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RESEARCH ARTICLE

Optimisation of Ecobrick Density and Strength as a Building Material to Reduce Plastic Waste

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ABSTRACT

Bricks are an essential material in construction, but the production has considerable environmental and health impacts. Consequently, ecobricks have emerged as a potential sustainable alternative to conventional bricks. These environmentally friendly substitutes are made by filling recycled polyethylene terephthalate (PET) plastic bottles with compacted plastic waste to a specific density. In this study, the optimum density of plastic waste in PET bottles was optimised to produce ecobricks with suitable strength properties. This innovation aimed to use plastic bottles as a building material and offers a sustainable alternative for the construction industry. Seven samples with a density of 0 g/mL to 0.65 g/mL were empirically tested for compressive strength, impact resistance, flexural strength, and failure behaviour. The findings revealed that Sample E exhibited the best performance compared to other samples. This sample achieved a compressive strength of 17.54 N/mm^2, demonstrating strong structural performance. In the drop test (1 m, 2 m, and 3 m), Sample E also showed no visible denting, with a measured density (0.45 g/mL) exceeding 0.33 g/mL. It also recorded flexural strengths of 4.65 N/mm^2 at the neck, 6.59 N/mm^2 at the body and 11.96 N/mm^2 at the bottom. These results not only exceed the minimum compressive strength for bricks (5.2 N/mm^2) required by the Malaysian Public Works Department but also fulfil the Global Ecobrick Alliance guideline for minimum density (0.33 g/mL) of an ecobrick. In summary, this study helps to reduce the amount of plastic disposed of in landfills by reusing plastic waste as functional building materials. Most importantly, these findings support the United Nations Sustainable Development Goals (SDGs), specifically SDG 9 (Industry, Innovation and Infrastructure) by promoting the sustainable development of infrastructure through innovative materials and SDG 13 (Climate Action) by reducing the impact on the environment through the reduction of plastic waste.

1. INTRODUCTION

Plastics are versatile, durable, lightweight and resistant to degradation. These functional advantages contribute to the extensive use of this material across the globe. Nevertheless, plastic is widely recognised as environmentally harmful due to the slow decomposition, which takes approximately 450 years to biodegrade under natural conditions (Gammage, 2022). The persistence of presents a major environmental challenge. As plastic waste continues to accumulate in landfills, these sites are rapidly reaching the maximum capacity and becoming saturated, limiting their availability for future use. Soon, urban development and expansion will potentially come to a halt without effective waste management systems (Kumar & Agrawal, 2020). In addition, the leachates and microplastics generated during the slow breakdown of plastics may contaminate soil and groundwater, further endangering environmental and public health.

In response to the growing environmental concerns associated with plastic waste, this study aimed to find a solution to this problem by incorporating plastic bottles into building materials. Construction was chosen as the study focus as this sector is one of the most dynamic and fastest-growing globally, with significant demand for raw materials, thus presenting an opportunity to incorporate recycled materials in the industry (Ahmed, 2023). Furthermore, the construction industry serves as a major economic contributor through job creation and revenue generation, significantly impacting the national gross domestic product (GDP). In Malaysia, the construction sector employs 1.2 million individuals, accounting for 9.5% of the total workforce (CIDB Malaysia, 2022). This sector directly contributes 4.6% to the national economy, has a multiplier effect of 2.03, and is linked to over 120 industries, 90% of which are small and medium enterprises (SMEs). Apart from this, bricks are the most essential building materials in construction, besides cement, concrete, clay and metals (Jonnala et al., 2024). These materials are used extensively for the construction of building walls, partitions, pavements and structural components in residential, commercial and industrial buildings. The widespread use of bricks in construction is attributed to the durability, efficiency, and long-term strength, and the ability to create a healthy and comfortable environment (Homes, 2020).

In recent years, numerous studies have been carried out to incorporate waste materials as alternative bricks in brick production. Previous research has demonstrated the feasibility of using polyethylene terephthalate (PET) bottles in construction. Studies have shown that bottle-filled bricks can achieve competitive compressive strength and better thermal insulation (Shahriar et al., 2024). Experimental wall systems using mortar-lined plastic bottles also exhibited adequate structural performance and thermal comfort comparable to conventional bricks (Aterezi et al., 2024). These efforts aim to reduce environmental degradation, reduce landfill overcapacity, and conserve natural resources. The integration of plastic bottles into construction is in line with this growing body of research, offering the dual advantage of effectively managing plastic waste while contributing to more sustainable construction methods.

Despite growing interest in ecobricks as an innovative solution for managing plastic waste, there remains a significant research gap regarding the strength properties and potential as building materials (Jha & Kewate, 2024). Most studies have focused on the environmental benefits of ecobricks, with limited attention given to the structural performance and suitability for construction (Yadav et al., 2024). The lack of comprehensive data on the strength, durability and reliability of ecobricks hinders the widespread adoption in the construction industry (Arulraj et al., 2019). Thus, this study aimed to address this gap by investigating the strength properties of ecobricks made from plastic waste fillers, specifically the compressive strength, impact resistance, and flexural strength, to assess the feasibility as a sustainable alternative to conventional building materials.

The study outcomes will not only offer a sustainable substitute for conventional bricks but also contribute to reducing the volume of plastic waste that ends up in landfills or the natural environment. Moreover, this research supports broader global sustainability efforts, aligning with the United Nations Sustainable Development Goals (SDGs) (Omer & Noguchi, 2020): SDG 9 (Industry, Innovation and Infrastructure), by promoting innovative and sustainable construction practices and SDG 13 (Climate Action), by addressing the environmental impact of plastic pollution.

2. MATERIALS AND METHODS

2.1. Preparation of sample size

An ecobrick is a PET plastic bottle densely filled with inorganic plastic waste, designed to serve as a reusable building component for constructing furniture, walls, and other structures (Patel, 2021). The concept was introduced in South America in 2000 by German architect Andreas Froese, who used sand-filled PET bottles to construct homes, schools and water reservoirs, starting with a project in Yelwa, Nigeria (Hopkins, 2014). In this study, recycled PET bottles and plastic waste were collected to produce seven ecobrick samples with various densities for laboratory testing (see Table 1). Density was used as a measurement to provide an accurate prediction of ecobrick strength by considering the volume of the bottle and the weight of plastic waste, unlike methods that rely only on the mass of the bottle or the filler percentage (Global Ecobrick Alliance, 2019). A higher density indicates stronger ecobricks (Global Ecobrick Alliance, 2019), making this approach more reliable.

Table 1: Preparation of ecobrick samples

Sample	Density (g/mL)	Mass of sample (g)
A	0	15 (empty bottle with no plastic filler content)
B	0.15	0.15 g/mL x 500 mL = 75
C	0.25	0.25 g/mL x 500 mL = 125
D	0.35	0.35 g/mL x 500 mL = 175
E	0.45	0.45 g/mL x 500 mL = 225
F	0.55	0.55 g/mL x 500 mL = 275
G	0.65	0.65 g/mL x 500 mL = 325

2.2. Laboratory tests on ecobrick samples

Once the ecobrick samples were prepared, all samples were subjected to strength assessment as building materials. The laboratory tests conducted include compressive strength test, drop test and flexural strength test, followed by a failure analysis to evaluate the performance of each sample after testing. All tests were performed once, except for the compressive strength test.

2.2.1. Compressive strength test

Compressive strength measures the ability of a material to withstand axial pushing forces without cracking or deflecting (Krishna, 2020). This property is evaluated using compression testing equipment, which assesses the load-carrying capacity of bricks and serves as a key indicator of flexibility, workability, and load-displacement characteristics. According to the Malaysian Public Works Department (2020) the minimum permissible average compressive strength is 5.2 N/mm^2 for bricks and 2.8 N/mm^2 for hollow blocks.

In this test, each density is represented by three ecobrick samples. The density of each ecobrick sample was tested thrice during the compressive strength test to ensure accuracy. Subsequently, the results were added, and the average compressive strength for each sample was calculated. The experiments were conducted based on ASTM D695, which measures the modulus of elasticity, yield stress, deformation beyond the yield point, and compressive strength or the performance of a material under compressive loading. The load is applied at a relatively low and uniform rate (Victor, 2020).

2.2.2. Drop test

A drop test evaluates the performance of bricks under site conditions, with methods such as drop-height, drop-weight, projectile impact, instrumented pendulum, and Charpy-type impact tests (Zhu et al., 2015). Among these, the drop-weight impact test is preferred due to the simplicity, cost-efficiency, and straightforward approach (Jayaprakash, 2019). This test involves dropping the material from a specified height onto a hard surface to assess the ability to withstand impact without damage, ensuring that the structural integrity of the material is maintained after the drop (Jamal, 2023). The drop test can be performed manually at the construction site (Skillsewa, 2023), where a brick is manually dropped from a height of 1 m to 1.5 m onto the floor. If the brick breaks during the drop, the sample is not considered a high-quality brick. Conversely, the brick is deemed as strong, safe, and can be used as a building material if the brick does not break or crack (Skillsewa, 2023).

Following Skillsewa (2023), the drop test in this study was conducted manually at three different heights (1 m, 2 m, and 3 m. These heights were selected for safety reasons, as specified in the Institute for Civil Engineers (2020) guidelines. This test will ensure that the bricks can withstand falls from greater heights to prevent structural failure during and after construction. This characteristic is particularly important for buildings exposed to dynamic loads and accidents, such as seismic activity or strong winds (Gkournelos et al., 2022). After dropping, the appearance of the sample was observed to determine if there was a difference from the time of dropping. Any difference in the appearance of the bottle was recorded. These steps were repeated for other ecobrick samples with different drop heights.

2.2.3. Flexural strength test

Flexural strength, expressed in newtons per square millimetre (N/mm^2), measures the resistance of a material to breaking or cracking under bending stress, indicating the ability to withstand tension, compression, and deformation (Hamakareem, 2017). This property can be tested using either the three-point load test (ASTM C78) for smaller specimens or the centre point load test (ASTM C293) for larger samples (Bose-Filho et al., 2020).

Despite using recycled PET plastic bottles, the flexural test was conducted according to the ASTM standards designed for concrete instead of plastics. This decision was made based on the research objective, which aimed to evaluate PET in the repurposed form as a building material, not as a raw polymer. Adopting concrete standards such as ASTM C78 enables direct comparison with conventional bricks, providing a practical framework for assessing load-bearing capabilities and determining the optimal compaction weight required for structural and non-structural applications. This approach is consistent with a previous study by Al-Tulaian et al. (2016), who assessed recycled PET as a component in construction materials using ASTM C78 or C293 to evaluate flexural strength.

Each density was represented by one ecobrick sample. Every sample was tested at three parts of the PET bottle (neck, body, and bottom). The ecobrick samples were tested to ASTM C78 at a rate of 125–175 psi/min to the breakage point. The three bending points on the surface of the ecobrick sample were marked with a blue marker to determine the accurate testing parts on the PET bottle.

2.2.4. Failure analysis

Failure analysis is the process of collecting, identifying, and investigating the reason for failure to prevent future failures (Zerbst et al., 2015; Hussin et al., 2016).

Common techniques for this assessment include root-cause failure analysis (RCFA), failure modes and effects analysis (FMEA), fault tree analysis (FTA), and hazard and operability study (HAZOP). Among these, RCFA is one of the most widely applied methods and is suitable for this study (Ali et al., 2020).

The first step involved placing the bottle on a sheet of paper on the table to observe the defect pattern, which was recorded in a photograph. After identifying the issue, the next step was to analyse the cause of the defect. The before-and-after comparison of the samples was performed to determine the degree of failure of the bottle. Once the cause of the failure had been analysed, appropriate corrective measures were determined to prevent the bottle from future failures.

3. RESULT AND DISCUSSION

3.1. Strength properties of samples with different densities

3.1.1. Compressive strength test

Figure 1 illustrates the average compressive results of seven samples (A, B, C, D, E, F, and G) with different densities. There was a steady increment in compressive strength as the sample density increases. Sample A (0 g/mL) had the lowest compressive strength (0.39 N/mm^2), whereas Sample G (0.65 g/mL) recorded the highest compressive strength (53.09 N/mm^2). These outcomes align with an earlier study by Othman et al. (2021), who reported that compressive strength increased with sample density. Porosity decreases when the density of the ecobrick sample increases as more plastic is packed into the same volume. This design creates a more continuous solid structure that can bear greater stress, resulting in higher compressive strength. In addition, finer capillaries are indirectly formed, allowing samples to withstand greater forces (Ahmad et al., 2022). Therefore, compressive strength increases proportionally with density (Albatayneh & Akhtar, 2024).

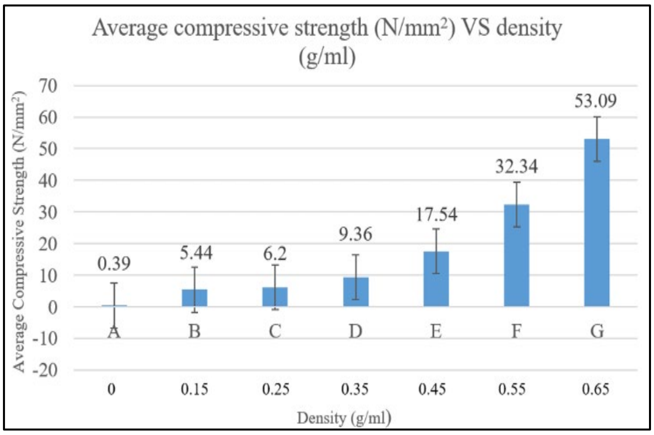


Figure 1: Average compressive strength of ecobricks with different densities

Figure 2 demonstrates that the samples are arranged from Sample A (left) to Sample G (right). The failure analysis revealed that Sample A exhibited more significant deformation and damage compared to Sample G. Greater fractures and buckling under compression were evident in the lower-density Sample A, likely due to the inability to withstand the applied load and the presence of more voids from lower filler content (Akkaya & Çağatay, 2021). In contrast, Sample G, with a higher density, experienced less damage, highlighting the superior load-bearing capacity and structural integrity.

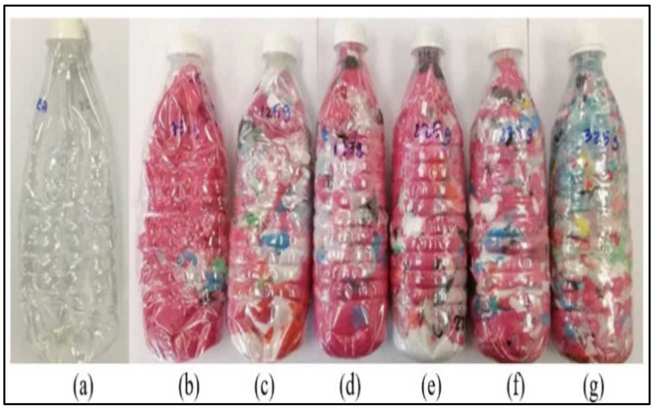


Figure 2: Ecobrick sample after compressive test: (a) Sample A, (b) Sample B, (c) Sample C, (d) Sample D, (e) Sample E, (f) Sample F, and (g) Sample G.

The force against elongation analysis was conducted to demonstrate the strength properties of the samples during the compressive strength test. According to Roylance (2001), the greater the sample density, the greater the force applied, and the lower the elongation that occurs on the curve. Based on Figure 3, it can be concluded that the force exerted on the sample increased as the density of the sample increased. Sample G (0.65 g/mL) recorded the greatest force of (17,068.69 N) at an elongation of 1,187 mm. Meanwhile, Sample A (0 g/mL) exhibited the lowest force (927.21 N) and an elongation of 1,700 mm.

These outcomes indicated that Sample G (0.65 g/mL) performed best during the force against elongation analysis. As density increases, the porosity decreases, leading to higher resistance to the applied force, thus reducing the elongation. When the density increases, the internal structure of the ecobrick sample is more tightly packed and becomes more compact (Akkaya & Çağatay, 2021). This design leads to fewer voids or pores between the particles, contributing to a strong structural integrity (Martínez-García et al., 2022). As Sample G has the highest density, the ecobrick could withstand more force and distribute the force better over the other samples.

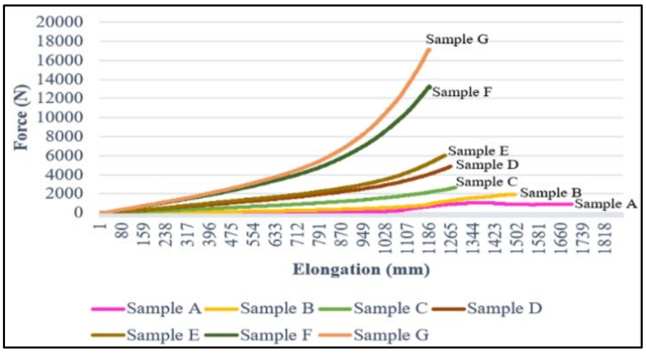


Figure 3: Force against elongation analysis of ecobricks with different densities

3.1.2. Drop test

The drop test results revealed that heavier samples maintained better structural integrity after being dropped from heights of 1 m, 2 m, and 3 m (see Table 2). Sample A (0 g/mL) exhibited noticeable dents, particularly at the lower part of the bottle when dropped from 3 m compared to 1 m. Similarly, Sample B (0.15 g/mL) exhibited smaller and less obvious dents under the same conditions. Meanwhile, samples C and D displayed more pronounced dents at higher drop heights, with Sample D demonstrating less damage than Sample C. In contrast, Samples E, F, and G showed no visible dents when dropped from any height, highlighting the superior durability and resistance to impact.

Based on the results, it can be concluded that the drop height significantly influenced the bottle condition, with higher drops causing more noticeable dents. Nonetheless, the density of the bottle also plays a critical role, as increased plastic filler content enhances resistance to fracture propagation through crack pinning, improving impact strength (Rothon, 2003). Additionally, epoxy interfacial bonding and reduced micro-voids between particles contribute to greater hardness and strength (Mohamed & Saleh, 2019). Therefore, Samples E, F and G (0.65, 0.55, 0.45 g/mL) withstood all drop tests without damage, unlike the lower-density Samples A to D (0 to 0.35 g/mL).

3.1.3. Flexural strength test

Figure 4 details the flexural strength of each density at three different parts of the ecobrick. The results indicated that the body of the bottle exhibited more flexural strength than the neck and bottom as the density increased. Furthermore, increased ecobrick density demonstrated higher flexural strength of the three parts of the bottle. However, the pattern of the results for Sample G differed slightly from the other samples. Even though the flexural strength for the neck (7.78 N/mm²) and body (11.02 N/mm²) of Sample G was higher than that of Sample F, the result of the bottom part of Sample G decreased significantly (0.53 N/mm²) compared to that of Sample F. The significant drop in flexural strength for the bottom part of Sample G (0.53 N/mm²) indicated a structural or compositional weakness, potentially due to a higher stress concentration in this area compared to the neck and body. According to Lyu et al. (2001), a structure exposed to higher stresses often leads to failure or cracking. Therefore, cracks occurring at the bottom of the bottle resulted in lower strength. In addition, the polymer molecules in the bottle have less time to reorganise and absorb the applied force at higher strain rates. Therefore, the ecobricks are more likely to fail suddenly without significant plastic deformation (Wang et al., 2024).

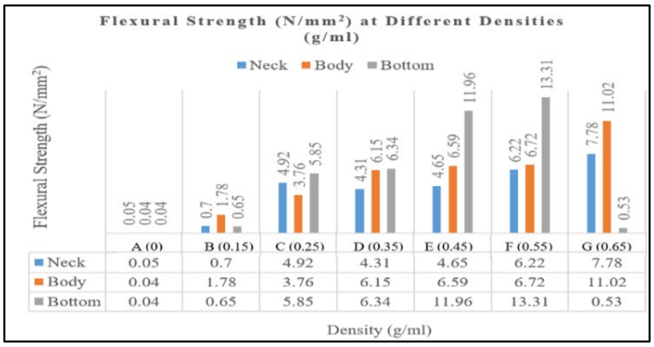
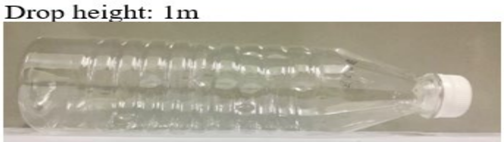
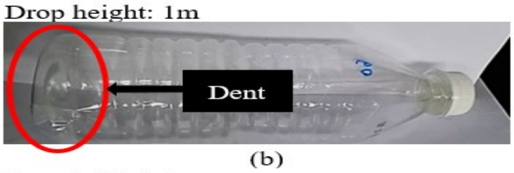
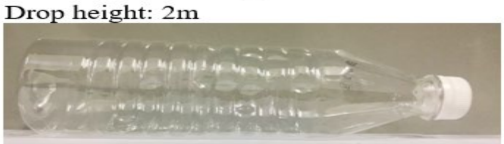
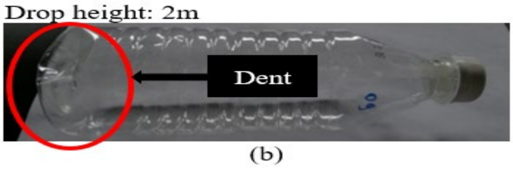
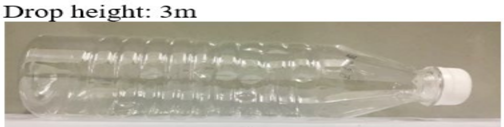
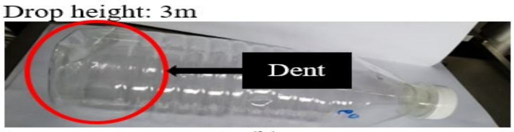
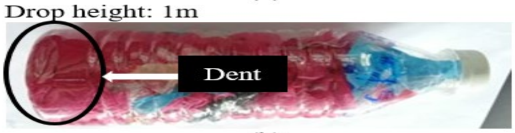


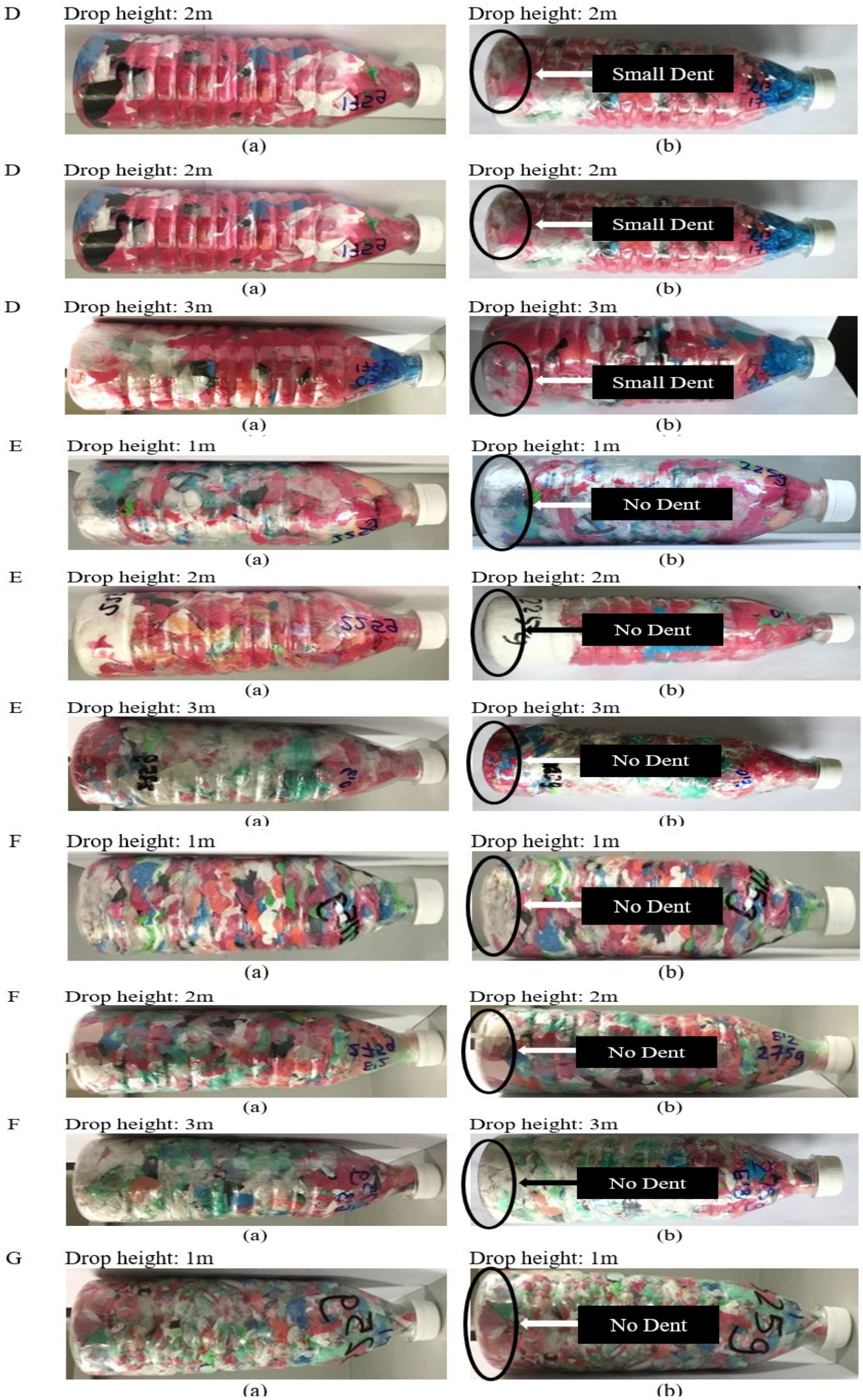
Figure 4: Flexural strength test results of ecobricks with different densities

Figure 5 illustrates the ecobrock samples after being subjected to failure analysis of the flexural test; Sample A (left) to Sample G (right). Sample E cracked more insignificantly than Samples A, B, C, and D. Meanwhile, Sample F ruptured more than Sample E, and Sample G deformed more completely than the other samples. The samples cracked and failed at the maximum point after the flexural test because the plastic content in the PET bottle reached the maximum bending point, and was unable to provide adequate flexural strength (Al-Darzi, 2022).

Figure 5: Ecobrick sample after flexural test: (a) Sample A, (b) Sample B, (c) Sample C, (d) Sample D, (e) Sample E, (f) Sample F, and (g) Sample G

Table 2: Drop test results: (a) Samples before the test, (b) Samples after the test

Sample	Before drop	After drop
A	Drop height: 1m  (a)	Drop height: 1m  (b)
A	Drop height: 2m  (a)	Drop height: 2m  (b)
A	Drop height: 3m  (a)	Drop height: 3m  (b)
B	Drop height: 1m  (a)	Drop height: 1m  (b)
B	Drop height: 2m  (a)	Drop height: 2m  (b)
B	Drop height: 3m  (a)	Drop height: 3m  (b)
C	Drop height: 1m  (a)	Drop height: 1m  (b)
C	Drop height: 2m  (a)	Drop height: 2m  (b)
C	Drop height: 3m  (a)	Drop height: 3m  (b)
D	Drop height: 1m  (a)	Drop height: 1m  (b)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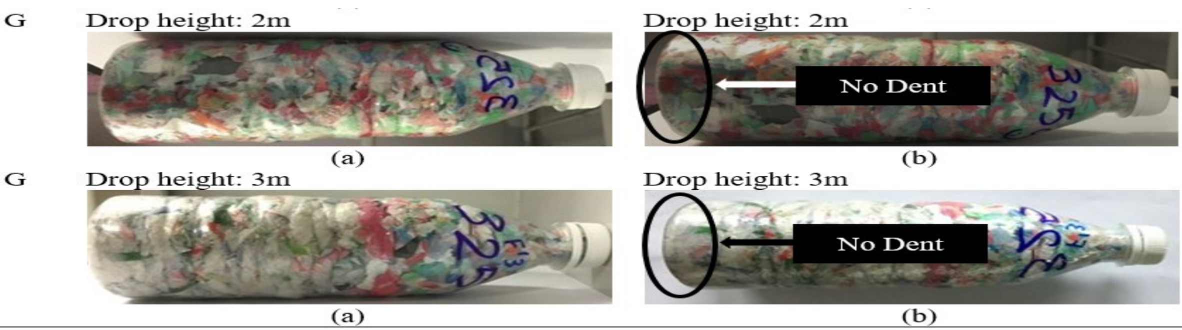

3.2. Determination of the optimum mass of an ecobrick as a building material

After conducting all strength property tests, the results of the compressive strength test, drop test, flexural test, and failure analysis were compared to determine the optimum sample for ecobrick production as a building material. The results for each strength property test are summarised in Table 3.

Table 3: Summary of strength property test results

Descriptions/Samples	A	B	C	D	E	F	G
Compressive strength test					√	√	√
Drop test					√	√	√
Flexural strength test				√	√		

Table 3 indicates that Sample E (0.45 g/mL) outperformed other samples by passing all conducted tests, making this ecobrick the optimal choice for production. While Samples E, F, and G were suitable for compressive strength and drop tests, and Samples D and E performed well in the flexural test, Sample E stood out as the ecobrick obtained a compressive strength of 17.54 N/mm^2. This value exceeded the minimum recommended compressive strength for bricks (5.2 N/mm^2), as regulated by the Malaysian Public Works Department (2020). Sample E also showed no damage in drop tests and achieved a significant flexural strength of 6.59 N/mm^2 without fractures. Despite excelling in compressive and drop tests, Samples F and G failed the flexural test. Meanwhile, Sample D failed the compressive and drop tests, despite performing well in the flexural test. Consequently, Sample E with (0.45 g/mL) also complied with the guidelines on ecobrick production, which requires a minimum density of 0.33 g/mL (Global Ecobrick Alliance, 2019). Therefore, Sample E, weighing 225 g with a density of 0.45 g/mL, is the optimum mass for producing ecobricks as building materials, complying with Malaysian standards and Global Ecobrick Alliance guidelines.

4. CONCLUSION

This study has contributed to the innovation of plastic bottles as a building material, offering a sustainable alternative in the construction industry. Repurposing plastic waste into functional building materials can reduce the volume of plastic being disposed of in landfills. Nevertheless, this study primarily focused on assessing the feasibility of using ecobricks as an alternative material for structural and non-structural building applications based on their strength properties. Further investigation is required to confirm the suitability of these ecobricks as a true replacement for traditional bricks. Future studies could benefit from conducting additional tests, such as durability, long-term performance, fire resistance and thermal insulation, to ensure that the plastic bottle bricks are truly suitable for use in construction. These tests could also identify opportunities for improvement and aid in enhancing the performance and reliability of ecobricks for wider building applications.

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