

## Microwave absorption performance of surface textured PET-POFA composite bricks: effect of slot geometry and incidence angle

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### ABSTRACT

This study presents the development and evaluation of PET-POFA composite bricks with surface slot arrays to improve electromagnetic absorption across the 1 to 12 GHz range, with particular emphasis on the X-band. CST Studio simulations were conducted on two slot geometries with lengths of 7.5 mm and 15 mm, corresponding to quarter-wavelength and half-wavelength resonances at 10 GHz. The results indicate that the 7.5 mm design produces broader and deeper absorption, including a pronounced dip within the X-band, while the 15 mm configuration exhibits shallower absorption and reduced impedance matching at higher frequencies. Bricks were manufactured using a mix design that replaced 10% of the sand with PET and 30% of the cement with POFA. The bricks were then evaluated using the NRL free-space arch method to assess their performance at incidence angles of 0°, 30°, and 60° in vertical orientation. Experimental measurements confirm that the 7.5 mm textured brick achieves reflectivity below -20 dB over wide frequency spans, with peak absorption reaching -39.36 dB in the X-band. In contrast, the 15 mm variant shows inconsistent performance and positive reflectivity at lower frequencies due to impedance mismatch, while the untextured control sample demonstrates comparatively lower absorption across all bands. The combined simulation and experimental findings establish that precise quarter-wavelength slotting in PET-POFA composites enables effective impedance matching and stable angular performance, highlighting a sustainable and high-performance solution for electromagnetic shielding in building applications.

**Keywords:** Brick absorber, POFA, PET, Surface texture, Microwave absorption, EMI shielding

### 1. INTRODUCTION

Electromagnetic interference (EMI) is a growing problem in modern environments due to the rapid development of wireless communications infrastructure, including radio, television, satellite systems, and cellular networks [1]. There is increasing concern about the potential effects of prolonged exposure to electromagnetic fields (EMF), especially for individuals living near telecommunications infrastructure in residential areas [2]. Although devices that emit non-ionizing radiation, such as cell phones and Wi-Fi routers, generally produce a mild heating effect, ongoing research suggests a potential link to health problems, including disturbed sleep patterns and the risk of developing brain tumors. Ionizing radiation poses greater risks, including an increased risk of cancer [3–6]. Regulatory bodies such as the WHO and ICNIRP have issued exposure guidelines, but there remains public and scientific interest in reducing EMF and EMI exposure in residential spaces [7, 8]. In response, research into EMI shielding and absorbing materials for buildings has intensified [9]. However, traditional shielding materials are often unsustainable and expensive. As the construction sector shifts toward more environmentally friendly practices, there is an urgent need for sustainable EMI solutions [10, 11]. Recent advances have included the incorporation

of diverse industrial byproducts and recycled waste into construction composites, which both enhance sustainability and impart functional properties for electromagnetic shielding [12–15].

Among these alternative materials, two have attracted significant attention due to their abundance and unique characteristics. Polyethylene terephthalate (PET) is a synthetic polymer produced by the polycondensation of terephthalic acid and ethylene glycol, and it is commonly recycled from consumer packaging [18]. Palm oil fuel ash (POFA) is obtained through the controlled combustion of palm oil residues and is composed primarily of silica, alumina, and other oxides, which act as pozzolanic additives. Both PET and POFA contribute to composite lightening and mechanical reinforcement, while also providing thermal insulation and dielectric-loss characteristics conducive to microwave absorption [19]. Recycled PET is widely available as post-consumer waste that is capable of improving thermal insulation and reducing density, while POFA, which is a byproduct of the palm oil industry, can improve the mechanical performance and dielectric properties of the cement matrix [16, 17]. Previous studies have shown that POFA and PET improve sustainability and mechanical strength, but their potential

in EMI absorption, particularly through engineered surface structures, remains unexplored.

Broadband microwave absorption enhancement in pyramidal absorbers can be effectively achieved by modifying the surface structure through the implementation of an optimized slot pattern. This geometrical pattern improves impedance matching and enhances energy dissipation within the absorber, thereby improving its overall performance [20]. However, there is little systematic research addressing how such textures affect the electromagnetic performance of PET-POFA building bricks, especially across different incident angles and the main frequency bands used in telecommunications.

Therefore, this study aims to experimentally investigate the microwave absorption characteristics of PET-POFA composite bricks featuring surface slot textures. Two sets of bricks with slot dimensions of 7.5 mm and 15 mm were manufactured together with reference bricks without surface texture. All bricks were formulated using a mixture of recycled PET as a partial sand replacement, POFA as a partial cement replacement, sand, and cement. The NRL free-space arch method was used to measure the reflectivity of each brick design across various frequency bands and at different incident angles. This study aims to determine the optimal surface texture for maximizing absorption in sustainable construction bricks and to demonstrate the potential of waste-based composites as a practical and environmentally friendly solution for EMI shielding in buildings.

## 2. THEORETICAL BACKGROUND

Bricks remain a fundamental material in building construction due to their strength and flexibility. However, modern demands for sustainability and increased functionality have driven significant innovation in brick production [2]. One effective approach is the incorporation of waste materials, such as recycled PET and POFA, into the brick matrix [21–23]. PET, derived from used plastic bottles and packaging, can reduce the weight of bricks and improve their thermal insulation properties [24, 25]. Palm oil fuel ash, which is produced from the combustion of palm oil residue, serves as a pozzolanic additive that can increase

the compressive strength and durability of cement-based composites while lowering the overall environmental footprint of the mixture [26, 27]. POFA also demonstrates promising microwave absorption characteristics, which support the development of construction materials that combine structural integrity with effective electromagnetic shielding capabilities [28, 29].

The microwave absorption efficiency of a material is influenced by a combination of factors, including its intrinsic composition, geometric design, thickness of the absorbing layer, effectiveness of impedance matching with the surrounding environment, and the ability to dissipate electromagnetic energy [30]. Achieving strong and uniform microwave absorption often requires the use of advanced materials and precision engineering of the absorber surface [31].

Surface modification, particularly through the introduction of slot textures, has recently been developed to improve microwave absorption properties. The integration of well-designed surface slots in pyramidal structures can significantly improve impedance matching and minimize dielectric losses. This results in superior electromagnetic-wave absorption in the 1 to 12 GHz frequency range commonly used in radar and communication systems [20]. Based on these advances, current research explores the use of surface slot textures on PET-POFA composite bricks to enhance microwave absorption.

## 3. METHODOLOGY

### 3.1. Raw Materials and Mixing

These composite bricks were produced from a mixture that included recycled PET sourced from used plastic bottles, palm oil fuel ash (POFA) produced as a residue from the combustion process in palm oil mills, ordinary Portland cement, sand, and water. The PET was sourced from Tian Li Eco Group Holdings Sdn Bhd, Semenyih, Selangor, while the POFA was obtained from a palm oil mill factory located in Padang Serai, Kedah, Malaysia. Figure 1 shows the PET recycling factory and the cleaned PET flakes, while Figure 2 displays the palm oil processing factory and the collected POFA.



**Figure 1.** (a) PET recycling factory and (b) cleaned recycled PET flakes



**Figure 2.** (a) Palm oil processing factory and (b) collected palm oil fuel ash (POFA) residue

The proportions in the mixture were refined based on findings from previous studies to ensure optimal structural integrity and electromagnetic absorption. Specifically, 10% PET and 30% POFA were added as partial replacements for sand and cement, respectively, to achieve these improvements. Table 1 outlines the exact proportions used for each batch in this study.

The selection of 10% PET and 30% POFA was based on previous studies showing that higher PET fractions (above 10%) can reduce compressive strength and durability, while POFA contents exceeding 30% can negatively impact the workability of the mixture and increase porosity [32]. This ratio provides a practical balance between strength, durability, and increased dielectric loss, which is desirable for microwave absorption applications. Inverse or significantly different ratios were not considered here, as existing literature indicates a risk of impairment of mechanical or electromagnetic properties outside this range. Recent research has confirmed that 10–15% PET and up to 30% POFA offer optimal results for environmentally friendly EMI-shielding construction materials [33].

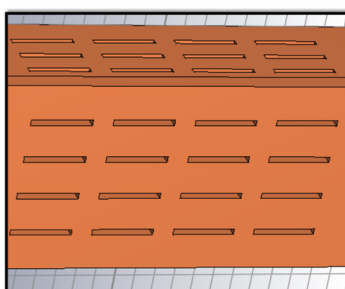
All materials were thoroughly dry-mixed and then combined with water using a water-to-cement ratio of 1:3 to form a workable paste. The prepared mixture was poured into a brick mold with dimensions of 200 mm (length) × 100 mm (width) × 60 mm (height). After 24 hours, the freshly formed bricks were removed from the molds and further cured at room temperature for a period of 28 days to ensure adequate strength development, following the MS 76:1972 standard [34].

### 3.2. Slot Design and Fabrication

After the drying stage, slots were formed on the brick surface to enhance microwave absorption, with particular focus on improving performance in the X-band range (8–12 GHz). A target frequency of 10 GHz was selected for slot optimization. This frequency corresponds to the center of the X-band and aligns with the range in which baseline testing of solid bricks demonstrated promising absorption performance. Its selection directly targets the frequency

**Table 1.** Material composition for the production of individual PET–POFA bricks

Material	PET	Sand	POFA	Cement	Water
Weight (kg)	0.16	1.48	0.15	0.35	0.21



**Figure 3.** CST simulation model with surface slot array

region where enhanced absorption is most critical for practical electromagnetic shielding applications in built environments. The free-space wavelength,  $\lambda$ , at a frequency of 10 GHz was determined by applying the standard wave Equation (1):

$$\lambda_o = \frac{c}{f} = \frac{3 \times 10^8}{10 \text{ GHz}} = 0.03 \text{ m} \quad (1)$$

From the wavelength result in Equation (1), two slot lengths were fixed for subsequent simulation work and physical prototyping, as indicated in Equations (2) and (3):

$$L_1 = \frac{\lambda_o}{2} = \frac{0.03}{2} = 0.015 \text{ m} \quad (2)$$

$$L_2 = \frac{\lambda_o}{4} = \frac{0.03}{4} = 0.0075 \text{ m} \quad (3)$$

Slot lengths of 7.5 mm and 15 mm were deliberately chosen to correspond to the quarter-wavelength and half-wavelength resonances at the X-band center frequency (10 GHz). This choice allows for a systematic study of resonance-driven absorption behavior, where quarter-wavelength slot placement is widely recognized for optimal impedance matching, while half-wavelength provides a meaningful suboptimal comparison. While additional slot sizes could yield further insights, the present study focuses on establishing the key physical mechanisms within practical design constraints. Exploring broader geometries could further improve understanding and is recognized as a key direction for future research.

The slots were formed using an angle grinder with carefully measured and distributed textures to ensure geometric accuracy and repeatability. These textures were intended to maximize microwave absorption in the X-band by exploiting resonance effects and improving impedance matching. To establish a baseline for comparison, a set of PET-POFA solid bricks without surface gap textures was also prepared using the same material composition and fabrication process. The untextured solid bricks served as control samples, allowing the specific influence of surface gaps on microwave absorption performance to be isolated and quantitatively assessed.

The CST simulation model of a brick designed with surface slots is shown in Figure 3, while Figure 4 presents a physical PET-POFA brick specimen fabricated with the corresponding surface slot arrangement. The CST Studio



**Figure 4.** PET-POFA composite brick with surface slot array

Suite simulations in this study were performed for normal incidence ( $0^\circ$ ) only, which is widely recognized as the standard basis in EMI absorber and shielding research for evaluating material performance. In this study, experimental measurements were intentionally extended to  $30^\circ$  and  $60^\circ$  to thoroughly characterize angular performance in realistic application scenarios, although only normal incidence was simulated. This dual approach allows the model to be validated at  $0^\circ$ , while the impact of the incidence angle on absorption performance can be systematically assessed through experiments. The differences observed at higher angles are thus attributed to geometric and electromagnetic effects not represented in the baseline simulations and will serve as a basis for future simulation refinements.

### 3.3. Experimental Absorption Performance

The NRL free-space arch measurement setup utilizes a pair of antennas for signal transmission and reception, which are positioned on opposite sides of a reference metal plate. During measurement, the transmitting antenna directs microwave signals at the material positioned midway between the antennas, while the receiving antenna captures the signal reflected from the material. Reflectivity measurements for solid and composite bricks were carried out using  $60\text{ cm} \times 60\text{ cm}$  absorber tiles, with evaluations performed at incidence angles of  $0^\circ$ ,  $30^\circ$ , and  $60^\circ$ . By observing microwave absorption at these various angles, the angular stability and real-world absorption performance of the bricks can be characterized.

In real-world applications, electromagnetic waves do not always strike surfaces perpendicularly, but rather come from a variety of directions due to environmental reflections and scattering. This study assessed both normal and oblique incidences to evaluate how effectively each composite brick sustains its absorption capability when subjected to different angles of electromagnetic-wave interaction. This methodology also enabled a detailed examination of impedance matching at multiple angles in the vertical orientation, ensuring that the brick maintains reliable microwave absorption performance when installed in structural applications such as walls. Testing the composite bricks across a range of incident angles in the vertical position validated the absorber's dependability,



**Figure 5.** NRL Arch free space measuring equipment with PET-POFA composite brick specimens in vertical orientation

versatility, and robustness under realistic operating conditions, where electromagnetic waves arrive at various incidence angles. The experimental setup used to measure absorption performance under these conditions is illustrated in Figure 5. Figure 6 illustrates the PET-POFA composite bricks prepared for vertical-orientation testing.

## 4. RESULTS AND DISCUSSION

This section presents and analyzes the absorption performance of texture-modified PET-POFA composite bricks in vertical orientation. Slot arrays with lengths of 7.5 mm and 15 mm were evaluated for their effectiveness in absorbing microwaves, together with a control sample consisting of a plain solid brick without any surface pattern.

Reflectivity testing was performed using the NRL free-space arch method, with the hardware prototypes arranged vertically to simulate installation on a wall structure. Measurements were performed at incidence angles of  $0^\circ$ ,  $30^\circ$ , and  $60^\circ$ , covering a frequency range of 1–12 GHz. For in-depth evaluation, the data were segmented into four standard microwave frequency bands: L-band (1–2 GHz), S-band (2–4 GHz), C-band (4–8 GHz), and X-band (8–12 GHz). This approach provides a clear basis for comparing the absorption behavior associated with different slot sizes across the examined spectrum.

### 4.1. CST Simulation Result

Initial evaluation of the reflectivity characteristics of PET-POFA composite bricks with various slot configurations was carried out through simulations using CST Studio Suite. For slot lengths of 7.5 mm and 15 mm, the S11 parameter, which quantifies reflection loss, was extracted over the frequency range of 1 to 12 GHz. Figure 7 presents the simulated absorption curves for a brick with a 7.5 mm slot length. The results show deep and broad absorption, with absorption consistently below  $-20\text{ dB}$  in the main frequency band, especially in the X-band (8–12 GHz). Several significant dips can be observed, indicating effective impedance matching and strong resonant microwave absorption over a wide spectrum. In particular, the maximum absorption exceeds  $-60\text{ dB}$  at certain frequencies, indicating the high absorption efficiency of the quarter-wavelength slot array in this orientation.



**Figure 6.** PET-POFA composite brick in vertical orientation

Figure 8 displays the S-parameter magnitude curves for the 15 mm slot-array design. While the 15 mm slot also achieves substantial absorption at some frequencies, its response is less consistent across the band, exhibiting shallower absorption levels and less bandwidth compared to the 7.5 mm configuration. The maximum absorption reaches approximately  $-45$  dB, but the strong absorption bandwidth is reduced, and some frequency regions exhibit significantly higher reflection values, nearly  $-15$  dB. These results indicate less optimal impedance matching and frequency-selective resonance behavior, which is typical of longer slot geometries that are not efficiently aligned with the quarter-wavelength resonance conditions of the electromagnetic wave.

Overall, the simulation results show that the 7.5 mm slot array provides more stable and broadband microwave absorption in the vertical orientation, especially in the X-band, compared to the 15 mm slot length. The observed increased efficiency with the shorter slot configuration is likely due to better impedance matching and more effective resonance-based energy dissipation. These findings emphasize the rationale for using fine-surface slot patterns in microwave brick design.

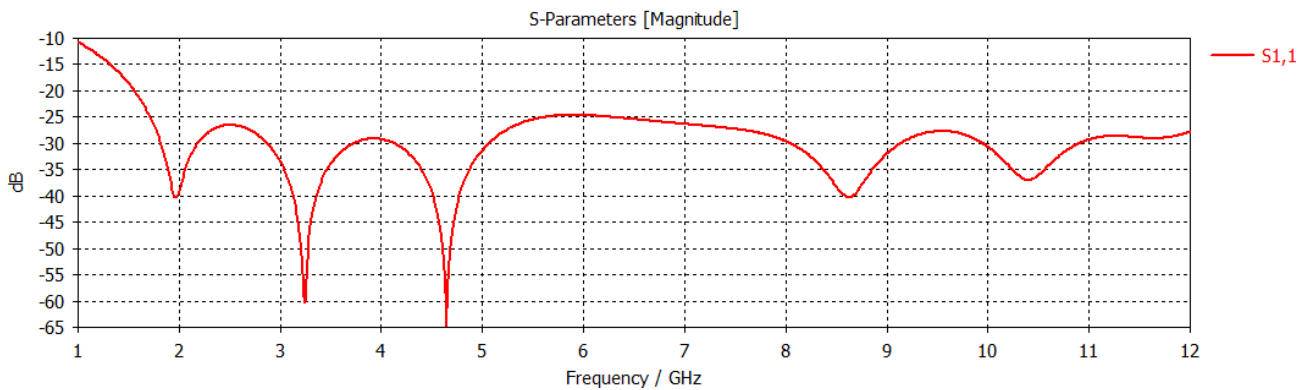
#### 4.2. Experimental Result at $0^\circ$ Measurement Angle

Figure 9 shows the overall absorption performance of the PET-POFA composite bricks at  $0^\circ$  incidence angle in the frequency range of 1 to 12 GHz. The minimum and maximum absorption performance for each PET-POFA brick configuration are summarized in Tables 2 and Table 3,

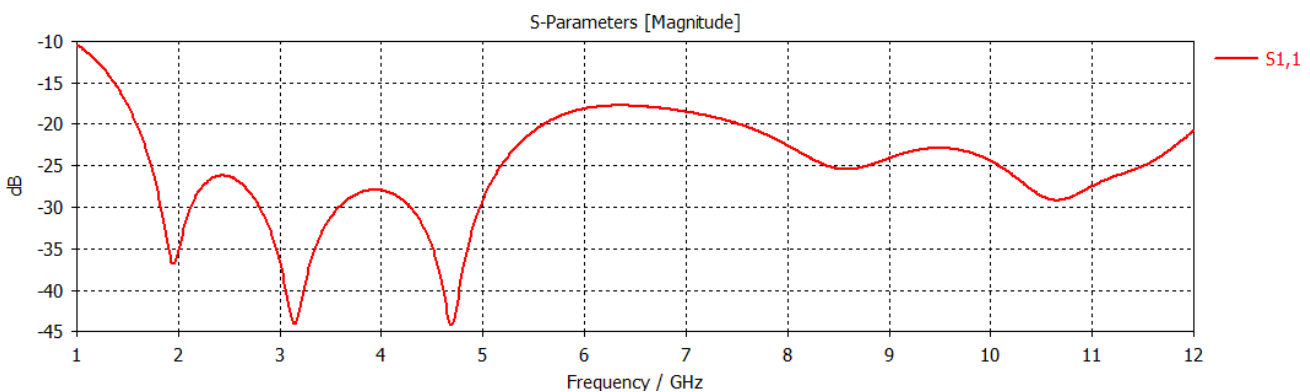
which cover the L, S, C, and X-band frequency ranges. More negative reflectivity (dB) values indicates better microwave absorption performance.

Comparative analysis shows a significant difference in microwave absorption among the three PET-POFA brick configurations. The 7.5 mm slot array consistently exhibits strong broadband absorption, achieving minimum reflectivity values of  $-23.64$  dB in the L-band,  $-29.90$  dB in the S-band,  $-25.39$  dB in the C-band, and an outstanding  $-33.89$  dB in the X-band. Even its peak reflectivity values remain very low, with maximum values of  $-15.73$  dB in the L-band,  $-29.90$  dB in the S-band,  $-25.39$  dB in the C-band, and  $-33.89$  dB in the X-band. This superior performance demonstrates stable impedance matching and consistent energy dissipation across the relevant frequency spectrum, especially at higher frequencies where shielding effectiveness is critical.

In contrast, the 15 mm slot array exhibits much weaker absorption with minimum reflectivity values of only  $-6.23$  dB in the L-band and  $-12.27$  dB in the S band, dropping to  $-18.39$  dB in the C-band and  $-22.21$  dB in the X-band. Its maximum reflectivity values confirm this trend, with relatively high readings which are near zero in the X-band highlighting more pronounced reflection, rather than absorption, in the key regions. These results indicate that the longer slot design fails to achieve broad and deep resonance, thus suffering from poor impedance matching and inconsistent coupling with the incident electromagnetic wave.



**Figure 7.** Simulated absorption performance for PET-POFA brick with 7.5 mm slot array



**Figure 8.** Simulated absorption performance for PET-POFA brick with 15 mm slot array

The solid brick, without any surface texture, exhibits inherent absorptive properties, with minimum reflectivity reaching  $-32.21$  dB in the L-band,  $-28.71$  dB in the S-band, and  $-31.60$  dB in the C-band. However, its performance in the X-band decreases drastically, with a minimum reflectivity of only  $-13.99$  dB. The peak absorption for the solid brick does not exceed  $-14.58$  dB in any band and is weakest in the X-band, recorded at  $-10.04$  dB. This indicates that, although the PET-POFA composite base material has a relatively high loss factor, precise surface structuring, especially at the optimal scale of  $7.5$  mm, is crucial for superior high-frequency absorption.

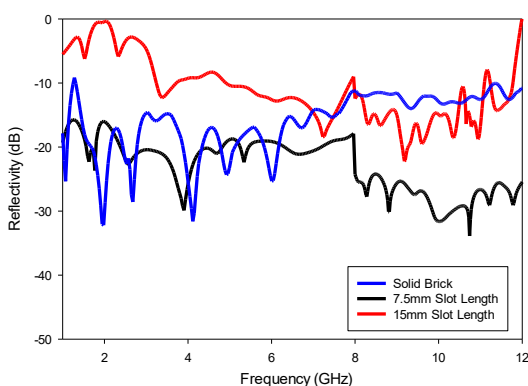
These findings are reinforced by the absorption spectra, which show that the  $7.5$  mm slot configuration not only achieves a deeper and more continuous absorption band, but also maintains its effectiveness over a wider frequency range compared to the  $15$  mm slot and solid samples. These results clearly demonstrate that optimizing the slot geometry to the quarter-wavelength scale dramatically improves the brick's ability to shield electromagnetic energy, particularly in the demanding X-band. This makes the  $7.5$  mm slot design an effective and robust solution for a sustainable microwave-absorbing construction material, while the  $15$  mm and untextured variants provide limited and inconsistent performance, particularly at high frequencies.

**Table 2.** Minimum reflectivity performance at  $0^\circ$  incidence angle

Test Material	Reflectivity (dB)			
	L-Band	S-Band	L-Band	X-Band
Solid Brick	$-32.21$	$-28.71$	$-31.60$	$-13.99$
$7.5$ mm	$-23.64$	$-29.90$	$-25.39$	$-33.89$
$15$ mm	$-6.23$	$-12.27$	$-18.39$	$-22.21$

**Table 3.** Maximum reflectivity performance at  $0^\circ$  incidence angle

Test Material	Reflectivity (dB)			
	L-Band	S-Band	L-Band	X-Band
Solid Brick	$-9.14$	$-14.58$	$-11.20$	$-10.04$
$7.5$ mm	$-15.73$	$-29.90$	$-25.39$	$-33.89$
$15$ mm	$-0.46$	$-0.35$	$-8.28$	$0.21$



**Figure 9.** Microwave absorption (dB) of PET-POFA composite bricks with solid,  $7.5$  mm, and  $15$  mm slot designs at  $0^\circ$  incidence angle across the  $1$ – $12$  GHz frequency range

### 4.3. Experimental Result at $30^\circ$ Measurement Angle

At an incidence angle of  $30^\circ$ , the comparison of minimum and maximum absorption illustrated in Figure 10, Table 4, and Table 5 shows a clear difference in broadband microwave attenuation among the solid brick,  $7.5$  mm slot, and  $15$  mm slot PET-POFA brick samples. The  $7.5$  mm slot array exhibits strong and stable absorption across all frequency bands. For this configuration, absorption values reached as low as  $-24.57$  dB,  $-22.27$  dB,  $-29.61$  dB, and  $-31.73$  dB within the L-, S-, C-, and X-band ranges, respectively. The highest measured absorption also remained strong, with values of  $-18.05$  dB in the L-band,  $-17.05$  dB in the S-band,  $-18.97$  dB in the C-band, and  $-26.28$  dB in the X-band. This high level of attenuation in the X-band is highly significant, highlighting the effectiveness of the quarter-wavelength slot geometry for high-frequency electromagnetic shielding.

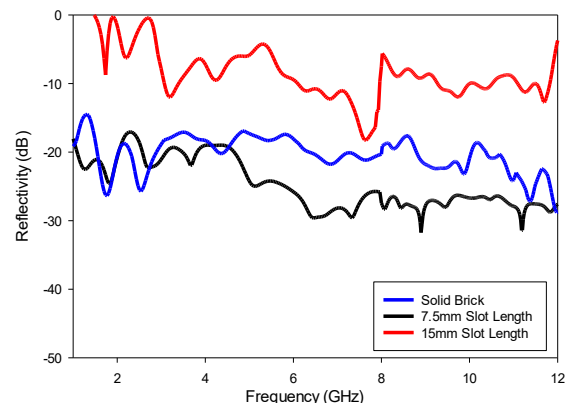
The untextured solid brick showed moderate microwave absorption properties due to the inherent lossy nature of the PET-POFA composite. Within the L-, S-, C-, and X-bands, its lowest absorption readings were  $-26.35$  dB,  $-25.70$  dB,  $-21.77$  dB, and  $-28.79$  dB, respectively. However, the maximum absorption values in these bands were lower, measured at  $-14.50$  dB,  $-17.08$  dB,  $-16.93$  dB, and  $-17.59$  dB, respectively. Although the solid brick provides

**Table 4.** Minimum reflectivity performance at  $30^\circ$  incidence angle

Test Material	Reflectivity (dB)			
	L-Band	S-Band	L-Band	X-Band
Solid Brick	$-26.35$	$-25.70$	$-21.77$	$-28.79$
$7.5$ mm	$-24.57$	$-22.27$	$-29.61$	$-31.73$
$15$ mm	$-10.73$	$-20.52$	$-22.32$	$-8.45$

**Table 5.** Maximum reflectivity performance at  $30^\circ$  incidence angle

Test Material	Reflectivity (dB)			
	L-Band	S-Band	L-Band	X-Band
Solid Brick	$-14.50$	$-17.08$	$-16.93$	$-17.59$
$7.5$ mm	$-18.05$	$-17.05$	$-18.97$	$-26.28$
$15$ mm	$2.61$	$-7.61$	$-8.42$	$-2.76$



**Figure 10.** Microwave absorption (dB) of PET-POFA composite bricks with solid,  $7.5$  mm, and  $15$  mm slot designs at  $30^\circ$  incidence angle across the  $1$ – $12$  GHz frequency range

adequate microwave attenuation, it falls short of the 7.5 mm grooved brick, especially in the C- and X-bands, where enhanced surface interaction and impedance matching are critical for optimal performance.

In comparison, the 15 mm slot array exhibited the weakest and most inconsistent absorption. Its minimum values were -10.73 dB in the L-band, -20.52 dB in the S-band, -22.32 dB in the C-band, and only -8.45 dB in the X-band. For this slot size, the peak absorption was less effective, including a positive value of 2.61 dB in the L-band, which suggests signal reflection rather than absorption. In the S-, C-, and X-bands, absorption was recorded at -7.61 dB, -8.42 dB, and -2.76 dB, respectively. These weaker results, especially the positive value in the L-band, highlight poor impedance matching and the inability of longer slots to produce broad resonances across the studied spectrum.

These absorption characteristics are confirmed by the experimental spectra in Figure 10, where the 7.5 mm slot sample consistently outperforms the 15 mm slot and solid brick, especially at higher frequencies. The significant broadband attenuation produced by the fine slot array in the C- and X-bands confirms its suitability for advanced electromagnetic shielding in building applications. In contrast, the variable and often inadequate absorption of the 15 mm slot array further emphasizes the need for precise surface-size optimization to achieve reliable performance and full frequency coverage.

#### 4.4. Experimental Result at 60° Measurement Angle

At an incidence angle of 60°, the minimum and maximum absorption results for PET-POFA composite bricks with different surface textures show a significant difference in electromagnetic shielding effectiveness. Examining Tables 6 and 7, the performance of the 7.5 mm slot array stands out. This array exhibits very low reflectivity across all measured frequency bands, dropping to -25.50 dB, -26.95 dB, and -28.67 dB for the L-, S-, and C-bands, respectively, and reaching its strongest response of -39.36 dB in the X-band. Overall, these findings underscore the effectiveness of the slot array in broadband absorption, especially at higher frequencies. Even at these steep angles, the 7.5 mm slots still provide high absorption and low reflectivity, confirming the superiority of the quarter-wavelength geometry for oblique electromagnetic-wave incidence. The maximum absorption for the same configuration remains strong, especially in the X-band, reaching -29.84 dB, and shows consistently negative values even in lower bands, although some frequencies approach zero, indicating minor reflection at the most oblique angles.

In comparison, the solid brick achieved excellent absorption in the higher-frequency bands, with minimum values dropping to -38.10 dB within the S-band, -33.38 dB in the C-band, and an impressive -47.13 dB in the X-band. However, its performance in the L-band dropped to -15.90 dB, and maximum absorption values in all bands were much weaker, with the X-band reaching only -11.50 dB. This suggests that, although the intrinsic properties of the PET-POFA composite facilitate substantial

energy dissipation, especially at high frequencies, the lack of surface texture limits its impedance matching and thus its broadband performance at extreme angles of incidence.

On the other hand, reduced absorption was evident with the 15 mm slotted design, where the lowest absorption values were -10.73 dB in the L-band and -8.45 dB in the X-band, and maximum values remained close to or exceeded zero, especially in the L- and X-bands. Positive absorption values indicate net reflection, confirming poor impedance matching and frequency selectivity due to the inefficient half-wavelength slot geometry. This configuration significantly underperforms in both the low- and high-frequency ranges, reinforcing that optimization of the surface geometry is crucial to achieve strong and stable absorption at oblique incidence.

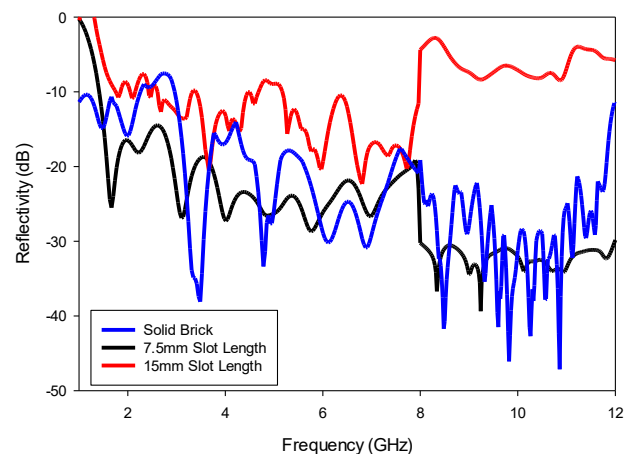
The absorption spectra further illustrate this difference, as shown in Figure 11, with the 7.5 mm slot brick retaining the deepest and broadest attenuation band at 60°, while the solid brick exhibits strong but more frequency-dependent absorption, and the performance of the 15 mm slot array remains inconsistent and suboptimal across the spectrum. These findings reinforce the importance of precision slot design, as the 7.5 mm array consistently outperforms the

**Table 6.** Minimum reflectivity performance at 60° incidence angle

Test Material	Reflectivity (dB)			
	L-Band	S-Band	L-Band	X-Band
Solid Brick	-15.90	-38.10	-33.38	-47.13
7.5 mm	-25.50	-26.95	-28.67	-39.36
15 mm	-10.73	-20.52	-22.32	-8.45

**Table 7.** Maximum reflectivity performance at 60° incidence angle

Test Material	Reflectivity (dB)			
	L-Band	S-Band	L-Band	X-Band
Solid Brick	-10.37	-7.52	-14.03	-11.50
7.5mm	-0.24	-14.47	-19.14	-29.84
15 mm	2.61	-7.61	-8.42	-2.76



**Figure 11.** Microwave absorption (dB) of PET-POFA composite bricks with solid, 7.5 mm, and 15 mm slot designs at 60° incidence angle across the 1–12 GHz frequency range

longer slot variant, even under severe-angle conditions, validating its application for architectural electromagnetic-interference shielding where multi-angle incidence is inevitable.

## 5. CONCLUSION

This study explores how surface slot patterns with lengths of 7.5 mm and 15 mm affect the microwave absorption of PET-POFA composite bricks by using an untextured brick as a baseline reference. Broadband reflectivity was measured for each configuration with an NRL free-space arch, examining vertical placements at 0°, 30°, and 60° across the full L-, S-, C-, and X-band frequency ranges. Notably, the 7.5 mm slot size provided consistently superior and reliable absorption behavior across the tested orientations and frequency ranges.

At every incidence angle, whether normal (0°), intermediate (30°), or highly inclined (60°), the 7.5 mm slot configuration maintained deep minimum absorption in the X-band and strong attenuation across all other bands, confirming optimal impedance matching and robust energy dissipation in the PET-POFA composite. In contrast, the 15 mm slot array exhibited inconsistent performance and poor absorption, particularly at oblique incidence. Although some absorption was observed in the solid brick, especially at lower frequencies, its performance did not match the bandwidth or effectiveness of the optimally textured design, particularly under oblique-incidence conditions. These results demonstrate that the quarter-wavelength (7.5 mm) slot architecture provides reliable electromagnetic shielding across all frequencies, particularly in the demanding X-band, and remains stable at multiple angles. Although solid bricks sometimes exhibit absorption values comparable to or exceeding those of slotted designs in certain frequency bands, this behavior arises from the composite's uniform lossy composition and the absence of reflections at lower frequencies. However, solid bricks fail to achieve the deep broadband absorption required in the X-band for practical EMI shielding. The addition of slotting to the composite is therefore essential for tailoring and improving high-frequency performance, allowing for more consistent absorption across bands and angles of incidence, as demonstrated by the 7.5 mm slot configuration.

These findings highlight the importance of precise surface-geometry optimization in eco-friendly construction bricks, which supports a practical solution for sustainable buildings that require effective electromagnetic-interference protection across a wide range of operating conditions. The performance is not limited to a single angle, but remains robustly effective at 0°, 30°, and 60°.

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