with constrained vertical load-bearing capacity. To address these competing requirements, normalized strength indices and a composite performance-based evaluation framework are employed, consistent with established approaches for comparing heterogeneous materials while decoupling performance trends from absolute strength values (Gibson & Ashby, 1997; Neville, 1995) . Finally, the implications of the observed trade-offs are interpreted within a multi-criteria decision-making context, where weighted aggregation enables rational mix optimization based on application-driven priorities rather than universal material constants.

3.2.1. Orientation-Dependent Mechanical Behaviour

The orientation-dependent mechanical response observed in PW-Bricks reflects fundamental masonry behaviour, in which compressive strength cannot be treated as an isotropic or orientation-independent material property. In masonry and composite materials, axial and horizontal loading activate distinct stress-transfer mechanisms and failure modes, particularly in heterogeneous systems containing low-stiffness phases such as polymers (Hendry, 1998). Consequently, variations in compressive performance under horizontal and vertical loading provide critical insight into the internal load redistribution and deformation characteristics of plastic–mineral composites.

3.2.2. Mechanical Performance Trade-Off

The contrasting responses of PW-Bricks under horizontal and vertical loading introduce an inherent mechanical trade-off between horizontal resistance, axial stability, and material sustainability. Such trade-offs are characteristic of composite masonry systems, where improvements in deformation tolerance and horizontal resistance may occur at the expense of axial stiffness and load-bearing capacity (Debski et al., 2021). Understanding this trade-off is essential for defining performance objectives that align material composition with intended structural function, rather than maximizing a single strength parameter. For clarity, a qualitative summary of the observed performance trade-offs is provided in Table 16, which synthesizes the quantitative trends to support interpretation and practical decision-making, without replacing the underlying numerical analysis.

Table 16. Performance trade-off summary for PW-Bricks mix ratios

Criterion	Low PW	Medium PW	High PW
Horizontal strength	Moderate	High	Very high
Vertical strength	Moderate	Low	Low
Sustainability	Low	Medium	High
Application suitability	Structural	Semi-structural	Non-structural

Notes: (1) Qualitative descriptors are relative classifications, rather than absolute performance thresholds. (2) Sustainability refers to the degree of plastic waste utilization in each mix category.

3.2.3. Quantitative Interpretation using Normalized Strength Indices

To interpret the identified trade-offs objectively, normalized strength indices provide a robust means of comparing mixtures with different compositions while eliminating the influence of absolute strength magnitudes. Strength normalization is widely adopted in the evaluation of heterogeneous materials to isolate relative performance trends and distinguish governing constraints from differentiating parameters (Gibson & Ashby, 1997). In this context, normalized vertical compressive strength functions primarily as a minimum stability constraint, whereas normalized horizontal strength serves as the principal performance discriminator among PW-Bricks mixtures.

3.2.4. Composite Performance and Optimal Mix Ratio

While normalized indices clarify individual performance trends, practical material selection requires an integrated metric capable of balancing competing mechanical requirements. Composite performance indices based on weighted linear aggregation are commonly used in performance-based material evaluation to synthesize multiple criteria into a single comparative indicator (Belton & Stewart, 2012). This approach enables rational identification of an optimal PW-Bricks mix ratio by explicitly balancing enhanced horizontal resistance against the requirement to maintain sufficient axial compressive capacity.

3.2.5. Engineering Implications

The orientation-sensitive mechanical behaviour identified in this study has direct implications for the engineering application of PW-Bricks. In masonry design, axial compressive capacity governs suitability for load-bearing elements, whereas horizontal resistance and deformation tolerance are more critical for non-load-bearing and semi-structural applications (Hendry, 1998). Interpreting PW-Bricks performance within this framework clarifies their appropriate use in applications where sustainability and horizontal performance are prioritized over vertical load capacity.

3.2.6. Synthesis and Optimal Mix Selection

Synthesizing the orientation-dependent mechanical responses, normalized strength indices, composite performance evaluation, and qualitative trade-off analysis, PW-40 (40% plastic waste) is identified as the optimal specimen within the tested range. Based on the composite performance evaluation, PW-40 achieves the most favourable balance between enhanced horizontal resistance, minimum vertical stability, and material homogeneity. Although PW-50 exhibits the highest horizontal compressive strength and composite performance value, its vertical compressive capacity does not improve relative to other mixtures, while the higher plastic content increases material heterogeneity and reduces stiffness, limiting robustness under gravity-dominated loading. Furthermore, the marginal increase in composite performance achieved by PW-50 does not proportionally compensate for the increased material heterogeneity and reduced axial stability associated with higher plastic incorporation. In contrast, PW-40 combines high horizontal resistance with marginally higher vertical stability and reduced plastic-induced heterogeneity, satisfying minimum axial stability requirements while maximizing horizontal performance and plastic waste utilization.

From an engineering perspective, this outcome aligns with established masonry mechanics, in which axial compressive capacity governs suitability for load-bearing elements, whereas horizontal resistance and deformation tolerance are more critical for non-load-bearing and semi-structural applications (Hendry, 1998) . Accordingly, the optimal mix ratio is defined not by the highest single strength parameter, but by the configuration that maximizes composite performance while meeting minimum vertical stability constraints. Durability-related properties, including water absorption, density, porosity, thermal performance, and long-term degradation behavior, were beyond the scope of this study and remain important subjects for future investigation. The absence of density, porosity, water absorption, and microstructural characterization represents a limitation of the present study because these properties may significantly influence long-term durability, moisture transport behavior, dimensional stability, and stress-transfer mechanisms within heterogeneous plastic–mineral composites.

4. Conclusions

It should be noted that the findings of this study are limited to short-term compressive performance under controlled laboratory conditions. Long-term durability, creep behaviour, and environmental degradation effects were not evaluated and remain topics for future investigation

4.1. RQ1: Effect of plastic waste content under different loading orientations

Increasing plastic waste content significantly enhances compressive strength under horizontal loading, with the highest value observed at 50% plastic waste, indicating improved horizontal resistance due to enhanced stress redistribution and deformation tolerance. In contrast, vertical compressive strength remains low and largely insensitive to plastic waste content, showing only marginal variation across all PW-Bricks mixtures. This confirms that plastic incorporation primarily affects horizontal, rather than axial, mechanical performance.

4.2. RQ2: Role of orientation-dependent behaviour

Orientation-dependent behaviour governs the mechanical performance of PW-Bricks to a substantial extent. While horizontal compressive strength increases markedly with plastic waste content, vertical performance remains constrained by reduced stiffness and heterogeneous stress transfer within the plastic–mineral composite. As a result, compressive strength cannot be treated as an orientation-independent property for plastic-modified masonry materials.

4.3. RQ3: Optimal plastic waste proportion

An optimal balance between mechanical performance and sustainability is achieved at 40% plastic waste. Although PW-Bricks with 50% plastic waste attain the highest horizontal compressive strength and composite performance index, they offer no improvement in vertical stability and introduce greater material heterogeneity. PW-Bricks with 40% plastic waste provide a more balanced performance, combining high horizontal resistance, adequate vertical stability, and efficient plastic waste utilization, making them the most suitable mix for general non-load-bearing and semi-structural applications.

Therefore, based on the experimental results and the orientation-sensitive evaluation framework, the following conclusions are drawn:

1. Both conventional bricks and PW-Bricks show increasing compressive strength with curing age, with maximum values consistently achieved at 10 days.
2. PW-Bricks containing 20–50% plastic waste exhibit significantly higher compressive strength under horizontal loading than conventional bricks, confirming the beneficial role of plastic waste in enhancing horizontal resistance.
3. Under vertical loading, conventional bricks retain superior compressive strength, while PW-Bricks display lower and relatively constant vertical capacity regardless of plastic waste content.
4. PW-Bricks mechanical performance is strongly orientation-dependent, demonstrating that single-value compressive strength metrics are insufficient for their evaluation.
5. The composite performance index provides a rational basis for mix optimization, identifying PW-Bricks with 40% plastic waste as the optimal configuration for non-load-bearing and semi-structural applications.
6. PW-Bricks with higher plastic waste content (50%) remain viable for applications prioritizing horizontal resistance and plastic waste valorisation, provided that their vertical load-bearing limitations are recognized.

Overall, this study demonstrates that plastic waste–based PW-Bricks can function as sustainable masonry units when their application is aligned with orientation-dependent mechanical behaviour. The proposed evaluation framework supports rational mix design and contributes to the development of waste-based construction materials for sustainable building practices.

Author Contributions

Conceptualization, Nicco Plamonia; methodology, Nicco Plamonia and Agung Riyadi; experimental design and investigation, Agung Riyadi, Sarjono Sarjono, Hadi Supratikta, Gani Soehadi, Budi Kurniawan, and Muhamad Komarudin; data acquisition and curation, Sarjono Sarjono, Hadi Supratikta, Maria Holly Herawati, Sutrisno Hutagalung, Budi Kurniawan, and Muhamad Komarudin; formal analysis and interpretation, Nicco Plamonia; validation, Nicco Plamonia and Agung Riyadi; visualization, Nicco Plamonia; writing—original draft preparation, Nicco Plamonia; writing—review and editing, Nicco Plamonia, Maria Holly Herawati, Sutrisno Hutagalung, Ignatius Subagjo, and Etty Sisdiana; supervision, Nicco Plamonia; project administration, Nicco Plamonia; funding acquisition, Nicco Plamonia. All authors have read and agreed to the published version of the manuscript. Authorship is limited to those who have contributed substantially to the work reported.

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The authors declare no conflicts of interest.

Data Availability Statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to ongoing analyses and data integration for related studies.

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