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Developing 3D Printed Hexagon Tiles from Recycled Plastic Bottles for Sustainable Construction

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Abstract

This study investigates the development of sustainable construction materials by repurposing 30 kg of recycled plastic bottle caps into 3D-printed hexagonal tiles. The process involved cleaning, drying, shredding, and extruding the caps into consistent polypropylene (PP) filaments. The hexagonal geometry was selected for its efficient space utilization, structural stability, and reduced material wastage. Mechanical and physical performance tests were conducted, including Shore D hardness (average 65) and surface quality analysis using grayscale microscopy, confirming uniformity and durability comparable to commercial plastic tiles. The resulting tiles demonstrated adequate rigidity and surface integrity for applications such as flooring and wall cladding, offering a low-cost and eco-friendly alternative to conventional materials. This project highlights the viability of integrating waste management, 3D printing, and modular design to promote circular economy principles, reduce landfill-bound plastic, and encourage greener construction practices such as wall panel.

1. Introduction

Plastic pollution poses a major environmental issue in Malaysia, which ranked eighth globally in plastic waste generation, producing nearly one million tonnes of mismanaged plastic waste in 2010, with up to 0.37 million tonnes entering the ocean [1][2]. This project focuses on addressing plastic pollution by transforming discarded polypropylene (PP) bottle caps into sustainable construction materials. Malaysia is among the world's highest contributors to plastic waste, much of which ends up mismanaged and polluting the environment [3]. To mitigate this issue, the study developed a process to convert waste plastic into 3D-printable filament through systematic collection, cleaning, shredding, and extrusion. Using this recycled filament, interlocking hexagonal tiles were designed and produced as an eco-friendly alternative to conventional construction materials [4][5]. The study evaluated the filament's dimensional accuracy, surface quality, and the tiles' mechanical performance to ensure suitability for light-duty construction applications. This project demonstrates the potential of recycled plastic as a valuable resource, supporting circular economy principles and promoting innovation in sustainable building practices [6]. The outcomes highlight that plastic waste can be repurposed into durable, high-quality products, offering a scalable solution for reducing environmental impact in the construction industry [7].

2. Materials Selection and Preparation

At this stage, research is focused on the preparation and selection of materials such as plastic bottle caps. There were three procedures in this stage which are collecting plastic bottles, cleaning and drying the material and the last one is the shredding process for the next step.

2.1 Collecting Plastic Bottles

This document outlined a systematic process to collect plastic bottles and prepare them for use in sustainable construction projects. A collection activity was conducted across the UTHM Pagoh campus as the initial step in a plastic recycling initiative. The focus of the activity was to gather plastic bottles, with particular attention to the segregation of plastic bottle caps for subsequent processing [8]. This effort marked the beginning phase of the project, aimed at promoting sustainable waste management and environmental conservation practices on campus.

2.1.1 Cleaning and Drying

Following the collection of plastic bottle caps, a thorough cleaning process was conducted to remove any dirt, debris, or residual contaminants. The collected polypropylene (PP) bottle caps, weighing a total of 20.10 g, were first washed thoroughly with clean water to remove dirt and residue. After cleaning, the caps were placed in an oven at 100 °C for 24 hours to eliminate moisture. Following the drying process, the mass was reduced to 15.33 g, showing a total moisture loss of 4.77 g before proceeding to the shredding stage.

Fig. 1 *Oven Drying*

2.1.2 Shredding

After drying, the PP bottle caps were shredded using a mechanical plastic shredder into uniform flakes measuring approximately 1–2 cm in size. The shredded material was collected and stored in airtight containers to prevent contamination and moisture absorption prior to extrusion.

Fig. 2 *Shredding process*

2.2 Filament Production

The dried and shredded PP flakes were fed into the Felfil Evo Pro extruder for filament production. The extrusion temperature was set between 180 °C and 200 °C, producing a 1.75 mm ± 0.05 mm diameter filament. The extruded filament was spooled under controlled tension, with the filament radius verified microscopically to be 0.880 mm to 0.904 mm, ensuring dimensional consistency for 3D printing.

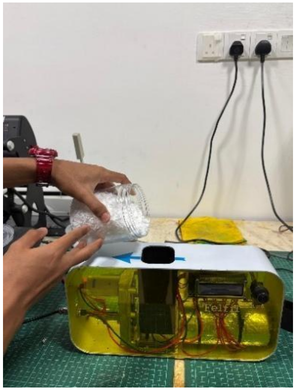

Fig. 3 *Filament extrusion using Felfill Evo Pro machine*

2.3 3D Printing of Hexagonal Tiles n

The 3D printing of hexagonal tiles using recycled plastic bottle caps offered an innovative and sustainable approach to construction. Bottle caps, typically made from High-Density Polyethylene (HDPE) or Polypropylene (PP), were ideal materials due to their durability, lightweight properties, and recyclability. After being cleaned, the caps were ground into granules and converted into 3D printing-ready pellets or filaments. This approach created useful and adaptable building components while reducing plastic pollution by repurposing waste materials [8]. The hexagonal design of the tiles minimized material waste and improved structural efficiency.
The tiles were first modeled using Computer-Aided Design (CAD), which provided precise control over their thickness and dimensions. Once the design was completed, Creality software was used to configure parameters such as print speed, infill density, and layer height to prepare the model for 3D printing. These parameters ensured production quality, structural strength, and material efficiency [9]. Felfil Evo Pro was used to extrude the recycled plastic layer by layer during the fabrication process. To enhance durability and appearance, post-processing procedures including surface polishing and the application of protective coatings were carried out.

Despite challenges such as maintaining consistent plastic quality and optimizing printer settings, this method demonstrated the potential for producing ecofriendly construction materials. Recycling bottle caps into tiles reduced waste, promoted a circular economy, and provided an alternative to traditional manufacturing methods. The combination of 3D printing versatility and sustainable materials highlighted a promising pathway for innovation in the construction industry.

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2.4. Testing

2.4.1 Mechanical Testing

The mechanical performance of the 3D-printed hexagonal tiles was evaluated using the Shore D hardness test, following the ASTM D2240 standard. Testing was performed using the HBD 100-0 Durometer, with a test pressure of 50 N, a depth of indentation range of 0–2.5 mm, and a measuring spring force of 0.55–44.5 N. Three tile samples were tested, yielding Shore D hardness values of 67.0, 68.3, and 66.5, resulting in an average hardness of 67.3. These values place the tiles within the typical range for semi-rigid thermoplastics, confirming their suitability for lightweight construction applications such as wall cladding and decorative panels [9].

Fig. 4 *Shore D test*

2.4.2 Physical Testing

3D printing Physical testing was carried out to evaluate the surface quality of the 3D-printed tiles through gray scale analysis. Tile samples were photographed under uniform lighting and compared with a standard gray scale chart to assess color consistency. The results helped determine whether the recycled plastic produced a uniform surface appear Physical testing was carried out to evaluate the surface quality of the 3D-printed tiles through gray scale analysis [4]. Tile samples were photographed under uniform lighting and compared with a standard gray scale chart to assess color consistency. The results helped determine whether the recycled plastic produced a uniform surface appearance suitable for construction applications. The surface roughness of the tiles was examined using a Dino-Lite digital microscope as shown at Figure 6, which provided high-magnification images of the tile surfaces. This allowed for the observation of print layer lines and any surface irregularities caused during the 3D printing process, offering insight into the quality of the surface finish [4].

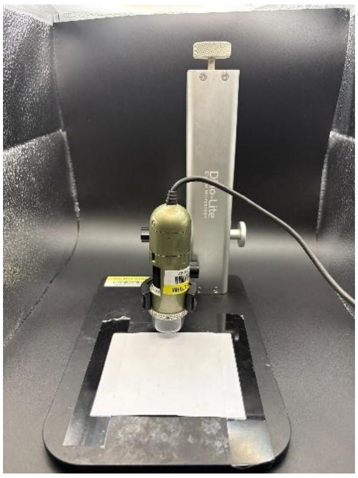

Fig. 5 *Dino-Lite microscope used during the surface inspection*

2.4.3 Data Analysis

Data analysis is essential for evaluating the effectiveness of 3D-printed hexagonal tiles made from recycled plastic bottles. It involves assessing performance indicators such as production cost, environmental impact, material efficiency, and mechanical properties like tensile strength, load-bearing capacity, and surface durability [10]. These metrics are compared against industry standards to determine the tiles' viability in real-world applications. Sustainability is also evaluated by analyzing material waste reduction, energy usage, and print consistency across batches. Through trend analysis, the relationship between design parameters, printer settings, and tile performance is identified, guiding improvements in production. Ultimately, the analysis supports continuous optimization and confirms the potential of recycled 3D-printed tiles as a scalable and eco- friendly construction material.

3. Result

3.1 Filament Analysis

The recycled filament used in this study was produced from polypropylene (PP) bottle caps through crushing, heat treatment, and extrusion. To ensure proper extrusion quality, the filament diameter must comply with the industry standard of 1.75 mm ± 0.05 mm. Therefore, five samples of the produced filament were analysed under a digital microscope to measure their radius and assess dimensional uniformity.

The microscopic images of each sample are shown in Figure 4.6a to Figure 4.6e. All measurements were taken at 50x magnification, with radius ranging from 0.880 mm to 0.904 mm. These values correspond to diameters between 1.760 mm and 1.808 mm, which fall within the acceptable tolerance range. The consistent size across all samples indicates a stable extrusion process and good control over temperature and feed rate during filament production [7].

3.2 Gray Scale Surface Analysis

The surface quality of the 3D-printed hexagonal tiles was evaluated using grayscale surface analysis to assess uniformity and detect potential printing defects. Optical scans were performed along a 1,000 μm (1 mm) surface profile using a Dino-Lite digital microscope. This method measures variations in grayscale intensity, which correlate with surface roughness, irregularities, and overall print consistency [8]. The grayscale values of all scanned samples ranged between approximately 45 and 52, with minimal fluctuations across the measured distance, as shown in Fig. 6. This narrow range indicates a smooth and uniform surface finish with no significant surface defects. The consistent intensity levels also confirm even material deposition and proper interlayer bonding during the printing process. These results demonstrate that the recycled polypropylene filament, when printed under controlled extrusion parameters, can produce high-quality, defect-free surfaces. The uniform surface profile supports the filament's suitability for light-duty decorative and functional applications, comparable in quality to components printed with virgin polymer materials.

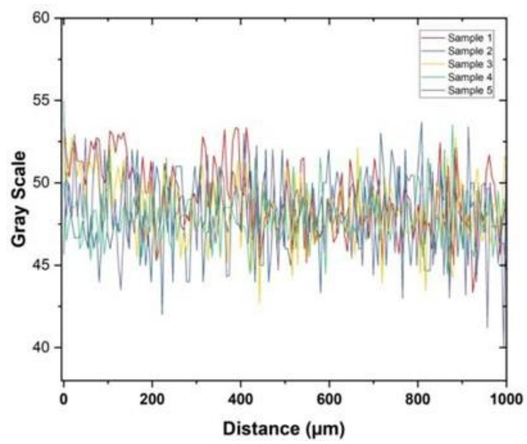

Fig. 6 *Gray scale Surface Analysis*

3.3 Shore D-Hardness Test

The average Shore D hardness of the 3D-printed recycled plastic tiles was 67.3, placing them within the ASTM D2240 standard range (65–75) for semi-rigid thermoplastics. This indicates that the tiles have sufficient strength and wear resistance, making them suitable for indoor wall and light-duty construction applications. The consistent hardness values also suggest strong interlayer bonding during printing, reflecting proper processing. These findings support previous research [5] showing that recycled polypropylene can retain mechanical properties comparable to virgin plastic when processed correctly amd three samples were tested, yielding values of 67.0, 68.3, and 66.5, with an average hardness of 67.3. According to the ASTM D2240 classification, this range corresponds to semi-rigid thermoplastics, confirming the tiles suitability for non-structural construction uses such as interior wall cladding, decorative panels, and light-traffic flooring. These results also indicate that the recycled polypropylene filament retained mechanical integrity comparable to commercially available plastic products, demonstrating its potential as an eco-friendly alternative to traditional materials [8].

Table 1 *Shore D Hardness Values for 3D Printed Tile Samples*

Sample	Shore D Hardness (HD)
1	67.0
2	68.3
3	66.5

4. Conclusion

The study confirmed that 3D-printed tiles made from recycled polypropylene bottle caps meet key quality standards. The extruded filament maintained a consistent diameter within the acceptable range (1.75 mm ± 0.05 mm), and microscopic analysis showed uniformity across samples. Gray scale surface analysis indicated smooth extrusion and strong layer bonding. The printed tiles demonstrated accurate dimensions with no shrinkage, and Shore D hardness tests showed they were strong enough for indoor wall use, aligning with standards for semi-rigid plastics. Overall, the results validate the use of recycled plastic for sustainable 3D-printed construction components, proving that with proper processing, recycled materials can perform comparably to conventional filaments.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Mohamad Azim Mohammad Azmi;* ***data collection, analysis and interpretation of results and draft manuscript preparation:*** *Nur Najwa Zainal, Raja Muhammad Farishilmi Raja Muhammad Putra, Zureen Aleya Aminudin. All authors reviewed the results and approved the final version of the manuscript.*

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