https://doi.org/10.24191/jeesr.v28i1.003

Effect of PET and POFA Incorporation on Microwave Absorption of Porous Cement Bricks

Linda Mohd Kasim, Hasnain Abdullah *, Mohd Nasir Taib, Noorshafinas Abdul Jabar, Norhayati Mohamad Noor, Azizah Ahmad, Noor Azila Ismail and Nazirah Mohamat Kasim

***Abstract*—The growing reliance on wireless infrastructure and increasing electromagnetic pollution is prompting the development of building materials that are both multifunctional and environmentally sustainable. Conventional cement bricks are less capable of absorbing electromagnetic waves and are highly dependent on non-renewable resources. This study examines the microwave absorption performance of porous cement bricks using recycled polyethylene terephthalate (PET) as a partial sand replacement and palm oil fuel ash (POFA) as a partial cement replacement. Two experimental brick formulations, PB1 (65% cement, 30% POFA, 5% PET, foam) and PB2 (65% cement, 30% POFA, 20% PET, foam), were developed and evaluated alongside commercial cement bricks (CB). The electromagnetic properties were studied using the NRL free-space arch method at frequencies of 1 to12 GHz for vertical (10 cm thickness) orientations at 0°, 30°, and 60°. Band-specific analysis (L, S, C, X) shows that PB1 and PB2 exhibit enhanced microwave absorption compared to CB, with PB2 achieving the highest absorption of -30.17 dB in the C-band and exhibiting the lowest dielectric constant (ε=2.53). This enhancement is attributed to the increase in PET and porosity, which promotes interfacial polarization and impedance matching. These findings highlight the potential and environmental impact of waste-derived PET and POFA for sustainable and high-performance electromagnetic shielding in construction materials.**

***Index Terms*—Cement brick, electromagnetic absorption, palm oil fuel ash (POFA), polyethylene terephthalate (PET).**

I. Introduction

The widespread use of electronic devices, wireless networks, and smart technologies has led to a significant increase in electromagnetic radiation (EMR) in homes, workplaces, and industrial environments.

This manuscript is submitted on August 27, 2025, revised on February 16, 2026, accepted on April 1, 2026, and published on April 30, 2026.

Linda Mohd Kasim, Hasnain Abdullah, Mohd Nasir Taib, Noorshafinas Abdul Jabar, Norhayati Mohamad Noor, Azizah Ahmad, Noor Azila Ismail and Nazirah Mohamat Kasim are with the Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Selangor, Malaysia.

*Corresponding author
Email address: hasnain@uitm.edu.my

While radio frequency (RF) and microwave technologies are essential to modern life, researchers have also raised concerns about electromagnetic pollution which describes the continued exposure to man-made EMR from various sources[1],[2],[3],[4]. Prolonged exposure to electromagnetic fields (EMFs) particularly in the radio and microwave spectrum has been linked to several adverse health effects. The International Agency for Research on Cancer (IARC) has classified RF EMFs as "possibly carcinogenic to humans" (Group 2B), with calls for further evaluation considering more recent epidemiological and biological evidence. Complementary analyses by the World Health Organization (WHO) and other scientific authorities reaffirm concerns regarding chronic EMF exposure and highlight the urgent need to investigate potential biological effects, particularly in vulnerable populations such as children[1],[5].

Beyond health concerns, electromagnetic interference (EMI) poses a significant and growing challenge to the electronics industry and the construction sector. EMI can disrupt device functionality and data integrity, making electromagnetic compatibility (EMC) a critical requirement for modern electronic systems. The increasing density of electronics within buildings has increased the demand for new materials that efficiently absorb or dampen unwanted electromagnetic waves[6][7],[8].

Historically, metals such as copper, aluminum, and nickel have been the primary materials for EMI shielding due to their excellent electrical conductivity and high attenuation capabilities. However, limitations such as heavy weight, stiffness, and susceptibility to corrosion have limited their applications, particularly in lightweight or flexible structural applications. This has driven a surge in research seeking lightweight, cost-effective, and flexible EMI shielding alternatives, with carbon-based materials becoming the leading force in recent years[8],[9].

Carbon black, carbon nanotubes (CNTs), graphene, and other engineered carbon nanostructures exhibit high conductivity and strong dielectric loss, making them effective in microwave and RF absorption[10]. When derived from biomass, carbon materials further benefit from inherent microporosity and multiphase interfaces, which enhance microwave attenuation through mechanisms such as multiple scattering and interfacial polarization[11]. POFA, an abundant agricultural byproduct in palm oil-producing regions is gaining increasing attention for its value as a green carbon source and as a functional additive in cement matrices[12].

The use of POFA in building materials meets both waste management and sustainability goals. Research shows that its rich carbon content and pozzolanic activity can provide beneficial properties such as porosity, microstructural complexity, and tailored dielectric behavior that are essential for effective electromagnetic absorption[13].

Concurrently, plastic waste, particularly polyethylene terephthalate (PET) continues to pose a challenge to global environmental management efforts as PET is highly durable, chemically inert, and very slow to degrade[14]. The use of recycled PET in concrete and mortar as a partial replacement for sand or aggregate offers two advantages: mitigating environmental pollution and reducing natural resource consumption[15],[16]. A review article confirms that the use of PET in cementitious composites can reduce density and improve certain durability properties, but the consequences for electromagnetic properties such as dielectric constant and absorption have not been fully characterized[17],[18].

Therefore, the design of advanced microwave absorbers for building applications focuses on optimizing material composition, microstructure, and interfaces to achieve high reflection loss , RL, with larger negative dB indicating greater absorption, broad absorption bandwidth, low density, and environmental compatibility[8]. Contemporary research indicates that a combination of tailored porosity, dielectric and/or magnetic loss, and impedance matching is crucial to maximizing electromagnetic wave dissipation in absorbing materials. In cementitious systems, the synergy of a porous matrix (often foamed or air-filled), conductive or dielectric fillers, and engineered interfaces can significantly improve microwave absorption and broaden the frequency band performance[7],[19]. Recent research modeling concrete as a four-phase composite which is mortar, aggregate, water, and air confirms that increasing air content and porosity substantially reduces the dielectric constant with similar results observed for the use of low-permittivity and non-polar polymers. This reduction in dielectric constant is important for optimizing impedance matching and maximizing microwave absorption[20].

Despite recent progress, there is still a clear lack of studies comparing how well the recycled material such as PET and POFA-modified cement bricks absorb and respond to electromagnetic waves especially when compared to regular commercial bricks. This gap is most noticeable in tests that use standard frequency bands (L, S, C, X) and different angles of wave exposure under strict experimental conditions.

Therefore, this study investigates the electromagnetic absorption properties of porous cement bricks containing PET as partial sand replacement and POFA as partial cement replacement in varying proportions, which are produced together with a foaming agent for controlled porosity. Two formulations (PB1 and PB2) are systematically compared with commercial cement bricks (CB) using the NRL free-space arch method at frequencies of 1 to 12 GHz at various incidence angles in vertical orientation. Particular attention is for the impact of PET and POFA content on the microstructure, dielectric constant, and electromagnetic absorption with the aim of providing insights into sustainable strategies for high-performance electromagnetic absorption in construction.

II. MATERIALS AND METHODS

A. Materials Preparations

The PET material used in this study was obtained as a by-product of shredded bottles from Glowmore Express Sdn Bhd, North Port Klang, Malaysia. The average PET particle size was approximately 5 mm. POFA was sourced from a palm oil mill in Padang Serai, Kedah, and is produced by the combustion of oil palm shells and husks. POFA was used due to its potential effectiveness as a microwave absorber. Ordinary Portland Cement (OPC) Type 1 was used, with quarry sand (average particle size ≈5 mm) as the fine aggregate. All aggregates were cleaned to ensure they were free from impurities. Porosity was increased by adding a synthetic foaming agent "NORAITE SA-1", purchased from DRN Resources (Penang, Malaysia). All selected materials were used to manufacture prototype brick absorbers for subsequent resistivity and dielectric evaluation.

B. Brick Absorber Design

A standard solid brick design is implemented conforming to commercial dimensions of 200mm (length) × 100mm (width) × 60mm (height), as illustrated in Fig.1.

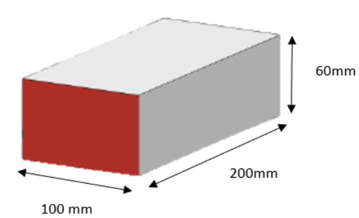


Fig. 1. Brick design.

C. Measurement of Dielectric

The dielectric properties of PET and POFA were characterized using an open coaxial dielectric probe coupled with an Agilent N5230A PNA-L Vector Network Analyzer (VNA). The measurements covered a frequency range of 1 to 12 GHz. In this method, the material sample was brought into close contact with the probe, and the reflection coefficient was measured. The dielectric constant values were obtained for each sample.

D. Prototype Development

A prototype plastic brick absorber was developed to optimize material ratios before full-scale production. Small batches of concrete, prepared in trial proportions, were cast in plastic molds and cured at room temperature for a minimum of seven days. The resistivity of the prototypes was measured to determine the optimal composition for maximum microwave absorption. Previously published research on the use of PET and POFA was also used as a reference[21][22]. The final composition selected was the one that produced a resistivity value closest to the target of 1 MΩ. Table I details the mix ratios for the two developed samples PB1 and PB2.

TABLE I. MATERIALS PROPORTION

Material Ratio (%)	Brick Type	
	PB1	PB2
Cement	65%	65%
POFA	30%	30%
PET	5%	20%

E. *Resistivity Measurement*

Resistivity was determined for each prototype. A metal plate was placed on top of the brick with a minimum gap of 5 cm between the two plates. The resistivity of a commercial absorber (1 MΩ) was used as a benchmark. Only prototypes with resistivity values close to this standard were studied for further analysis. Since conductivity is the inverse of resistivity, materials with high resistivity and low conductivity were prioritized based on their suitability as dielectrics.

F. *Manufacturing Process of Brick Microwave Absorber*

The manufacturing of absorbent bricks follows the following step: preparation of materials (PET, POFA, cement, foaming agent), dilution of the foaming agent in water (1:30 volume), and thorough mixing of all components to achieve a homogeneous mixture as shown in Fig.2. The mixture is poured into the oiled moulds and allowed to dry naturally to form the final bricks.

Fig. 2. Raw material preparation.

G. *Resistivity Measurement*

Microwave absorption performance was determined using the Naval Research Laboratory (NRL) free-space arch method as shown in Fig.3. The measurement equipment included a semicircular wooden arch, a reference metal plate, a flat sample holder, and two horn antennas (transmitter and receiver). The transmitting antenna emitted microwaves to the test sample; the receiving antenna recorded the reflected signals. A metal plate with known perfect reflectivity was used for calibration. All instruments were connected to a Vector Network Analyzer (VNA) and a PC. The VNA generated and detected microwave signals, while the measurement results were analyzed and displayed via dedicated software connected to the PC.

Fig. 3. NRL Free Space Arch Measuring setup.

III. RESULT AND DISCUSSION

A. *Dielectric Properties and Resistivity*

The dielectric constant of the developed porous bricks was measured using an open coaxial probe and a Vector Network Analyzer over a frequency range of 1 to 12 GHz. PB1 showed a dielectric constant of 3.46, while PB2 showed a lower value of 2.53. These values are lower compared to conventional cement bricks reported in the literature, reflecting the combined effect of increased PET content and higher porosity. In addition, the average resistivity test yielded values close to the target of 1 MΩ, indicating that the composition is suitable for use as a microwave absorber as shown in Table II.

TABLE II . MATERIALS RESISTIVITY

Resistivity(Ω)	
P2	P2
1.4M	1.4M
0.9M	0.9M

B. *Overall Microwave Absorption Trend (1 to 12 GHz)*

Fig. 4 through Fig. 6 illustrate the overall microwave absorption trends for CB, PB1, and PB2 at 0°, 30° and 60°. The frequency-dependent absorption curves show a clear impact of material composition and incident angle on the microwave absorption performance for all types of bricks.

At all incidence angles of 0°, 30°, and 60°, PB1 and PB2 which are brick modified with PET and POFA consistently achieve higher negative reflectivity (dB) than the commercial brick (CB) across almost the entire 1 to 12GHz frequency range. This is particularly evident for PB2, which exhibits the deepest (most negative) absorption trough all angles, confirming its superior overall absorption capability. Higher negative reflectivity values indicate higher absorption: thus, PB1 and especially PB2 act as more effective microwave absorbers than the commercial benchmark in all tested configurations.

At 0° incidence as in Fig.4, PB2 shows several deep absorption minima, outperforming PB1 and CB across the entire band. PB1 shows a clear increase over CB, but not as pronounced as PB2.

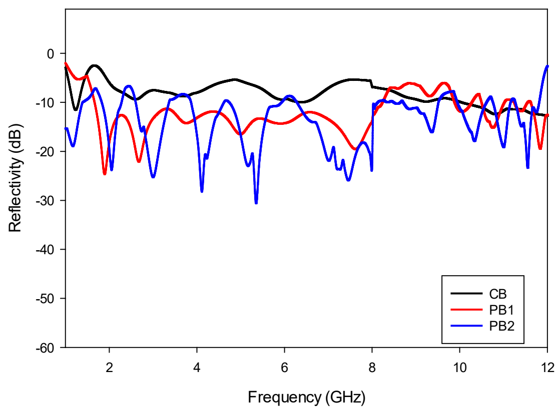


Fig. 4. Absorption performance at 0° incidence angle.

As the angle increases to 30° as in Fig. 5, all bricks become more frequency sensitive and the absorption characteristics of PB1 and PB2 are further enhanced. Both bricks exhibit some sharp and deep absorption dips, especially at higher frequencies. The maximum absorption of PB2 becomes more pronounced, with some regions well below -40 dB indicating remarkable microwave attenuation and showing an angle-dependent increase for the modified composition.

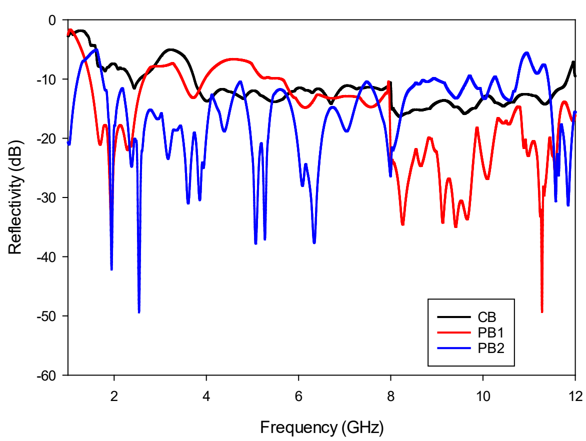


Fig. 5. Absorption performance at 30° incidence angle.

At the 60° incidence presented by Fig. 6, the overall trend continues where PB2 again exhibits the greatest number of deep absorption troughs, often exceeding -40 dB at certain frequencies, while PB1 maintains a clear advantage over CB, even though with some increased variability. In contrast, CB remains consistently less absorbing, with several dips exceeding -20 dB. Larger angles of incidence generally produce deeper and sharper absorption minimum for both modified bricks, especially in the higher frequency bands.

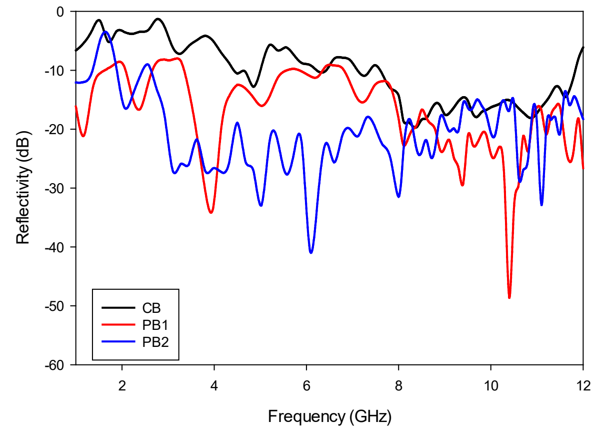


Fig. 6. Absorption performance at 60° incidence angle.

C. Band by Band Microwave Absorption Analysis

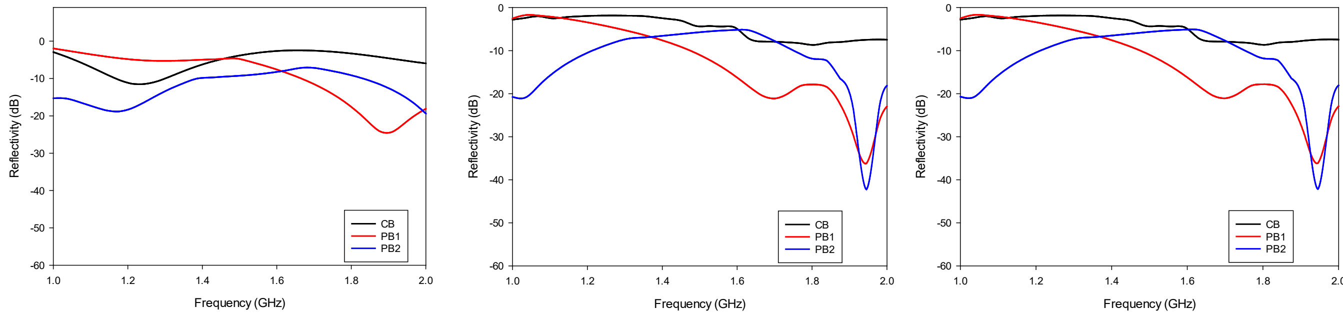
The microwave absorption performance of CB, PB1, and PB2 was analyzed at the L, S, C, and X frequency bands for incidence angles of 0°, 30°, and 60°. The L-band absorption characteristics in Fig. 7 show a strong dependence on material composition and angle of incidence.

At an angle of 0°, PB1 exhibits exceptional absorption, achieving a maximum reflectivity of -24.33 dB. This performance significantly exceeds that of PB2 (-18.89 dB) and more than doubles that of the commercial brick (-11.48 dB).

At an angle of 30°, the absorption performance of both modified bricks improves significantly. PB2 performs the best, achieving an exceptional maximum reflectivity of -42.16 dB, while PB1 also exhibits excellent absorption at -36.12 dB. In contrast, the commercial brick's absorption remains low at -8.65 dB.

At an angle of 60°, performance decreases but remains strong for the modified bricks. PB1 again exhibits the highest absorption with a maximum reflectivity of -21.06 dB. The performance of PB2 is -14.44 dB, while CB is the least effective at -6.63 dB.

Overall, in L-band, both PB1 and PB2 provide superior absorption compared to CB. Performance is significantly enhanced at a 30° angle for both modified bricks. PB1 is the most consistent high performer at 0° and 60°, while PB2 shows the best peak performance at 30°.



(a) (b) (c)

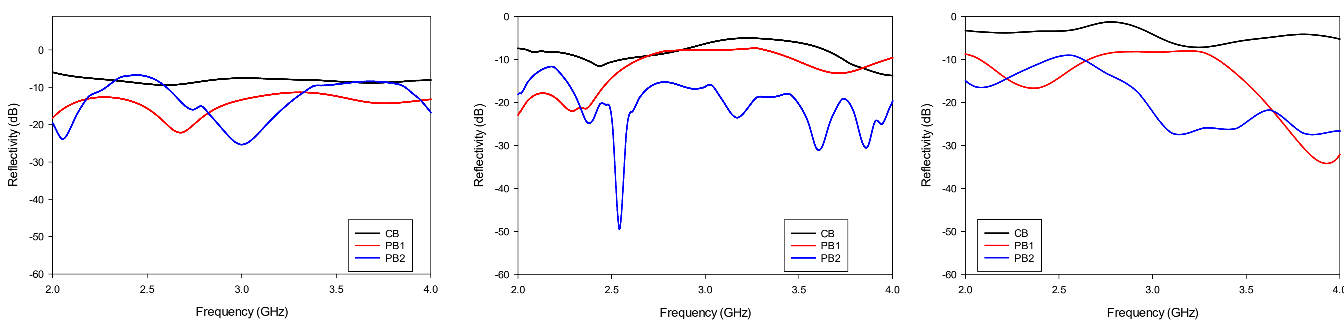
Fig. 7. Absorption performance of L-band at (a) 0° (b) 30° (c) 60° incidence angle.

In the S-band shown in Fig. 8, the trend of superior performance of the modified bricks continues, with significant angle dependence. At 0° incidence, PB2 exhibits the best absorption, with a maximum reflectivity of -25.25 dB. PB1 also performs very well at -22.09 dB, while the commercial brick is significantly less effective at -9.38 dB.

At 30° incidence, PB2 exhibits excellent absorption performance, achieving a maximum reflectivity of -49.38 dB. This indicates excellent microwave attenuation. PB1 performance remains strong at -21.94 dB, while CB exhibits only moderate absorption (-13.63 dB).

At 60° incidence, a shift in performance occurs, with PB1 becoming the dominant absorber, achieving an exceptional maximum reflectivity of -48.86 dB. PB2 also remains highly effective at -36.94 dB. Both are significantly superior to CB, which has a maximum reflectivity of only -7.89 dB.

Overall, the S-band results particularly PB2 at 30° and PB1 at 60°, are highly effective absorbers in the S-band. The results show a strong angular dependence, with different compositions being optimal at different angles.



(a) (b) (c)

Fig. 8. Absorption performance of S-band at (a) 0° (b) 30°(c) 60° incidence angle.

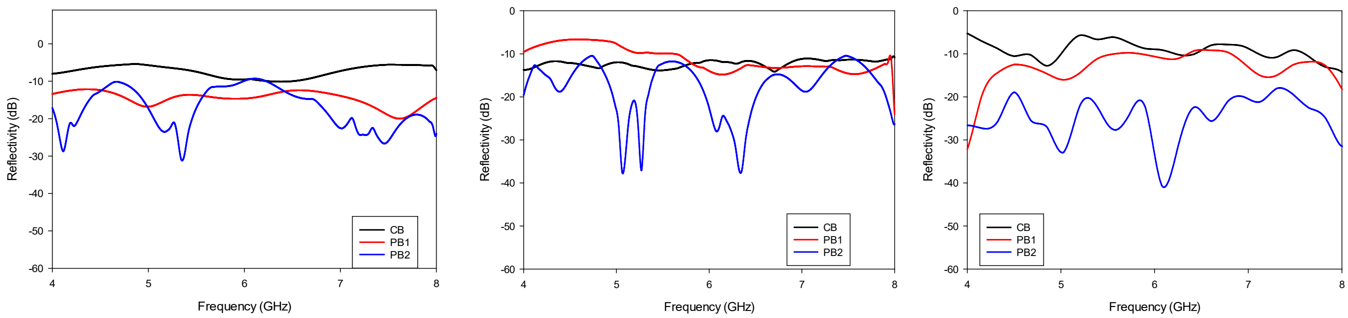
The C-band analysis of Fig. 9 highlights the consistently high performance of the PB2 sample.

At 0° incidence, PB2 clearly performs best, with a minimum reflectivity of -30.17 dB. This value is within the threshold for high-performance shielding materials. PB1 performs well at -19.53 dB, while CB is ineffective at -9.97 dB.

At 30° incidence, PB2's performance improves further, reaching a maximum reflectivity of -37.25 dB. In this case, PB1's performance (-14.81 dB) is only slightly better than CB's (-14.16 dB).

At 60° incidence, PB2 again demonstrates the best absorption with a maximum reflectivity of -40.61 dB. PB1 also shows significant improvement at this angle, reaching -29.30 dB, while CB's performance remains moderate at -13.71 dB.

As a summary, PB2 is a superior absorber in the C-Band at all angles tested, with increased effectiveness at higher angles of incidence. This consistent and high level of performance makes it a prime candidate for broadband shielding applications.



(a) (b) (c)

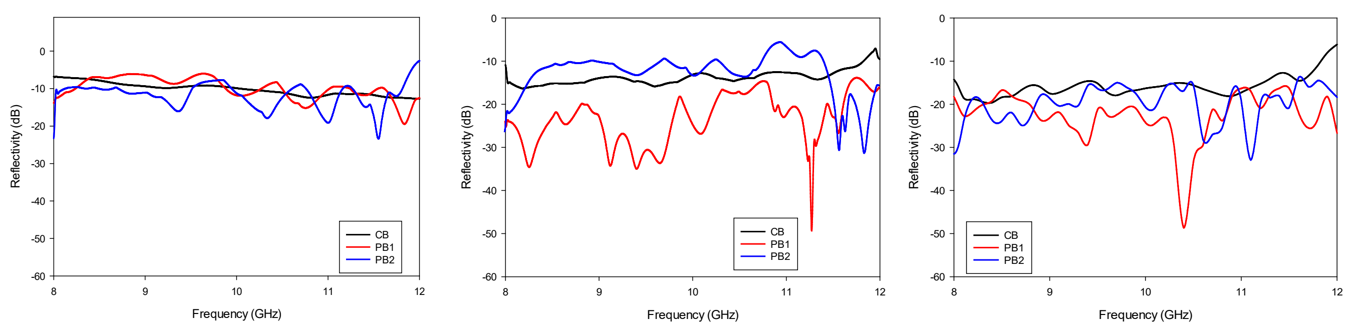
Fig. 9. Absorption performance of C-band at (a) 0° (b) 30° (c) 60° incidence angle.

In the high-frequency X-band as shown in Fig. 10, the modified bricks maintained their superior performance, with PB1 showing particularly strong results at oblique angles.

At 0° incidence, PB2 performed best with a maximum reflectivity of -23.25 dB, followed by PB1 at -19.44 dB. CB was the least effective at -12.74 dB. At 30° incidence, PB1 demonstrated excellent absorption, achieving a maximum reflectivity of -49.33 dB. PB2 also performed very well at -31.13 dB. Both were significantly better than CB (-16.33 dB).

At 60° incidence, PB1 continued to perform best with an outstanding maximum reflectivity of -48.63 dB. PB2 also performed very well at -33.05 dB. It is remarkable that the performance of CB improves to -20.48 dB at this angle but is still significantly superior to that of the modified brick.

As a summary, for X-Band modified bricks are highly effective high-frequency absorbers. PB1 exhibits exceptional performance at oblique angles (30° and 60°), making it ideal for applications where signals may come from multiple directions.



(a) (b) (c)

Fig. 10. Absorption performance of X-band at (a) 0° (b) 30° (c) 60° incidence angle.

A comprehensive summary of the minimum and maximum represented by most negative value indicating highest absorption and maximum represented by least negative indicating lowest absorption for each type of brick and test scenario is presented in Table III.

The results clearly demonstrate that the angle of incidence has a significant impact on the microwave absorption behavior of all tested bricks. As the measurement angle increases from 0° to 30° and 60°, both PB1 and PB2 bricks using PET and POFA consistently exhibit stronger absorption with more negative values across all frequency bands. This indicates that their microwave absorption capabilities not only persist but often improve at higher angles of incidence. Specifically, both PB1 and PB2 outperform commercial bricks (CB) at every angle, with PB2 exhibiting optimal absorption with maximum reflectivity below -40 dB at oblique angles across several bands. This improvement is particularly pronounced in the S, C, and X bands, where the modified brick exhibits deep and broad absorption minima at 30° and 60°, likely due to increased multiple scattering and better impedance matching at steeper angles.

In summary, PET/POFA porous bricks maintain superior microwave absorption and often increase with increasing incident angles, which highlight their effectiveness as electromagnetic absorbers for real-world applications where electromagnetic waves typically impact surfaces from multiple directions.

TABLE III . MINIMUM REFLECTIVITY (DB) FOR EACH SAMPLE IN FREQUENCY BAND AND ANGLE OF INCIDENCE

Angle (°)	**Freq. Band**		**Microwave Absorption (dB)**		
			CB	PB1	PB2
0°	L	Min	-2.49	-1.99	-7.24
		Max	-11.48	-24.33	-18.89
	S	Min	-6.17	-11.30	-6.67
		Max	-9.38	-22.09	-25.25
	C	Min	-5.33	-11.87	-8.68
		Max	-9.97	-19.53	-30.17
	X	Min	-6.79	-6.03	-2.58
		Max	-12.74	-19.44	-23.25
30°	L	Min	-1.84	-1.71	-5.10
		Max	-8.65	-36.12	-42.16
	S	Min	-5.04	-7.36	-11.69
		Max	-13.63	-21.94	-49.38
	C	Min	-11.07	-6.65	-10.44
		Max	-14.16	-14.81	-37.25
	X	Min	-7.17	-13.85	-5.59
		Max	-16.33	-49.33	-31.13
60°	L	Min	-0.27	-8.75	-3.63
		Max	-6.63	-21.06	-14.44
	S	Min	-1.19	-8.14	-8.34
		Max	-7.89	-48.86	-36.94
	C	Min	-5.38	-9.16	-17.16
		Max	-13.71	-29.30	-40.61
	X	Min	-6.11	-16.02	-12.49
		Max	-20.48	-48.63	-33.05

In summary, PET/POFA porous bricks maintain superior microwave absorption and often increase with increasing incident angles, which highlight their effectiveness as electromagnetic absorbers for real-world applications where electromagnetic waves typically impact surfaces from multiple directions.

IV. CONCLUSION

This study demonstrates that the addition of PET and POFA to porous cement bricks significantly improves their microwave absorption compared to conventional commercial bricks. Systematic measurements in the L, S, C, and X frequency bands and at various incidence angles show that PB1 (5% PET, 30% POFA) and PB2 (20% PET, 30% POFA) exhibit significantly higher negative reflectivity values, indicating superior electromagnetic wave absorption. The best-performing brick, PB2, consistently achieved the lowest dielectric constant and the highest absorption level, with maximum reflection losses exceeding-40 dB across multiple bands and incidence angles.

This enhanced absorption is due to the synergistic effect of increasing PET content and induced porosity, which lowers the dielectric constant, optimizes impedance matching, and promotes enhanced polarization and scattering mechanisms within the brick matrix. These results support existing literature on the effects of polymer inclusions and porosity on the dielectric properties of cementitious materials.

ACKNOWLEDGMENT

The authors would like to acknowledge Kementerian Pelajaran Malaysia and Research Management Unit (RMU), Universiti Teknologi MARA, Cawangan Pulau Pinang, Malaysia for the funding support of the research project 600-RMC/FRGS 5/3 (030/2022). Sincere appreciation is extended to all parties who contributed to the success of this project. Special acknowledgment is given to the Green Materials Microwave Absorbers Research Group (GMMA), the Institute of Postgraduate Studies (IPSis) of Universiti Teknologi MARA (UiTM) and Universiti Teknologi MARA Cawangan Pulau Pinang for their invaluable support and collaboration. The authors also wish to extend their deepest appreciation to the

Electrical Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, Malaysia, for providing access to the microwave laboratory facilities essential for this research.

REFERENCES

[1] R. Baan *et al.*, "Carcinogenicity of radiofrequency electromagnetic fields.," *Lancet Oncol.*, vol. 12, no. 7, pp. 624–626, 2011, doi: 10.1016/s1470-2045(11)70147-4.

[2] A. B. Miller *et al.*, "Risks to health and well-being from radio-frequency radiation emitted by cell phones and other wireless devices," *Front. Public Heal.*, vol. 7, no. AUG, pp. 1–10, 2019, doi: 10.3389/fpubh.2019.00223.

[3] L. Hardell and C. Sage, "Biological effects from electromagnetic field exposure and public exposure standards," *Biomed. Pharmacother.*, vol. 62, no. 2, pp. 104–109, 2008, doi: 10.1016/j.biopha.2007.12.004.

[4] A. Zamanian and C. Hardiman, "Electromagnetic Radiation and Human Health: A Review of Sources and Effects," no. July, 2005.

[5] J. H. Moon, "Health effects of electromagnetic fields on children," *Clin. Exp. Pediatr.*, vol. 63, no. 11, pp. 422–428, 2020, doi: 10.3345/cep.2019.01494.

[6] R. Raveendran and K. A. Tabet Aoul, "An Appraisal Among Wired, Hybrid and Wireless Smart Homes to Mitigate Electromagnetic Radiation," *Front. Built Environ.*, vol. 7, 2022, doi: 10.3389/fbuil.2021.764295.

[7] R. Yan *et al.*, "Construction strategies and recent advances of flexible EMI phase change composites," *Soft Sci.*, vol. 5, no. 1, 2025, doi: 10.20517/ss.2024.66.

[8] V. Shukla, "Review of electromagnetic interference shielding materials fabricated by iron ingredients," *Nanoscale Adv.*, vol. 1, no. 5, pp. 1640–1671, 2019, doi: 10.1039/c9na00108e.

[9] M. Nadeem, M. Mehrban, M. A. Javid, and M. A. Saeed, "Development of Electromagnetic Interference shielding materials over time: A review," *Int. J. Nanoelectron. Mater.*, vol. 14, no. 1, pp. 71–98, 2021.

[10] Y. Du, "Advances in Carbon-Based Microwave Absorbing Materials," *Materials (Basel).*, vol. 15, no. 4, 2022, doi: 10.3390/ma15041359.

[11] S. Cai *et al.*, "Preparation of a biomass-derived electromagnetic wave absorber with potential EM shielding application in interior decoration surface coating," *Appl. Surf. Sci.*, vol. 607, no. August 2022, 2023, doi: 10.1016/j.apsusc.2022.155037.

[12] A. Hasnain *et al.*, "Development of an economic and effective microwave absorber," *2007 Asia-Pacific Conf. Appl. Electromagn. Proceedings, APACE2007*, no. 1, pp. 1–5, 2007, doi: 10.1109/APACE.2007.4603966.

[13] N. O. L. Ching, S. C. Kiong, A. Zainudin, N. H. M. Nor, and Y. S. Khee, "Exploring the potential of palm oil fuel ash (POFA) in EMI shielding effectiveness," *J. Mech. Eng.*, vol. SI 2, no. 1, pp. 101–111, 2017.

[14] P. G. C. Nayanathara Thathsarani Pilapitiya and A. S. Ratnayake, "The world of plastic waste: A review," *Clean. Mater.*, vol. 11, 2024, doi: 10.1016/j.clema.2024.100220.

[15] J. M. L. Reis, R. Chianelli-Junior, J. L. Cardoso, and F. J. V. Marinho, "Effect of recycled PET in the fracture mechanics of polymer mortar," *Constr. Build. Mater.*, vol. 25, no. 6, pp. 2799–2804, 2011, doi: 10.1016/j.conbuildmat.2010.12.056.

[16] S. Akçaözoğlu, C. D. Atiş, and K. Akçaözoğlu, "An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete," *Waste Manag.*, vol. 30, no. 2, pp. 285–290, 2010, doi: 10.1016/j.wasman.2009.09.033.

[17] M. K. Askar, Y. S. S. Al-Kamaki, and A. Hassan, "Utilizing Polyethylene Terephthalate PET in Concrete: A Review," *Polymers (Basel).*, vol. 15, no. 15, 2023, doi: 10.3390/polym15153320.

[18] O. Y. Marzouk, R. M. Dheilly, and M. Queneudec, "Valorization of post-consumer waste plastic in cementitious concrete composites," *Waste Manag.*, vol. 27, no. 2, pp. 310–318, 2007, doi: 10.1016/j.wasman.2006.03.012.

[19] S. Lu, E. Bai, J. Xu, and J. Chen, "Research on electromagnetic properties and microwave deicing performance of carbon fiber modified concrete," *Constr. Build. Mater.*, vol. 286, 2021, doi: 10.1016/j.conbuildmat.2021.122868.

[20] Y. Zhong *et al.*, "Composite Dielectric Model for Cement Concrete Considering Water Saturation," *J. Mater. Civ. Eng.*, vol. 35, no. 7, 2023, doi: 10.1061/jmcee7.mteng-15174.

[21] X. Zeng, X. Cheng, R. Yu, and G. D. Stucky, "Electromagnetic microwave absorption theory and recent achievements in microwave absorbers," *Carbon N. Y.*, vol. 168, pp. 606–623, 2020, doi: 10.1016/j.carbon.2020.07.028.

[22] K. Hannawi, S. Kamali-Bernard, and W. Prince, "Physical and mechanical properties of mortars containing PET and PC waste aggregates," *Waste Manag.*, vol. 30, no. 11, pp. 2312–2320, 2010, doi: 10.1016/j.wasman.2010.03.028.