Sustainable PET-POFA Composite Bricks for Microwave Absorption Application

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***Abstract*—The integration of smart building technologies and the associated microwave radiation exposure highlights the need for sustainable and effective absorbent materials in construction. This study investigates the fabrication and electromagnetic characterization of composite bricks developed from polyethylene terephthalate (PET) plastic waste and palm oil fuel ash (POFA), targeting dual functionality in structural performance and microwave absorption. Bricks were produced with varying PET contents (5%, 10%, and 20%) as an aggregate replacement, and the selected composite contained 10% POFA. After a standard curing process of 28 days, all samples were evaluated for microwave absorption using the NRL Free Space Arch method in the frequency range of 1 to 12 GHz, in both horizontal (6 cm thick) and vertical (10 cm thick) representing the orientations for brick installation. The results showed that PET-modified bricks (P5, P10, P20) achieved significantly higher microwave absorption compared to conventional commercial bricks, and the addition of POFA further enhanced the absorption performance, with the P10F10 composite achieving an absorption peak of -49.65 dB in the S-band. The vertical orientation intensifies the absorption in all developed bricks, as indicated by the maximum absorption of the P20 brick of -35.58 dB in the X-band. Material property analysis showed PET increased electrical resistivity and dielectric permittivity, whereas POFA addition reduced permittivity and moderate resistivity, thereby optimizing impedance matching and dissipative losses. These findings demonstrate a promising approach to sustainable construction, leveraging waste-derived materials for high-performance microwave absorbers that support both environmental and technological demands in modern buildings.**

***Index Terms*—Composite brick, dielectric property, electromagnetic absorption, palm oil fuel ash (POFA), PET waste.**

I. Introduction

The integration of smart building technologies and associated microwave radiation exposure highlights the need for sustainable and effective absorbent materials in construction.

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Smart environments ranging from residential homes to high-performance commercial buildings are increasingly equipped with wireless networks, sensor nodes, and automation devices that increase the levels of microwave and electromagnetic energy in their surroundings[1]. These radiation spikes pose new health, privacy, and operational challenges, while also posing potential long-term risks to occupants. Furthermore, as society seeks more connected and energy-efficient living spaces, there is a corresponding demand for building materials that can protect occupants from electromagnetic interference without compromising structural or ecological performance[2][3].

Sustainability is now a key principle in construction materials research, driven by global climate commitments and the vision of a circular economy that seeks to transform waste streams into valuable building resources[4]. Industrial by-products such as POFA and recycled plastics like PET have emerged as promising raw materials, offering the dual benefits of reduced environmental impact and improved electromagnetic absorption performance[5][6]. However, systematic solutions that integrate environmentally friendly materials while offering advanced functions such as microwave absorption are still rare, especially in standard brick and masonry products. To address this gap, this study aims to develop and evaluate a PET–POFA composite brick designed to deliver effective microwave absorption, thus supporting safer, smarter, and more sustainable buildings of the future.

II. Literature Review

A. Microwave Absorbing Materials in Constructions

Recent advances in microwave absorption technology have resulted in the design of scalable, low-cost materials with applications in telecommunications, electronic safety, and architecture[7][8]. Polymer- and ceramic-based composites are often explored due to their tunable electromagnetic properties, light weight, and potential for production in brick or panel form[9][10]. Reflection loss (RL) is a widely used performance metric that quantifies how effectively a material attenuates incident microwave energy. Advanced absorbers typically achieve RL values below –40 dB across broad frequency ranges, indicating near-total absorption.[11].

Incorporating such materials into the building wall system offers passive defense against radiation from external sources such as base stations and minimizes electromagnetic interference in smart environments. This practice is supported by recent research showing that low-cost, easily scalable microwave-absorbing panels such as three-layer honeycomb structures can be integrated into building walls to enhance electromagnetic shielding, providing passive absorption capabilities superior to conventional metallic or conductive paints. [12]. Recent case studies report that microwave-absorbing bricks or panels can be integrated into existing walls, increasing the overall effectiveness of electromagnetic shielding without the drawbacks of metallic or conductive paint which often reflect rather than absorb energy[13].

B. PET Waste in Bulding Materials

Recent studies have demonstrated that recycled PET, most commonly used in food and beverage packaging, addresses waste management and resource insufficiency issues. In cement matrices, PET has been shown to increase tensile strength, reduce density, enhance durability, and increase internal porosity which is factors that can modulate dielectric properties and enhance electromagnetic dissipation[14]. Innovative works from 2020 to 2025 further confirms that PET not only lowers the carbon footprint of bricks but also in enhancing their electromagnetic attenuation in the gigahertz range[15][16].

C. POFA as Functional Filler

POFA is an abundant agro-industrial byproduct in palm oil-producing regions exhibits pozzolanic characteristics and a microstructure that can improve dielectric loss and conduction when used in composites[5]. Recent studies have validated the application of POFA as an environmentally friendly and cost-effective cement substitute that not only improves sustainability but also contributes to microwave absorption when used alone or in combination with other fillers for microwave and gamma rays shielding[15],[16],[17],[18]. The addition of POFA and activated carbon in mortar achieved RL values below -25 dB at the optimal frequency, outperforming many conventional solutions[5].

D. Current Gaps and Opportunities

Although PET and POFA have demonstrated their respective advantages as sustainable building material additives in the laboratory, there is a lack of systematic research incorporating these two residues into structural bricks specifically designed for broadband electromagnetic absorption. Most previous reports investigated composite powders, pastes, or thin panels and did not evaluate the effect of real brick thickness, standard brick shape, or wall orientation on microwave absorption which is critical determinants for real-world construction applications[5][19][20].

Given these limitations, this study presents the first comprehensive investigation of PET–POFA composite bricks, thoroughly characterizing their electromagnetic properties and free-space absorption performance both in horizontal and vertical orientations represent typical configurations for brick installation in wall systems. This fills a key knowledge gap and advances technologically sustainable construction solutions.

III. MATERIALS AND METHODS

A. Materials

PET plastic waste is a by-product of shredded bottles sourced by Glowmore Express Sdn Bhd, North Port Klang and Tian Li Eco Group Holdings Sdn.Bhd, Semenyih, Malaysia was used as a partial aggregate replacement.

POFA was sourced from a palm oil mill in Padang Serai, Kedah, Malaysia. POFA is produced from the combustion of oil palm shells and husks and was selected for its proven pozzolanic activity and effectiveness as a microwave absorber.

Ordinary Portland Cement (OPC) Type 1 served as the primary binder. Locally mined sand with an average particle size of approximately 5 mm was used as the fine aggregate to accurately simulate standard construction practices.

B. Initial Sample Preparation and Properties Assessment

To optimize the composite formulation, initial cube specimens (10 × 10 × 10 cm^3) were prepared using various PET replacement ratios based on the weight of fine aggregate. These mixtures were designed to systematically evaluate the effect of PET content on key electromagnetic properties. Freshly cast samples were removed from the mould after 24 hours and cured under standard laboratory conditions (23 ± 2 °C, >95% RH) for 28 days as shown in Fig. 1[21].

Fig. 1. Brick sample for properties assessment

The electrical resistivity of each sample was determined using a surface resistance meter with a target value of approximately 1 MΩ to comply with commercial brick standards. Dielectric permittivity was measured using a Microwave Nondestructive Testing (MNDT) system over 8 to 12 GHz (X-Band) frequency range relevant to microwave absorption applications as shown in Fig. 2.

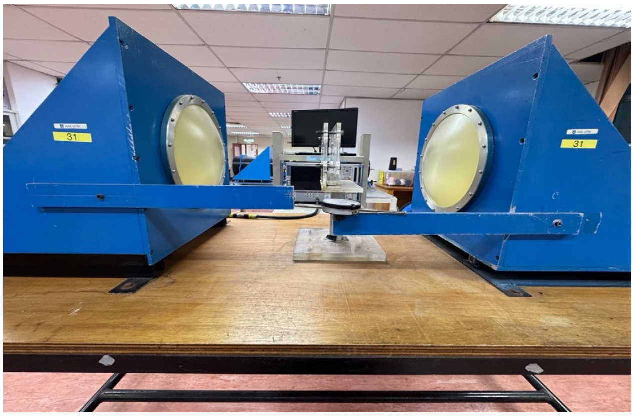

Fig. 2. Permittivity measurement using MNDT system

Based on a comprehensive evaluation of electrical resistivity (≈1 MΩ) and dielectric characteristics suitable for electromagnetic absorption, three optimum PET replacement ratios were selected: 5%, 10%, and 20% by weight of fine aggregate with a fixed addition of 10% POFA replacement by weight of cement for further experimental analysis. These formulations demonstrate an ideal balance between electrical properties requirements and electromagnetic absorption potential which forms the basis for subsequent full-scale brick fabrication and characterization.

C. Brick Fabrication

Two series of microwave-absorbing bricks were developed based on optimized compositions:

Series 1: PET-Only bricks, designated P5 (5% PET), P10 (10% PET), and P20 (20% PET).

Series 2: PET–POFA composite bricks, formulated by adding 10% POFA to a PET base. The selected compositions were P10F10 (10% PET + 10% POFA) and P20F10 (20% PET + 10% POFA).

Each mixture was prepared by dry-mixing PET and POFA particles with cement and sand, followed by the gradual addition of water and admixtures while stirring until a uniform consistency was achieved. The resulting mixture was cast into standard brick moulds to produce blocks measuring 20 cm × 10 cm × 6 cm. After being covered to prevent moisture loss, all bricks were removed from the moulds after 24 hours and then cured for 28 days according to MS 76: 1972 standard to ensure full hydration and strength development as shown in Fig. 3[22].

Fig. 3. Brick curing process

D. Mechanical Characterization

After curing, the compressive strength of all brick specimens was assessed according to relevant standards MS 76:1972 using a universal testing machine[22]. Each formulation was evaluated with a minimum of three replicates to report the average value and standard deviation to ensure suitability for structural applications and safe handling. The compressive strength test is shown in Fig. 4.

Fig. 4. Compressive strength test

E. Microwave Absorption Measurement

The electromagnetic absorption characteristics of all fabricated brick samples were systematically evaluated using the Naval Research Laboratory's (NRL) Free-Space Arch method as in Fig.5. Tests were conducted over a frequency range of 1 to 12 GHz, covering the major microwave communication bands L, S, C, and X. Measurements were conducted at normal incidence of 0° angle to simulate the perpendicular direction of electromagnetic waves in a building environment. To reflect real-world installation configurations, each brick type was tested in two orientations: horizontal, with a thickness of 6 cm, and vertical, with a thickness of 10 cm, corresponding to a full-wall arrangement.

For each measurement, the brick was precisely positioned between a pair of transmitting and receiving horn antennas, connected to a vector network analyzer. The key performance indicators extracted were reflection loss (RL, in dB) and absorption. In this context, a more negative RL value indicates superior microwave absorption indicating the brick sample's ability to absorb and dissipate incident electromagnetic energy, rather than reflect it. This reliable free-space methodology ensures reliable and repeatable broadband electromagnetic shielding performance assessments under conditions representative of actual construction use.

Fig. 5. *NRL Free Space Arch measurement setup.*

IV. RESULT AND DISCUSSION

A. Compressive Strength

The compressive strength of fabricated brick samples was evaluated according to standard procedures with the results summarized in Table I[22]. Each value is the average of three independent tests per composition.

P5 and P10 demonstrated the highest average compressive strengths, reaching 18.18 MPa and 17.92 MPa, respectively. The P20 brick achieved 10.09 MPa. For PET–POFA composite bricks, P10F10 recorded an average compressive strength of 8.58 MPa, while P20F10 achieved 11.02 MPa. All PET-containing bricks and PET–POFA composite bricks demonstrated compressive strengths above typical minimum requirements for non-load-bearing masonry, although higher PET or POFA contents generally resulted in decreased mechanical performance. These results confirm that the addition of PET and POFA can produce bricks with adequate structural integrity for building applications while also providing advanced functional properties.

TABLE I. COMPRESSIVE STRENGTH OF PET AND PET–POFA BRICKS

Brick Type	Average (MPa)
P5	18.18
P10	17.92
P20	10.09
P10F10	8.58
P20F10	11.02

B. Dielectric and Electrical Properties

The fundamental electromagnetic properties of the developed bricks were first examined. The dielectric permittivity increased with PET addition, recording values of 6.9971 for P5, 7.4232 for P10, and 7.7755 for P20. Conversely, the addition of POFA led to a significant decrease in permittivity: P10F10 and P20F10 recorded 3.9077 and 2.3174, respectively. The electrical resistivity showed a similar PET-driven trend, increasing from 3.709MΩ (P5) to 6.342MΩ (P20), while the addition of POFA moderated this resistance to 4.497MΩ (P10F10) and 3.460MΩ (P20F10). This dual tuning of dielectric and resistive properties builds the foundation for optimizing microwave attenuation through compositional design.

C. Microwave Absorption Performance of Solid PET Bricks (1 to 12 GHz)

Fig. 6 and Fig. 7 illustrate the absorption performance of PET-only bricks (P5, P10, P20) compared to conventional commercial bricks (CB) in the 1 to 12 GHz frequency range, with assessments performed in both horizontal (6 cm) and vertical (10 cm) orientations. A significant increase in microwave absorption was observed with increasing PET content. Specifically, in the L-band (1 to 2 GHz), the maximum absorption values achieved for P5, P10, and P20 in the horizontal orientation were -26.75 dB, -23.44 dB, and -16.61 dB, respectively, which substantially exceeded the -8.37 dB recorded for CB. This increase was even more pronounced when the bricks were tested in the vertical orientation, simulating a practical wall installation, where the P20 brick exhibited a maximum absorption of -30.18 dB, compared to -11.24 dB for CB.

The enhanced absorption performance for PET-containing bricks is not limited to the L-band; a similar trend also occurs in higher frequency ranges, including the C- and X-bands. Notably, the P20 vertical bricks achieve a maximum value of -35.58 dB in the X-band, confirming the material's superior electromagnetic absorption capability across a broad frequency spectrum. In addition to the enhanced maximum value, the PET bricks consistently exhibit much higher minimum absorption values than commercial bricks across all bands demonstrating their robust and stable absorption characteristics even under varying electromagnetic conditions. These results collectively highlight the effectiveness of PET modification in significantly improving the breadth and consistency of microwave absorption in brick materials intended for smart building applications.

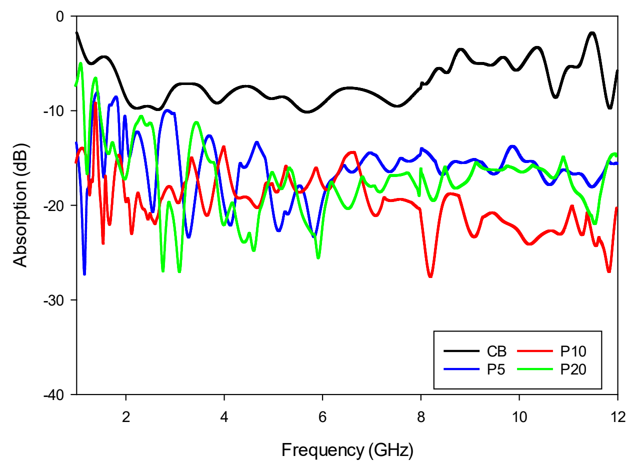

Fig. 6. Microwave absorption performance of PET-only bricks in horizontal orientation (6 cm) thickness

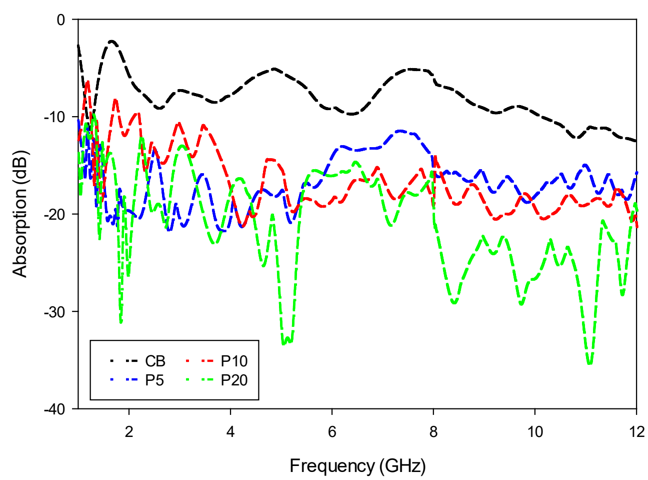

Fig. 7. Microwave absorption performance of PET-only bricks in vertical orientation (10 cm) thickness

D. PET-POFA Composite Bricks: Synergistic Effects

Fig. 8 and Fig. 9 present the absorption performance of PET–POFA composite bricks (P10F10 and P20F10), which clearly demonstrate the beneficial effect of POFA addition on the overall electromagnetic performance. The addition of 10% POFA to the PET-based formulation not only increases the intensity but also broadens the effective absorption bandwidth of the bricks. The P10F10 composite achieves a maximum absorption of -49.65 dB in the S-band (horizontal orientation) and -35.58 dB in the X-band (vertical orientation) values that substantially exceed those observed for both the PET composite alone and the commercial reference brick. The P20F10 brick also exhibits outstanding absorption characteristics, consistently achieving maximum absorption values greater than -30 dB and maintaining reflection loss values below -20 dB across the measured frequency spectrum. Furthermore, the minimum absorption level for the POFA-containing brick remains significantly greater than that of the other formulations, indicating robust and stable attenuation even under unfavorable conditions. These results collectively confirm that the synergistic use of PET and POFA results in a composite brick capable of providing reliable broadband microwave absorption across a wide range of installation orientations, making it highly suitable for integration into technologically advanced and electromagnetically resistant for wall system of the building.

E. Effect of Brick Orientation

In all brick formulations, vertical installation which simulates real-world wall stacking resulted in significantly higher absorption values than horizontal orientation for identical compositions. Vertically, P20F10 achieved -35.58 dB in X-band is significantly higher than its maximum horizontal value. This improved performance can be attributed to the increased microwave propagation path length and multiple internal reflections which are critical for practical electromagnetic shielding in building wall systems.

F. Summary of Absorption Performance

To provide a comprehensive comparison of electromagnetic attenuation across the tested formulations, Tables II and Table III summarize the maximum and minimum absorption values (in dB) for each brick type in the relevant frequency bands in both horizontal and vertical orientations.

Table II presents the maximum absorption values illustrating that PET–POFA composite bricks consistently outperform both PET-only and commercial bricks (CB) across all assessed frequency bands. Specifically, the P10F10 composition achieved a peak absorption of -49.65 dB in the horizontal S-band, while P20F10 reached as low as -35.77 dB in the vertical L-band. All PET-containing bricks exhibited significantly superior absorption values to CB, with the effect being more pronounced in the vertical orientation which simulates a full-wall assembly.

Table III details the minimum absorption measured under the same conditions, further demonstrating the robustness of the composite formulation. Even the lowest values for the PET–POFA bricks remained consistently below -20 dB across multiple bands and orientations which highlight their effective broadband shielding capacity.

The tabulated results in Table II and Table III clearly demonstrate that the synergistic integration of PET and POFA produces composite bricks with outstanding and stable broadband electromagnetic absorption. Specifically, PET–POFA blends (P10F10 and P20F10) achieve superior performance in both horizontal and vertical orientations across all frequency bands confirming their suitability for real-world architectural electromagnetic shielding applications.

TABLE II. MAXIMUM REFLECTIVITY (DB) OF PET AND PET-POFA BRICKS IN DIFFERENT FREQUENCY BANDS

Frequency Band	Orientation	CB	P5	P10	P20	P10F10	P20F10
L-band	Horizontal	-8.37	-26.75	-23.44	-16.61	-28.19	-30.64
	Vertical	-11.24	-21.2	-18.67	-30.18	-30.18	-35.77
S-band	Horizontal	-9.86	-23.14	-22.36	-26.37	-49.65	-31
	Vertical	-9.15	-21.87	-17.02	-23.44	-23.44	-37.82
C-band	Horizontal	-10.09	-23.09	-20.67	-24.98	-46.83	-34.96
	Vertical	-9.73	-21.32	-21.27	-33.47	-33.47	-35.58
X-band	Horizontal	-9.55	-17.71	-27.09	-21.27	-26	-36.11
	Vertical	-12.51	-18.81	-21.35	-35.58	-35.58	-29.61

TABLE III. MINIMUM REFLECTIVITY (DB) OF PET AND PET-POFA BRICKS IN DIFFERENT FREQUENCY BANDS

Frequency Band	Orientation	CB	P5	P10	P20	P10F10	P20F10
L-band	Horizontal	-1.74	-7.92	-9.44	-4.47	-16.28	-20.18
	Vertical	-2.25	-10.38	-6.19	-9.88	-9.88	-29.13
S-band	Horizontal	-7.11	-9.78	-13.84	-10.04	-21.76	-21.63
	Vertical	-5.94	-13.34	-9.56	-12.11	-12.11	-28.8
C-band	Horizontal	-7.36	-13.1	-13.42	-15.49	-20.7	-22.7
	Vertical	-5.1	-11.46	-14.41	-14.67	-14.67	-25.94
X-band	Horizontal	-1.59	-13.45	-18.32	-13.86	-19.74	-21.1
	Vertical	-5.83	-14.95	-14.26	-18.91	-18.91	-23.72

V. CONCLUSION

This study demonstrates the successful synthesis and comprehensive evaluation of sustainable PET–POFA composite bricks for use as multifunctional building materials. Through systematic material design and careful characterization, it is demonstrated that the incorporation of PET and POFA not only enables the production of bricks with adequate compressive strength which meet Malaysian standards for non-load bearing masonry but also provides exceptional broadband microwave absorption capability across the L, S, C, and X frequency bands.

Compared to conventional bricks, both PET-only and PET–POFA composite formulations achieve significantly better electromagnetic absorption especially when measured at realistic wall orientations and standard thicknesses. P10F10 and P20F10 bricks exhibit stable reflection loss values below -20 dB and maximum values reaching -49.65 dB which set a new benchmark for environmentally friendly microwave shielding in construction applications.

By presenting solutions that address waste management, resource recovery, and electromagnetic compatibility, this research advances the field of technologically robust and environmentally friendly smart building materials. Future research should explore long-term durability, full-scale placement, and performance under varying environmental conditions, which will further facilitate progress towards the adoption of a circular economy in the construction industry.

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