BORNEO JOURNAL OF SCIENCES AND TECHNOLOGY (BJoST)
VOL: 8, ISSUE: 1, 102-111
DOI: http://doi.org/10.35370/bjost.2026.8.1-09
e-ISSN: 2672-7439, UTS Publisher.

University of Technology Sarawak

ORIGINAL ARTICLE

Experimental Study of Lightweight Tile with Plastic Waste as Partial Replacement Materials

*[1,2]Yong Tat Lim, [2]Brandon Zong Hui Chuo, [1,2]Teck Sung Sie, [1,2]Wen Kam Leong, [1,2]How Teck Sia, [1,2]Nur Saffrina Binti Saffaee

[1]Centre for Research of Innovation and Sustainable Development, University of Technology Sarawak, 96000 Sibu, Sarawak, Malaysia
[2]School of Engineering and Technology, University of Technology Sarawak, 96000 Sibu, Sarawak, Malaysia

ABSTRACT – The growing demand for cement tiles in the construction industry has contributed to an increasing shortage of raw materials, particularly sand. Concurrently, the improper disposal of plastic waste has emerged as a major environmental concern. To address this issue, this research was carried out to explore the application of plastic waste in cement tile. Plastic waste was utilized to replace sand in the range from 5% to 35%, resulting in the fabrication of 21 cement tile specimens, in addition to three conventional specimens. The performance of the cement tiles was investigated through breaking strength, water absorption, density, and flatness tests. Most specimens satisfied the relevant industrial standard specifications. The results demonstrated that cement tiles containing 5% to 35% plastic waste achieved the minimum breaking strength requirements in accordance with BS EN 13748-1:2004. The water absorption and density of cement tiles were lower as compared to conventional tiles, indicating lower permeability and lighter product, respectively. The flatness measurements met the MS ISO 10545-2 specification limits. Among the tested mixes, the cement tile containing 35% plastic waste exhibited optimal performance, fulfilling all standard requirements and offering an alternative for sustainable construction applications.

ARTICLE HISTORY
Received: 29 June 2025
Revised: 24 Oct 2025
Accepted: 21 Nov 2025

KEYWORDS
Cement tile,
Sand,
Plastic waste,
Construction materials,
Lightweight.

INTRODUCTION

Cement tiles are essential construction materials with 10 billion square meters of production annually [1]. As the construction sector continues to expand at a rate of 10.3% per year, the corresponding demand for cement tiles is expected to rise [2]. This growing demand may contribute to a shortage of sand. One potential mitigation strategy involves the partial replacement of sand with industrial by-products.

Malaysia, ranked third globally for ocean pollution, is presently facing a severe environmental crisis. It releases about 73,098 metric tons of plastic waste into the ocean each year [3], which undergoes slow degradation over extended periods [4]. The main drawback of plastic materials lies in their persistence as waste, leading to pollution and the overcrowding of landfills [5]. Meanwhile, improper plastic waste management, such as open burning, contributes significantly to carbon dioxide (CO_2) emissions [6].

Few studies have explored the use of plastic waste as a partial replacement for sand in cement tiles to meet industrial specifications for breaking strength [7–8], water absorption [9], and density [10]. Such an approach not only minimizes environmental impacts but also reduces the consumption of natural resources in the tile production industry.

The incorporation of plastic waste as a sand substitute has been shown to slightly reduce breaking strength at a 10% replacement compared with conventional mixes, mainly due to the lower mechanical strength of plastic particles [7]. Similarly, cement tiles with 10–20% plastic waste exhibited lower water absorption than conventional cement tiles [9]. Furthermore, increasing the plastic waste content resulted in reduced specimen density, attributed to the lower density of plastic materials compared with sand, thereby decreasing the overall mass of the tiles [10].

*Corresponding Author: Yong Tat Lim. University of Technology Sarawak (UTS), email: limyongtat@uts.edu.my

This study introduces an innovative type of cement tile to the construction industry, emphasizing its advantages while expanding the range of available alternatives. It focuses on developing cost-efficient structural component designs that can help reduce overall construction cost, as well as producing more aesthetically appealing and versatile tile patterns to enhance visual quality and design flexibility.

With that, this research was conducted to investigate the effect of plastic waste in cement tiles. The optimum mix proportion that fulfills industry requirements can be determined. These can be achieved by carrying out an experimental study to evaluate the breaking strength, water absorption, density, and flatness.

MATERIALS AND METHODOLOGY

Materials

The specific gravity of plastic waste is 1.12 according to the research on [11]. The density of plastic was 279 kg/m^3. It was cut into small fragments capable of passing through a 2.36 mm sieve during the sieving process. Others physical properties of plastic waste are listed in Table 1.

Table 1. Physical Properties of Plastic Waste [12]

Physical Properties	Plastic Waste
Water absorption (%)	0.01
Softening point, T_g (^oC)	140 -150
Melting point, T_m (^oC)	160 - 166

Mechanical properties of plastic waste may offer advantages for several applications. Thus, the performance of cement tile could potentially be improved when incorporated plastic waste as a component in a mixture. Table 2 summarised the mechanical properties of plastic waste.

Table 2. Mechanical Properties of Plastic Waste [12]

Mechanical Properties	Plastic Waste
Tensile strength (N/mm^2)	22.06 – 34.47
Elongation (%)	3 – 700

The chemical properties of plastic waste are shown in Table 3. The table listed the crystallinity, acetaldehyde and carboxyl end group.

Table 3. Chemical Properties of Plastic Waste [12]

Chemical Properties	Plastic Waste
Crystallinity	$\geqslant$ 45
Acetaldehyde (parts per million)	$\leqslant$ 3
Carboxyl end group (Mol/t)	$\leqslant$ 20

For effective performance, the fine aggregate must meet specific particle size requirements. In this study, at least 90% of the selected fine aggregate particles pass through a 600 μm (Sieve No. 30) to align with conventional mix design specifications [13]. The sand should have a particle density of 2600 kg/m^3 and must be kept in an air-dried state to prevent alterations in its properties due to moisture or environmental exposure. Additionally, the water was sourced and supplied by the local utility company which was not contain any impurities that may affect the performance of cement tiles.

The Ordinary Portland cement used in this research will function as a cementitious binder for the sand and plastic waste. Achieving the desired consistency is essential, as it greatly influences the structural design. The particle density of the cement was 1,350 kg/m^3. Table 4 presents the physical properties of Ordinary Portland cement.

Table 4. Physical Properties of Ordinary Portland Cement [14]

Physical Properties	Cement
Specific Gravity	3.10
Standard Consistency (%)	35
Initial Setting Time (min)	65
Final Setting Time (min)	450
7 days Compressive Strength (MPA)	20.40
28 days Compressive Strength (MPA)	32.55

Table 5 presents the chemical properties of Ordinary Portland cement. Calcium oxide (CaO) constitutes over 60% of Ordinary Portland cement, while silica dioxide (SiO_2) comprises approximately 20%. Other chemical constituents, including magnesium oxide (MgO), iron (III) oxide (Fe_2O_3), sulphur trioxide (SO_3), aluminium oxide (Al_2O_3), and sodium oxide (Na_2O) constitute a minor portion of the total composition.

Table 5. Chemical Properties of Ordinary Portland Cement [15]

Chemical Properties	Cement
SiO_2	20.12
Na_2O	0.55
Al_2O_3	5.25
Fe_2O_3	1.29
CaO	63.13
MgO	1.53
K_2O	0.30
SO_3	2.54
Loss of Ignition	2.64

Mix Proportion

With regard to the production of cement tiles, the components that were used were plastic waste, Ordinary Portland cement, sand, and water. The percentage of plastic waste to be used in the mix should be determined before the materials were mixed.

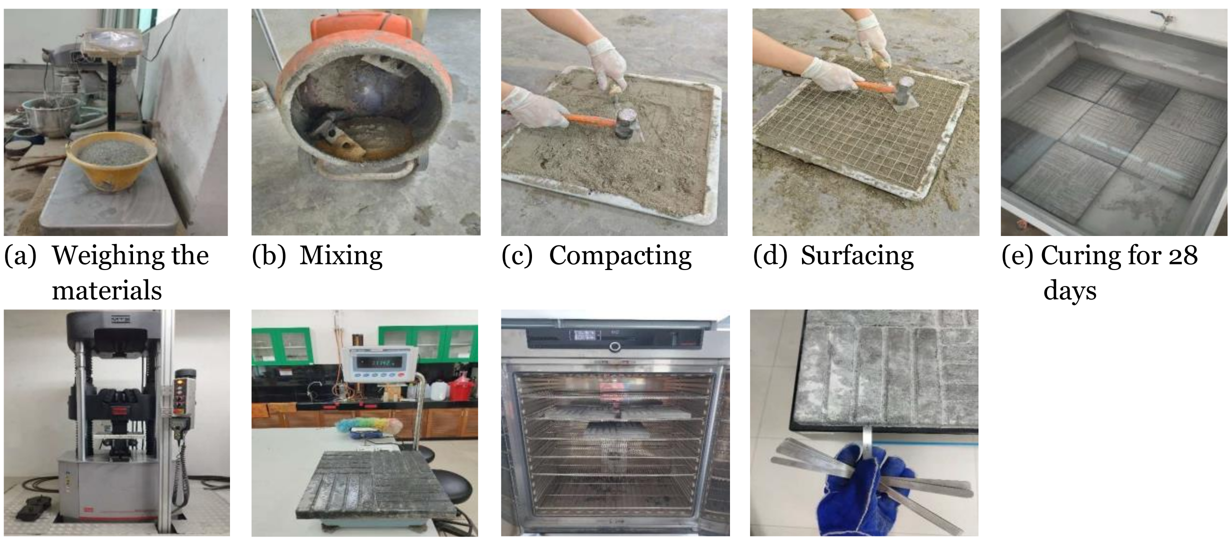
A water/cement ratio of 0.5 and a cement/sand ratio of 1:2 was used for mixing the cement tiles. A total of 21 cement tiles with a different amount of plastic waste in the mix which between 5% to 35%, as well as 3 conventional cement tiles were produced. Experiments results needed to be recorded were breaking strength, flatness, and weight. Additionally, the percentage of plastic waste and the number of specimens required for each mixing proportion were detailed in Table 6.

Table 6. Mix Proportion of the Cement Tiles with the Tests

Specimen	Breaking Strength (N), Water Absorption (%), Density (kg/m3), Flatness (mm)
	Day 28
Conventional tile (S-0)	3
5% plastic waste (P-5)	3
10% plastic waste (P-10)	3
15% plastic waste (P-15)	3
20% plastic waste (P-20)	3
25% plastic waste (P-25)	3
30% plastic waste (P-30)	3
35% plastic waste (P-35)	3
Total tile	24

Test Procedures

Tile specimens, in the size of 400 mm x 400 mm x 35 mm were cast in a mould. The specimens were mixed, cast and tested in accordance with the procedure. The mix was compacted by 25 strokes in 3 layers. The specimens were de-moulded 1 day after casting and were submerged in water for curing.



(a) Weighing the materials (b) Mixing (c) Compacting (d) Surfacing (e) Curing for 28 days

(f) Breaking test (g) Weighing specimen (h) Oven-dry (i) Flatness test

Figure 1. Preparation and testing of the tile specimens

The tile specimens were tested by a Universal Testing Machines (UTM) and weighted by an electronic weighting machine for the breaking strength, F_{bs}, density, ρ, and water absorption, WA. The results were calculated by using Equation 1 and 2 [16].

$$WA = \frac{W_s - W_d}{W_d} \times 100 \quad (1)$$

$$\rho = \frac{\text{Mass}}{\text{Volume}} \quad (2)$$

Where:
W_s = Weight of the saturated specimen, kg
W_d = Weight of the oven-dry specimen, kg
Volume = Length × Breadth × Thickness, mm^3

The flatness of the tile specimens was to determine the evenness and smoothness of the installation surface. The test should follow the requirements stated in ASTM C485-09 [17]. The tolerance variations of the specimens were expressed in terms of edge curvature, and warpage as specified in MS ISO 10545-2. Thus, the flatness of tile specimens was measured to be within the range defined by MS ISO 10545-2 [18].

RESULT AND DISCUSSION

Conformability to Requirements

Table 7 documented the test result of each mix design. The breaking strength on day 28, water absorption, density and flatness ranged from 4755.00 N to 3326.00 N, 9.79% to 7.75%, 1916.07 kg/m^3 to 1779.55 kg/m^3 and 0.2 mm to 1.6 mm, respectively.

The test results are analysed based on the following considerations:
(a) The tile should be able to carry some load including self-weight. Therefore, breaking strength should be achieved a minimum of 3000 N to comply with the industrial standards set by the BS EN 13748-1:2004 [19].
(b) According to the BS EN 13748-1:2004 [19], the water absorption of cement tiles must not exceed 8%.
(c) Lightweight tile is preferred for easy handling during construction. Thus, ρ should not exceed 1850 kg/m^3 [20].
(d) The tile installation should be of good quality to reduce the possibility of tile detachment. Thus, the flatness (edge curvature, warpage) difference should not exceed 2.0 mm.

Table 7. Summary of Test Result

Mix*1	Test Results*1			Evaluating Criteria*2				
							Flatness	
	F_{bs} (N)	WA (%)	ρ (kg/m^3)	F_{bs} (N)	WA (%)	ρ (kg/m^3)	Edge Curvature (mm)	Warpage (mm)
	Day 28	Day 28	Day 28	F_{bs} > 3000 N	$WA \leq 8\%$	$\rho \leq 1850$ kg/m^3	$x \leq 2.0$	
S-0	5280.50	10.02	1931.25	✓	×	×	✓	✓
P-5	4755.00	9.79	1916.07	✓	×	×	✓	✓
P-10	4259.00	9.66	1902.74	✓	×	×	✓	✓
P-15	4155.50	9.63	1899.91	✓	×	×	✓	✓
P-20	4114.00	9.51	1893.84	✓	×	×	✓	✓
P-25	4177.00	8.66	1884.38	✓	×	×	✓	✓
P-30	3540.50	8.09	1859.29	✓	×	×	✓	✓
P-35	3326.00	7.75	1779.55	✓	✓	✓	✓	✓

Notes: *1S = conventional tile, P = cement tile containing plastic waste
*2F_{bs}, WA, and ρ are the breaking strength, water absorption, and density of the mix, respectively.

From Table 7, the following is observed:
(a) All the tiles achieved a minimum of 3000 N to comply with the industrial standards set by the BS EN 13748-1:2004 [19].

(b) The tile specimen with 35.0% plastic mineral bottles waste (mix P-35) was less than 8% of the water absorption rate.
(c) The tile with 35.0% plastic mineral bottles waste (mix P-35) was considered lightweight. The density was less than 1850 kg/m3.
(d) All the tiles of flatness remained within specifications specified in MS ISO 10545-2 [18].

Breaking Strength

In Figure 2 demonstrates how the breaking strength of cement tile has been affected by replacement materials. The breaking strength of the tile will decrease as the proportion of replacement material increases, which is in aligning with earlier studies [21].

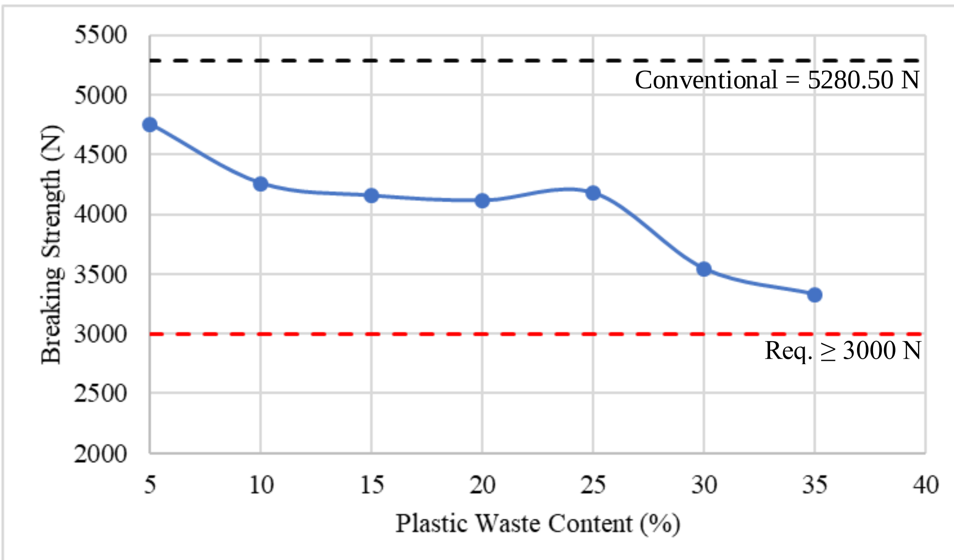


Figure 2. Effect of plastic waste on the breaking strength of cement tile.

The breaking strength of the tile specimens with 5.0% plastic waste content (mix P-5) was 4755.00 N. Conversely, the breaking strength of the tile specimens with 35.0% plastic waste content (mix P-35) decreased further to 3326.00 N. The breaking strength decreases as the percentage of plastic waste increases. These results are in accordance with Haile's previous analysis [8].

The breaking strength of the cement tile reduces significantly as the effects of the replacement of plastic waste in the cement tile, which may result in a lightweight tile. When the plastic waste percentage was increased from 5.0% to 35.0%, the breaking strength was noticed to decrease by 30.05%. This reduction can be attributed to the lower stiffness and mechanical integrity of plastic waste compared to sand. Furthermore, the weak interfacial bonding between the hydrophobic plastic surfaces and the hydrophilic cement limited effective stress transfer, thereby compromising the overall load-bearing capacity of the composite. Similar findings have been reported in previous studies [22], indicating that the substitution of sand with plastic materials tends to weaken the bonding between the cement and the plastic particle [22].

According to Figure 2, all the tile samples exhibited a breaking strength more than the standard specification of 3000 N [19]. Other than that, all the tile specimen with the presence of plastic waste showed a lower breaking strength as compared to the conventional tile (with 5280.50 N). Although the tiles specimens had lower breaking strength than conventional tile, all of the tiles were still allowed to be used for building purposes as the tiles satisfy the minimum standard specification.

Water Absorption

Water absorption is an indicator that determines the durability of cement tiles. Lower water absorption indicates lower permeability in cement tiles which helps prevent water from entering due to the presence of hydrophobic materials. Figure 3 shows the water absorption of cement tiles with different proportions of plastic waste.

According to Figure 3, the water absorption of the tile specimen with 5.0% plastic waste (mix P-5) was 9.79%, while the tile specimen with 35.0% plastic waste (mix P-35) decreased to 7.75%. The water absorption decreases as the percentage of plastic waste increases. Such reduction is due to the hydrophobic nature of plastic particles, which do not absorb or interact with water molecules. As the proportion of plastic increases, the overall pore connectivity within the cementitious is reduced, resulting in fewer capillary channels for water penetration. Moreover, the presence of plastic particles may occupy voids, thereby limiting water ingress. This finding aligns with previous research suggesting that hydrophobic inclusions enhance the impermeability of cement-based materials by disrupting the continuity of the capillary network [8].

The results indicated by Figure 3 show that tile samples mixed with plastic waste absorbed less than conventional tile when the material were mixed in a certain proportion. Furthermore, the water absorption for the 12.5% of the tile specimen is less than 8%. Thus, it can be concluded that the higher the plastic waste content, the lower the water absorption rate. Therefore, the water absorption for 35% plastic waste content of the tiles were allowed to be used for building purposes as the tiles satisfy the minimum standard specification [1].

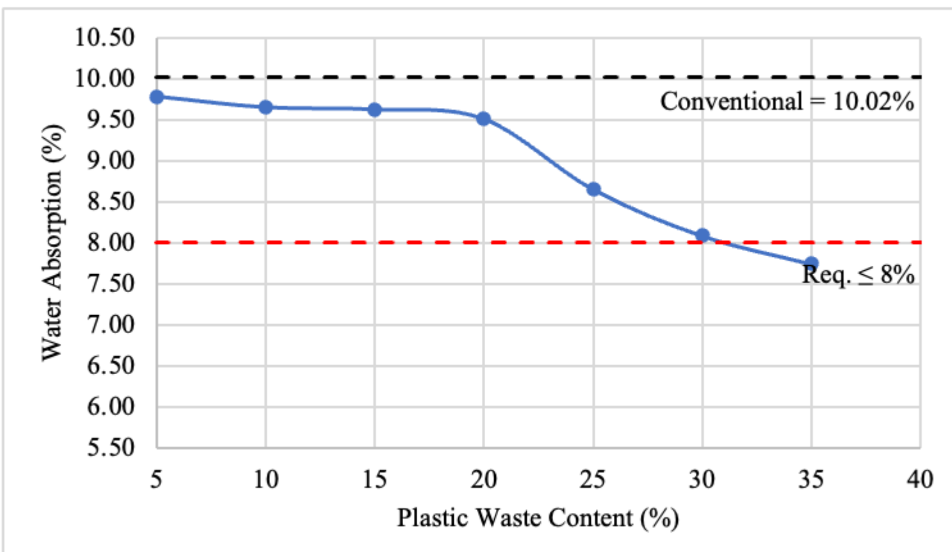


Figure 3. Effect of plastic waste on the water absorption of cement tiles.

Density

Figure 4 represents the density of tile specimens for different plastic waste content at day 28. In accordance with prior research, it is obvious that tile density continued to decrease as the quantity of replacement material increased [8].

Based on Figure 4, the densities of all mix proportions were decreased as the amount of plastic waste content increased. The highest density of 1916.07 kg/m^3 was discovered in the tile specimen with 5.0% plastic waste content (mix P-5), while the lowest density of 1779.55 kg/m^3 was found in the tile specimen with 35.0% plastic waste content (mix P-35). In comparison to conventional tile, the densities decreased by 15.18 kg/m^3 and 151.70 kg/m^3 representing reductions of 0.79% and 7.86% respectively. This decreasing trend is due to the low density of plastic waste (279 kg/m^3) compared to sand (2600 kg/m^3), resulting in lighter composite structures. The replacement of sand with plastic particles effectively reduces the bulk density of the mixture as the lighter plastic acts as a filler material, lowering overall mass [8]. Hence, the integration of plastic waste demonstrates potential for producing lightweight cement tiles suitable for applications where reduced self-weight is advantageous.

According to Figure 4, the tile specimens with 35.0% of plastic waste content are classed as lightweight tiles since their densities are less than 1850 kg/m^3. With respect to this, it was suggested that using plastic waste could be a suitable method to produce lightweight tiles for construction. Given that the density of plastic waste was significantly lower than that of sand, it is expected that the tile's density would decrease as the percentage of plastic waste increase.

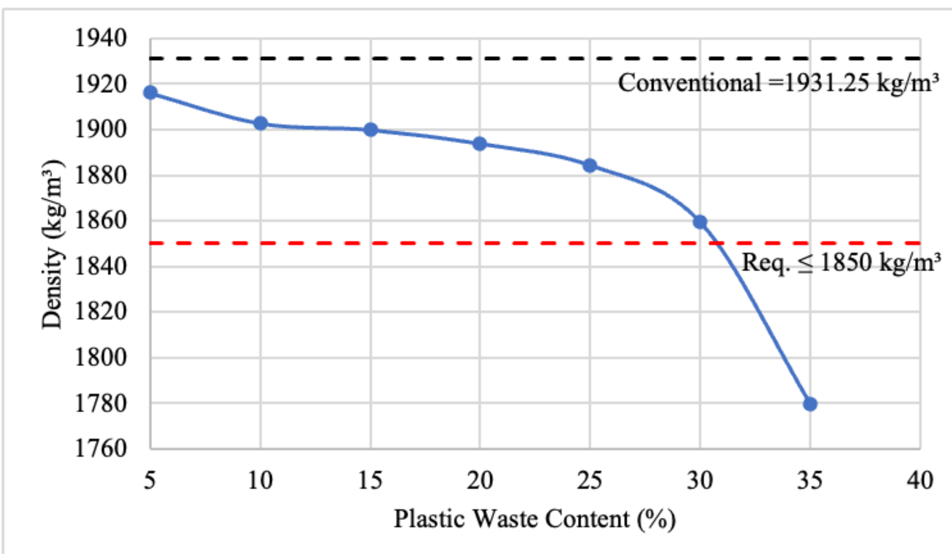


Figure 4. Effect of plastic waste on the density of cement tiles.

Flatness

According to the Table 8, the flatness of the tiles remained within specifications specified in MS ISO 10545-2 [18]. Other than that, the average flatness (edge curvature, warpage) of each tile specimen were acceptable. The acceptable tiles can be used in construction without any defect.

During tile installation, a flat tile surface enables more efficient work and improved the installation quality. It also provides even bonding of the tile adhesive to ensure structural stability and reducing the possibility of tile detachment or hollow spots. However, one common installation defect is lippage, which refers to the height difference between the edges of adjacent tiles. This not only affects the overall appearance but also can pose a tripping hazard.

Table 8. Flatness of Cement Tiles

Mix	Test Results	
	Edge Curvature (mm)	Warpage (mm)
Conventional tile (S-0)	0.4 – 1.1	0.2 – 1.2
5% plastic waste (P-5)	0.4 – 1.4	0.4 – 1.6
10% plastic waste (P-10)	0.4 – 1.3	0.7 – 1.4
15% plastic waste (P-15)	0.3 – 1.1	0.2 – 0.9
20% plastic waste (P-20)	0.3 – 1.2	0.4 – 1.2
25% plastic waste (P-25)	0.4 – 1.4	0.5 – 0.9
30% plastic waste (P-30)	0.4 – 1.4	0.3 – 1.4
35% plastic waste (P-35)	0.2 – 1.3	0.2 – 1.2

CONCLUSION

This study investigated the partial replacement of sand with plastic waste in cement tiles to determine the optimum mix proportion that meets established industry specifications. Experimental results disclosed that increasing the plastic waste content led to a decrease in breaking strength, water absorption, and density. Despite these changes, cement tiles containing 35.0% plastic waste were found to comply with the standard requirements for lightweight tiles. Furthermore, incorporating plastic waste in cement tile production offers environmental benefits by reducing waste and conserving natural raw materials like sand, making it a sustainable alternative in the construction sector.

FUTURE RESEARCH

Future research may focus on broadening the investigation to include the durability and performance of cement tiles with plastic waste under various environmental conditions such as temperature fluctuations, moisture, and ultraviolet exposure. Moreover, computational modeling techniques such as finite element analysis could be utilized to predict material properties. Life-cycle is also recommended to assess the environmental implications of large-scale implementation, thereby strengthening the potential of incorporating plastic waste in the cement tiles as a sustainable innovation in modern construction.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support provided by University of Technology Sarawak (UTS) through the internal grant UTS/RESEARCH/4/2024/09.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Wu, S., Zhang, N., Luo, X., and Lu, W. (2022). Multi-objective optimization in floor tile planning: coupling BIM and parametric design. *Automation in Construction*, 140: 104384. Doi: 10.1016/j.autcon.2022.104384.

[2] Sulaiman, N., Ismail, R., Saukani, N., and Lelchumanan, B. (2021). Skilled labour demand in the malaysian construction sector. *Journal of Sustainability Science and Management*, 16(4): 236–252. Doi: 10.46754/jssm.2021.06.018.

[3] Fernando, F. (2024). Malaysia ranks third in ocean pollution: A Rising Tide of Plastic Peril. *The Rakyat Post*, 24 February.

[4] Xuemiao, L., Tung, C., L., and Kim, H. H. (2020). Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete. *Construction and Building Materials*, 240. Doi: 10.1016/j.conbuildmat.2019.117869.

[5] Debele, A. D., Demeke, S., Bekele, T., and Malimo, M. (2024). Recycling and reusing potential of disposable low-density polyethylene plastic waste for flexible paver tile construction for outdoor application. *Heliyon*, 10(8). Doi: 10.1016/j.heliyon.2024.e29381.

[6] Ibrahim, N. R., and Noordin, N. N. M. (2020). Understanding the issue of plastic waste pollution in Malaysia: A case for human security. *Journal of Media and Information Warfare*, 13(1): 105–140.

[7] Ibrahim, A., Bassam, A. T., Rayed, A., Hisham, A., and Abdeliazim, M. M. (2020). Eco-friendly concrete containing recycled plastic as partial replacement for sand. *Journal of Materials Research and Technology*, 4631–4643. Doi: 10.1016/j.jmrt.2020.02.090.

[8] Haile, E., Quezon, E. T., and Kebede, G. (2019). Investigation on the suitability of waste plastic bottle as partial replacement of sand in a cement tile production. *American Journal of Civil Engineering and Architecture*, 7(3): 121–127. Doi: 10.12691/ajcea-7-3-1.

[9] Goud, K. A., Balakrishna, C., Prakash, A., and Munipally, S. K. (2024). Assessing the feasibility of using waste plastic as a partial replacement for fine aggregate in cement tile production: An experimental study. *Lecture notes in civil engineering*, 165–173. Doi: 10.1007/978-981-99-9458-8_16.

[10] Bamigboye, G. O., Ngene, B. U., Ademola, D., and Jolayemi, J. K. (2019). Experimental study on the use of waste polyethylene terephthalate (PET) and river sand in roof tile production. *Journal of Physics Conference Series*, 1378(4). Doi.: 10.1088/1742-6596/1378/4/042105.

[11] Salah,M.A., Abolazizi, A., Abdolbaset, A., and Osama, A. (2018). Experimental study on waste plastic as additional material to structural concrete. *The Second Libyan Conference on Chemistry and its Applications (LCCA-2)*, 8: 1–8.

[12] Divyabharathi, and Pavithran. (2019). Experimental study on mechanical properties of concrete by adding bottle caps and pet bottles in concrete. *International Research Journal of Multidisciplinary Technovation (IRJMT)*, 1(6): 490–495. Doi: 10.34256/irjmtcon70.

[13] BS EN 12620:2013+A1. (2019). *Aggregates for concrete*. British Standards Institution.

[14] Daniel, R. J., and Sangeetha, S. (2021). Experimental study on concrete using waste ceramic as partial replacement of aggregate. *Materials Today Proceedings*, 45: 6603–6608. Doi.org/10.1016/j.matpr.2020.11.772.

[15] Darweesh., H.H.M. (2022). Effect of banana leaf an ash as a sustainable material on the hydration of portland cement pastes. *International Journal of Materials Science*, 4(1): 1–11.

[16] ASTM C373–18. (2023). *Standard test methods for determination of water absorption and associated properties by vacuum method for pressed ceramic tiles and glass tiles and boil method for extruded ceramic tiles and non-tile fired ceramic whiteware products*. ASTM International.

[17] ASTM C485 – 09. (2009). *Standard test method for measuring warpage of ceramic tile*. ASTM International.

[18] Malaysia Standard. (2018). *MS ISO 10545-2 Determination of dimensions and surface quality*. Malaysia Standard Institution.

[19] British Standards Institution. (2004). *BS EN 13748-1:2004 Terrazzo tiles – Part 1: Terrazzo tiles for internal use*. British Standards Institution.

[20] ACI Committee 213. (2014). *Guide for structural ligthweight-aggregate concrete*, ACI 213R – 14. Farmington Hills, MI: American Concrete Institute.

[21] Omosebi, T.O., and Abas, N. F. (2020). Utilization and durability of PET waste aggregate for floor tiles production. *International Journal of Innovative Technology and Exploring Engineering*, *9*(12): 34–38. Doi.org/10.35940/ijitee.L7890.1091220.

[22] Almeshal, I., Tayeh, B. A., Alyousef, R., Alabduljabbar, H., and Mohamed, A. M. (2020). Eco-friendly concrete containing recycled plastic as partial replacement for sand. *Journal of Materials Research and Technology*, *9*(3): 4631–4643. Doi: 10.1016/j.jmrt.2020.02.090.