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ORIGINAL ARTICLE

Enhancing water resistance of PET composite board with spent garnet and sand

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Abstract: This study focuses on the development and optimisation of polyethylene terephthalate (PET) composite boards incorporating spent garnet (SG) and sand as fillers to enhance water resistance and overall performance. The experimental design was conducted using Response Surface Methodology (RSM) under the Central Composite Design (CCD) framework to evaluate the effects of two key parameters: the binder-to-filler ratio and the SG-to-sand ratio. A total of thirteen experimental runs were performed to examine compressive strength, thermal conductivity, and water absorption. The inclusion of SG up to an optimum proportion improved matrix densification and reduced water uptake. Among the developed statistical models, the water-absorption model achieved an R^2 value of 0.97, demonstrating strong predictive reliability. The optimum mix composition produced a minimum water-absorption value of 0.30%, significantly lower than the >0.50% reported for conventional PET composites. The optimisation process yielded a desirability value of 1.000, confirming model adequacy. The optimised PET–SG–sand composite exhibited enhanced moisture resistance and thermal stability, demonstrating the potential of utilising industrial-waste SG as a sustainable filler for PET-based construction materials.

Keywords: PET composite, spent garnet, sand, water absorption, optimisation

1 Introduction

The growing demand for sustainable building materials has intensified efforts to develop composite products derived from recycled resources. One such material, polyethylene terephthalate (PET), derived predominantly from discarded plastic bottles, has garnered considerable attention in recent years. While PET's potential as a binder material in composite boards has been well documented, its thermal performance and interaction with fillers such as sand and spent garnet (SG) remain insufficiently explored. These fillers, which offer distinct mechanical and thermal properties, can significantly influence the performance of composite boards, especially concerning water absorption, which is a critical factor governing durability and service life in construction applications [1], [2].

Water absorption in composite materials is a fundamental consideration due to its direct impact on

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structural integrity, durability, and long-term performance. Materials that absorb water excessively can undergo dimensional changes, leading to swelling, cracking, or deterioration under environmental conditions. Such behaviour can result in significant maintenance costs, reduced lifespan, and, in extreme cases, structural failure. For this reason, the ability to control water uptake is vital in the design of composite boards for construction [3].

In the context of PET-based composites, several studies have evaluated the role of PET as a binder; however, a clear optimisation strategy for improving its water-resistance performance when combined with different fillers is still lacking [4], [5]. Spent garnet, an abrasive material with high hardness and density, has shown potential as a sand replacement in concrete, enhancing compressive and flexural strength [6], [7]. However, its effect on water absorption in PET composites has not been extensively studied, and its synergistic interaction with natural sand for developing a balanced moisture-resistant composite has yet to be optimised.

Recent advances in Design of Experiments (DOE), particularly the application of Response Surface Methodology (RSM), offer a robust framework for optimising material formulations. RSM provides a powerful tool for exploring the interactions between multiple variables and predicting the optimal mix of components to achieve the desired material properties. The use of Central Composite Design (CCD) in RSM, with its ability to evaluate factorial and second-order effects, makes it especially suitable for fine-tuning composite formulations and controlling complex interactions affecting water absorption [8]. Therefore, RSM–CCD was selected in this study to establish predictive and optimisation models for PET composite boards containing SG and sand. Despite extensive research on PET, sand, and SG individually, limited information is available on their combined effect when configured as a binder–filler system. Consequently, this study aims to optimise the water-absorption characteristics of PET composite boards containing both SG and sand using RSM–CCD.

Given the rising concern over the environmental footprint of construction materials, the potential for using recycled PET as a binder and industrial by-products such as SG as fillers presents a dual benefit: reducing waste and producing more sustainable construction materials. This approach aligns with circular economy principles and contributes to reducing the carbon emissions associated with virgin aggregates. The water absorption of these composite boards is of particular importance, as it directly correlates with their performance in real-world construction environments. Previous studies have indicated that water absorption can be influenced not only by the nature of the matrix material but also by the characteristics of the fillers [9], [10].

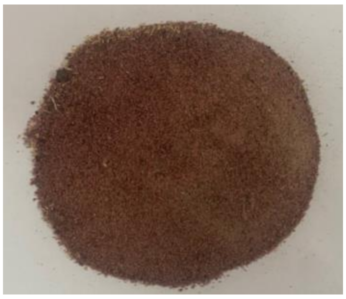
Accordingly, this research aims to develop and optimise PET composite boards incorporating SG and sand using RSM-CCD. The specific objectives are: (i) to characterise the physical properties of PET, SG, and sand; (ii) to evaluate the influence of these materials on compressive strength, thermal conductivity, and water absorption; and (iii) to develop and validate an optimisation model for predicting and improving these responses. Through this systematic approach, the study contributes to the development of durable, sustainable composite boards and provides a practical pathway for large-scale utilisation of recycled and industrial-waste materials in construction.

2 Materials and Methods

2.1 Materials

The raw materials used in producing the polyethylene terephthalate (PET) composite board include PET, spent garnet (SG), and sand, each serving specific functions in the composite formulation, as shown in Fig 1. PET, a thermoplastic polymer derived from discarded bottles, functions as the binder in the composite. The PET bottles were collected from local recycling bins, thoroughly cleaned to remove contaminants, and cut into flakes ranging between 10 and 15 mm to ensure uniform melting and mixing during fabrication. Spent garnet (SG), obtained as a by-product from abrasive blasting activities, was sourced from Boustead Naval Shipyard Sdn. Bhd., Lumut, Perak. The material was sieved to pass through a 0.6 mm mesh to achieve fine aggregate gradation. SG acts as a functional filler, contributing to strength and structural stability within the composite matrix due to its high density and angular morphology. Natural sand, used as a secondary filler, was sourced from the Advanced Materials Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM), and sieved to pass through a 1.18 mm mesh. Sand enhances the workability and homogeneity of the composite mixture by filling voids between SG particles. Sourcing and grading these materials from consistent sources ensured uniformity, repeatability, and quality control throughout the fabrication process. PET density was measured following ASTM D792, while the specific gravity and particle-size distribution of SG and sand were determined according to ASTM C128 and ASTM C136, respectively [4], [11]. These tests confirmed that the selected materials met the physical-property requirements for PET-based composite applications.

(a) PET



(b) Spent garnet

(c) Sand

Fig 1: Raw materials

2.2 Design Mix Proportion

The experimental mixtures were developed using the Central Composite Design (CCD) under the Response Surface Methodology (RSM) framework. The study investigated three primary components: polyethylene terephthalate (PET), spent garnet (SG), and sand, across thirteen distinct mixture runs (M1–M13), as presented in Table 1. CCD provides an efficient approach for exploring the interaction effects among multiple variables while minimising the number of experimental runs compared with traditional full factorial designs. This method allows the simultaneous evaluation of linear, quadratic, and interaction effects of the selected parameters, thereby enabling the development of accurate predictive models [12], [14].

Table 1: Design mix proportion

Mix	PET (%)	PET (kg)	SG (%)	SG (kg)	Sand (%)	Sand (kg)
M1	29	0.0620	0	0.0000	71	0.2408
M2	23.5	0.0503	19.13	0.0648	57.38	0.1946
M3	34.5	0.0738	16.38	0.0555	49.13	0.1666
M4	40	0.0771	35.5	0.1083	35.5	0.1085
M5	18	0.0433	35.5	0.1351	35.5	0.1353
M6	29	0.0620	35.5	0.1202	35.5	0.1204
M7	29	0.0620	35.5	0.1202	35.5	0.1204
M8	29	0.0620	35.5	0.1202	35.5	0.1204
M9	29	0.0620	35.5	0.1202	35.5	0.1204
M10	29	0.0620	35.5	0.1202	35.5	0.1204
M11	34.5	0.0738	49.13	0.1664	16.38	0.0555
M12	23.5	0.0503	57.38	0.1943	19.13	0.0649
M13	29	0.0620	71	0.2405	0	0.0000

A key advantage of CCD is the inclusion of centre-point replicates, as seen in mixtures M6–M10, which provide essential information for estimating pure experimental error and improving the reproducibility of the results. This feature enhances the statistical robustness and reliability of the findings, making CCD particularly suitable for materials research requiring precision and accuracy [15]. Overall, the use of CCD in this study ensured a comprehensive understanding of the relationships between binder and filler components, facilitating the optimisation of the PET composite board formulation.

2.3 PET Composite Board Fabrication Process

The manufacturing process of the polyethylene terephthalate (PET) composite boards consisted of seven essential stages, as illustrated in **Fig 2**. The process began with material preparation, ensuring that all raw materials were appropriately sized to achieve uniformity and eliminate any bias during mixing and testing. The collected PET bottles were cleaned and cut into flakes measuring between 10 and 15 mm, while spent garnet (SG) and sand were dry sieved to achieve particle sizes passing 0.6 mm and 1.18 mm, respectively. These gradations were selected to ensure consistent dispersion within the composite matrix.

Fig 2: The fabrication process of the PET composite board

The second stage involved precise weighing of the materials based on the mixture ratios specified in Table 1. Each constituent was measured using an electronic balance to maintain accuracy and reproducibility. The materials were then transferred into a heated mixing system, where they were gradually blended at 250 ℃ for approximately 30–40 minutes until a uniform molten consistency was achieved. Continuous stirring during this stage promoted homogeneous distribution of the fillers within the molten PET binder.

Prior to moulding, the steel mould used for compaction was preheated at 180 ℃ for 10 minutes to ensure uniform temperature distribution and facilitate consistent shaping of the composite boards. The molten mixture was then poured into the preheated mould and subjected to compression at 180 ℃ for 10 minutes. This compaction process ensured proper consolidation and removal of trapped air, thereby improving board density and surface finish.

After compression, the mould was allowed to cool to room temperature for approximately 20 minutes before demoulding. The boards were then removed and stored in a clean, dry environment to prevent moisture contamination before subsequent testing. This systematic procedure standardised the fabrication process, ensuring reproducibility across all samples and reliable comparison of test results.

2.4 Water Absorption Testing

The water absorption test for the polyethylene terephthalate (PET) composite boards was conducted in accordance with ASTM D5229 [16]. The procedure began by determining the dry weight of each specimen, recorded as W_1. The samples were then fully immersed in water at room temperature for 24 hours to simulate short-term moisture exposure. After immersion, the specimens were removed, drained for three minutes, and gently wiped with a damp cloth to remove any surface water. The saturated weight was recorded as W_2.

The percentage of water absorption (M) was calculated using Equation (1):

$$M\left(\%\right)=\frac{W_2-W_1}{W_1}\times 100 \tag{1}$$

where W_1 is the oven-dry weight of the specimen (kg) and W_2 is the saturated weight of the specimen (kg). This test provided a direct measure of the material's ability to absorb and retain moisture, serving as an essential indicator of its durability and suitability for construction applications.

3 Result and Discussion

3.1 Physical Properties

The physical parameters of the raw materials, namely polyethylene terephthalate (PET), spent garnet (SG), and sand, provide critical insight into their influence on the mechanical and durability performance of the composite boards. Density and specific gravity are particularly important in this context as they directly affect the packing efficiency, compaction, and interfacial bonding within the composite matrix [7], [17]. PET exhibited a density of 1426 kilograms per cubic metre and a specific gravity of 1.426, which are considerably lower than those of SG (2258 kilograms per cubic metre; 2.258) and sand (2261 kilograms per cubic metre; 2.261). As a low-density thermoplastic polymer, PET functions as the binder, while the denser SG and sand act as mineral fillers to enhance compactness, strength, and load transfer within the matrix [18], [19].

The difference in density and particle size between PET (10 to 15 millimetres) and the finer fillers (SG ≤ 0.6 millimetre and sand ≤ 1.18 millimetres) was crucial in achieving efficient packing and effective stress transfer. Studies by Huseien et al. (2019) and Muttashar et al. (2017) confirmed that fine and angular filler materials such as SG, owing to their high specific gravity and angular morphology, promote better interlocking and filler–binder contact, leading to improved compressive strength [7], [20]. Sand, being slightly coarser than SG, complements this effect by filling internal voids and improving matrix uniformity [21]. When proportioned optimally with PET, these fillers collectively increase the load-bearing capacity of the composite boards by promoting densification and reducing porosity [2].

The melting point of PET, approximately 220 degrees Celsius, ensures sufficient thermal stability during fabrication, enabling uniform coating and encapsulation of the fine filler particles without degradation. This thermal compatibility promotes strong adhesion and a homogeneous microstructure, which are essential for achieving high compressive strength. Aneke et al. (2021) similarly reported that maintaining appropriate binder to filler ratios and gradations enhances the mechanical strength of PET-based composites [2]. Hence, the synergistic utilisation of lightweight PET with dense mineral fillers such as SG and sand, supported by their measured physical parameters, plays a key role in improving the structural integrity and durability of the developed composite boards [22], [23].

Table 2: Physical properties of raw materials

Parameter	PET	Spent garnet	Sand
Density (kg/m^3)	1426	2258	2261
Specific gravity	1.426	2.258	2.261
Melting point (℃)	220	-	-
Size (mm)	10-15	0.6	1.18

3.2 Water Absorption

Fig 3 presents the water absorption results for thirteen different polyethylene terephthalate (PET) composite mixtures formulated with varying proportions of PET, spent garnet (SG), and sand, as detailed in Table 1. The data reveals a clear decreasing trend in water absorption from Mix 1 to Mix 13. Mix 1 recorded the highest water absorption at approximately 0.70 per cent, while Mix 13 showed the lowest value at around 0.30 per cent. This progressive reduction indicates that the optimisation of composition through Central Composite Design within the Response Surface Methodology framework effectively identified blend ratios that enhance the water resistance of PET composite boards.

The observed trend can be attributed to systematic variations in the proportions of PET, SG, and sand, where optimised formulations minimise the capillary pathways that facilitate water ingress. The lowest water absorption observed in Mix 13 demonstrates that the interaction between PET content and the combined effects of SG and sand fillers produces a denser and more impermeable matrix. Similar behaviour was reported by Budiea et al. (2022) and Baeră et al. (2022), who found that incorporating dense mineral fillers into polymer matrices reduces pore connectivity and limits moisture uptake [24], [25]. The hydrophobic nature of PET contributes to this performance, although its effectiveness depends on the degree of filler dispersion and bonding within the matrix [4].

The improvement in water resistance, particularly evident from Mix 9 onward, highlights the significant influence of filler composition and particle gradation. Previous studies have established that high-specific-gravity fillers such as SG increase packing efficiency and reduce interconnected voids, which in turn decreases water absorption [7], [18]. In the present work, as the proportion of SG increased while maintaining an appropriate balance with sand and PET, a continuous decline in water absorption was observed. Jamaludin et al. (2021) also reported that the angular morphology of garnet enhances particle interlocking and strengthens the transition zone between the polymer matrix and the mineral fillers [6].

The central region of the design, represented by Mixes 9 to 13, exhibited superior water resistance compared to the initial mixtures. These centre point replicates, characterised by balanced proportions of PET, SG, and sand, consistently achieved the lowest absorption values, suggesting the existence of an optimal compositional range where filler and binder synergy is maximised. This observation corresponds with the findings of Smaoui et al. (2023), who showed that maintaining optimised ratios between polymer binder and mineral fillers is essential for minimising moisture uptake in composite systems [26]. Furthermore, the continuous decrease in absorption without significant variability demonstrates the reliability of the Central Composite Design approach for fine tuning composite performance [8].

The water absorption values achieved in this study were notably lower than those reported for conventional PET-based composites without spent garnet, which typically exceed 0.50% [4], [5].The reduction to as low as 0.30% confirms the advantage of including SG as a functional filler, validating previous assumptions that industrial by-products can significantly enhance the moisture resistance of polymer composites [1], [25]. From a practical perspective, these results have considerable implications for the construction industry, where moisture penetration is a primary cause of long-term material degradation.

The PET composite boards developed in this study, particularly those based on optimised formulations, display the level of water resistance required for use in external cladding, insulation panels, and partition systems. These findings support the adoption of circular economy principles through the effective reuse of post-consumer PET and industrial SG waste [2], [27]. In summary, the systematic decline in water absorption across all experimental runs demonstrates the effectiveness of Response Surface Methodology in improving the moisture resistance of PET composite boards. The results confirm the feasibility of producing water-resistant and sustainable construction materials using recycled and waste-derived components while providing a sound foundation for future large-scale implementation.

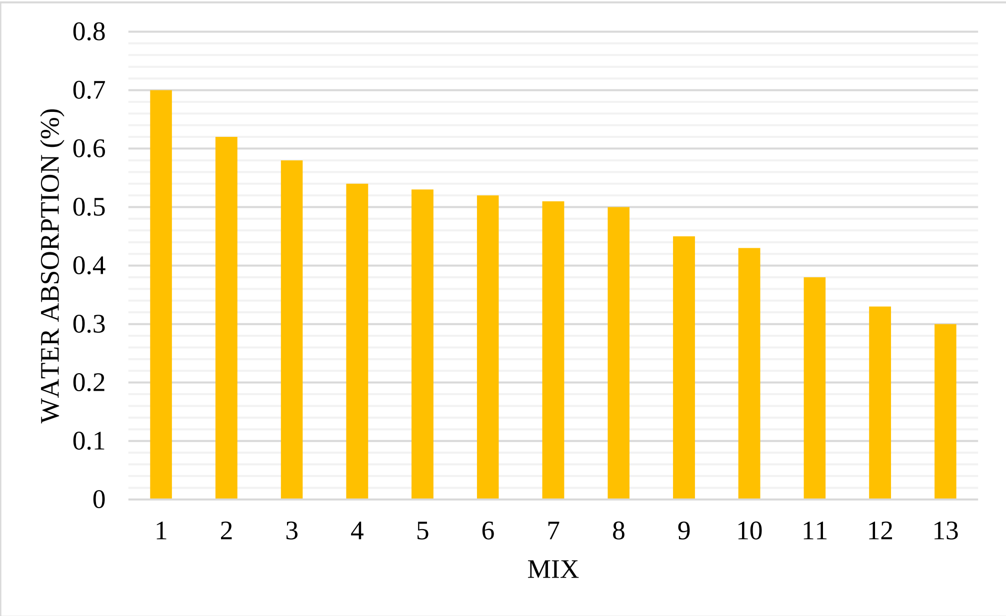


Fig 3: Water absorption of PET composite board

3.3 ANOVA Analysis

Table 3 summarises the analysis of variance results for the predictive model of water absorption in polyethylene terephthalate (PET) composite boards formulated using the Central Composite Design within the Response Surface Methodology framework. The statistical results indicate that the regression model is highly significant, with a model F-value of 52.2 and a p-value below 0.0001. This confirms that the linear and interaction effects of the variables, namely PET, spent garnet (SG), and sand contents, collectively explain a substantial portion of the variation in water absorption.

Among the model terms, the interaction between spent garnet and sand (B SG Sand) was the most significant, with an F-value of 241.99 and a p-value less than 0.0001. This demonstrates that the combined influence of the two fillers plays a critical role in controlling water uptake within the composite system. The result supports the findings of Baeră et al. (2022) and Lăzărescu et al. (2023), who reported that optimised combinations of mineral fillers in polymer composites can effectively disrupt moisture transport pathways and improve resistance to water penetration [18], [24].Conversely, the three-factor interaction (A B F) and the quadratic term for spent garnet (B^2) were not statistically significant ($p > 0.05$), indicating that further interactions beyond the main and two-factor effects contributed minimally to the model response. This pattern aligns with the results of Zhang and Zhai (2021), where the majority of response variability was attributed to primary and interaction effects, while higher-order terms exhibited negligible influence [8].

The residual mean square of 0.0094 and the low lack-of-fit value ($F = 1.12$, $p = 0.3243$) confirm that the model successfully accounted for the systematic variations without significant unexplained trends. The non-significant lack of fit implies that deviations between the observed and predicted values resulted primarily from random experimental error rather than deficiencies in the model itself, ensuring the model's adequacy and suitability for predictive analysis [12], [15]. The fit statistics further confirm the robustness of the developed regression model. The coefficient of determination (R^2) of 0.9739 indicates that approximately 97 per cent of the variance in water absorption was explained by the model variables and their interactions. The adjusted R^2 of 0.9552 closely matches the R^2 value, confirming the model's consistency after accounting for the number of predictors. The predicted R^2 of 0.8093 also demonstrates high predictive reliability, verifying the model's capability to forecast water absorption across different compositions. The small difference between adjusted and predicted R^2 values confirms that overfitting did not occur, a condition consistent with best practices for Response Surface Methodology modelling [28].

The model's standard deviation of 0.0239 and coefficient of variation of 4.87 per cent signify high precision and repeatability of the experimental results. The adequate precision value of 26.4399, which exceeds the commonly accepted threshold of 4.0, indicates a satisfactory signal-to-noise ratio, validating the model's suitability for navigating the design space [14]. The statistical strengths of this model are consistent with those reported in previous composite optimisation studies, where Response Surface Methodology-based regression models have successfully achieved high model adequacy and reliable predictive performance [3], [8]. The model's success is attributed to the judicious selection of independent variables, the inclusion of centre-point replicates, and rigorous experimental control, all of which ensure reliable identification of key effects.

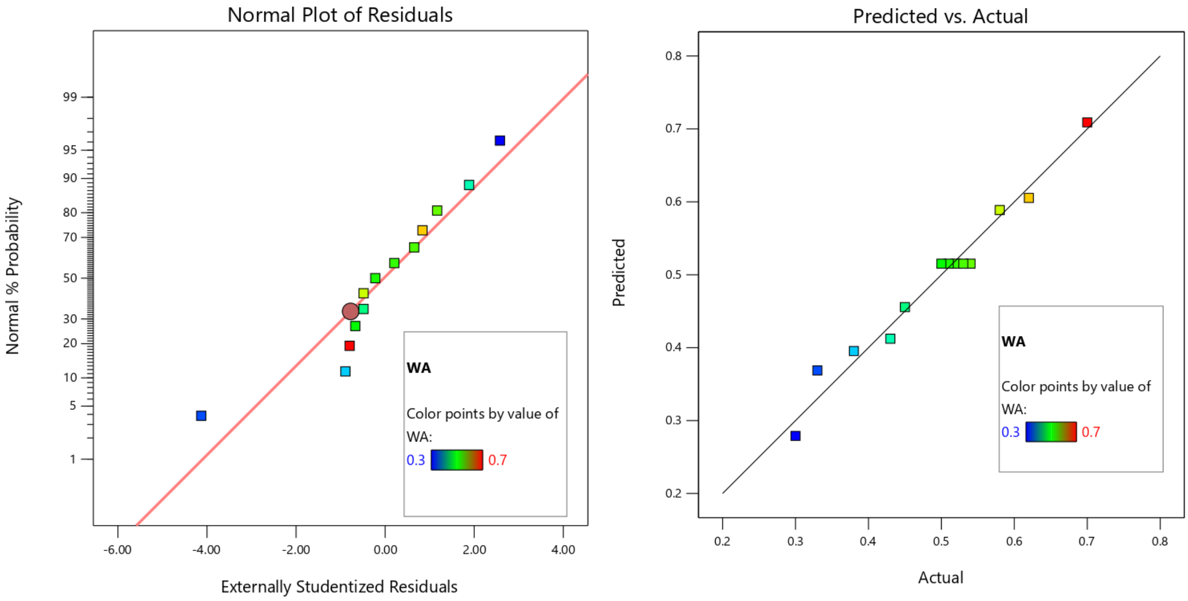
Table 3: ANOVA table for water absorption

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.1496	5	0.0299	52.20	< 0.0001	significant
A-B-F	0.0014	1	0.0014	2.46	0.1609	
B-SG-Sand	0.1387	1	0.1387	241.99	< 0.0001	
B^2	0.0000	1	0.0000	0.0436	0.8405	
Residual	0.0094	1	0.0094	16.48	0.0048	
Lack of Fit	0.0006	1	0.0006	1.12	0.3243	
Pure Error	0.0040	7	0.0006			
Cor Total	0.0030	3	0.0010	4.02	0.1063	not significant
			Fit Statistics			
Std. Dev.	0.0239		R^2	0.9739		
Mean	0.4915		Adjusted R^2	0.9552		
C.V. %	4.87		Predicted R^2	0.8093		
			Adeq Precision	26.4399		

The strong agreement between observed and predicted results demonstrates the accuracy and consistency of the model developed in this study. The significance of the SG and sand interaction highlights the importance of filler composition in improving moisture resistance, thereby establishing a framework for material optimisation. Furthermore, the non-significant higher-order terms confirm that the response surface is primarily governed by linear and primary interaction effects within the examined range, simplifying future optimisation and modelling procedures. Collectively, the ANOVA and model fit statistics validate the experimental design and provide a dependable basis for predicting the water absorption behaviour of PET composite boards, enabling their further application in moisture-resistant construction materials.

3.4 Diagnostics Plot

Fig 4(a) shows the normal probability plot of residuals for the water absorption of polyethylene terephthalate (PET) composite boards. The residuals were distributed closely along the theoretical straight line, confirming that they followed an approximately normal pattern. This observation supports the analysis of variance results, which indicated a non-significant lack of fit with a p-value of 0.3243, thereby validating the adequacy of the regression model. The absence of outlier clustering or systematic deviation implies that the residuals are random and uniform, satisfying the basic assumptions required for regression analysis and Response Surface Methodology optimization [28]. The normality of residuals is an essential criterion for the reliability of predictive models because it ensures the validity of statistical inferences and enhances the robustness of optimisation outcomes. Previous studies by Smaoui et al. (2023) and Zhang and Zhai (2021) also emphasised that normally distributed residuals are crucial for accurate determination of material composition using Response Surface Methodology [3], [8]. In this study, the conformity of residuals to a normal distribution confirms that the model was well calibrated and not influenced by uncontrolled experimental factors.



(a) Normal Plot (b) Predicted vs Actual

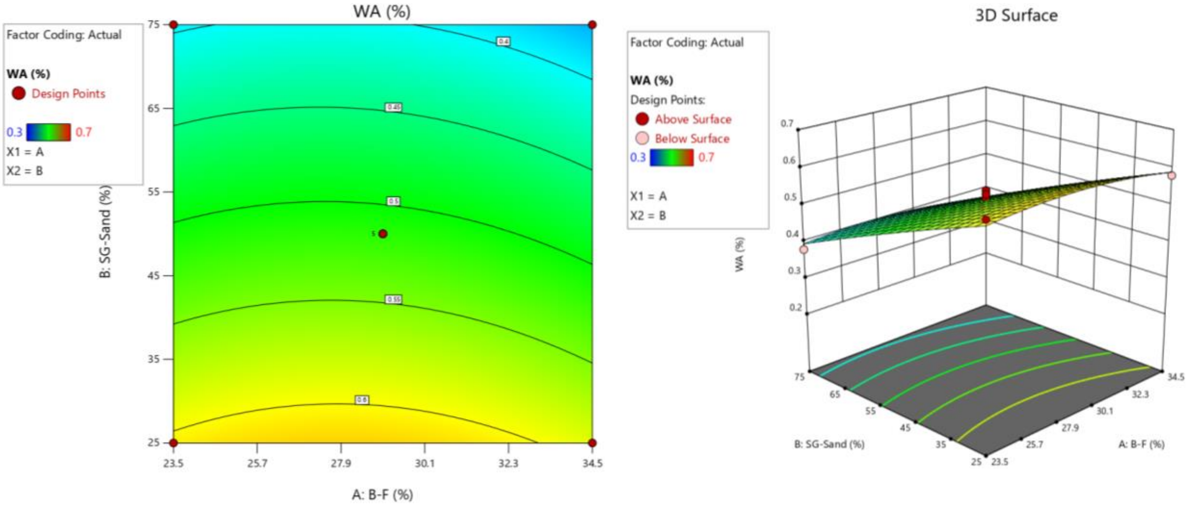
Fig 4: Diagnostics of thermal conductivity of PET composite board

Fig 4(b) presents the predicted versus actual values of water absorption, demonstrating the correlation between the experimental and model-predicted results. The data points are closely clustered along the 45-degree reference line within the range of 0.30 to 0.70 per cent water absorption. This linear relationship indicates an excellent model fit, as evidenced by the high coefficient of determination (R^2 = 0.9739) summarised in Table 3. The strong correlation and minimal deviation between predicted and actual values confirm that the regression model accurately represents the relationship between the composition and water absorption response. The high level of agreement between predicted and observed data underscores the robustness of the fitted model, validating its use for both interpolation within the studied range and potential extrapolation to similar systems. Similar diagnostic outcomes were reported by Baeră et al. (2022), who found that well-structured experimental designs coupled with statistical validation yield highly reliable predictive models for moisture control in composite materials [24]. The minimal deviation observed in this study, combined with the lack of heteroscedasticity, indicates that the model captures the dominant material interactions effectively, providing a strong foundation for optimisation. The results obtained in this diagnostic analysis are consistent with established literature benchmarks and demonstrate the predictive accuracy of the developed model. The validated model can be confidently used for guiding future formulation strategies and scale-up trials involving recycled polymer composites.

Fig 5(a) illustrates the contour plot, and Figure 5(b) presents the corresponding three-dimensional surface plot, both of which depict the influence of spent garnet and sand content on the water absorption of PET composite boards while maintaining constant PET content. The graphical analysis shows how systematic variation in SG and sand proportions governs the water absorption behaviour. The contour plot reveals a gradual gradient in water absorption across the design space. The region with low SG and high sand content shows the highest absorption, indicated by warmer colours, whereas the region with high SG and low sand content demonstrates the lowest absorption, represented by cooler colours. This trend indicates that increasing the proportion of SG while reducing the proportion of sand leads to improved water resistance. These results are consistent with the studies by Lăzărescu et al. (2023) and

Budiea et al. (2022), who concluded that the inclusion of dense mineral fillers enhances particle packing and decreases capillary porosity, thereby limiting water movement within polymer matrices [18], [25].

The three-dimensional surface plot displays a smooth convex response surface with the lowest water absorption values concentrated in the region of high SG and low sand content. The absence of abrupt curvature or irregular peaks suggests that the relationship between SG and sand is primarily linear within the studied factor range. This finding is supported by the analysis of variance results, which indicated a non-significant quadratic effect, confirming that the model adequately represents the factor-response relationship. Similar observations were made by Zhang and Zhai (2021) and Smaoui et al. (2023), who demonstrated that well-balanced filler ratios yield predictable and optimised water resistance in polymer composites [3], [8].



(a) Contour Plot (b) 3D Surface

Fig 5: Graphical of water absorption of PET composite board

The response surface analysis confirms the dominant role of SG as a functional filler in reducing water absorption. The enhanced water resistance is attributed to the high specific gravity and angular particle morphology of SG, which facilitates dense packing and effective interfacial bonding with the PET matrix. Although sand contributes to matrix stability and texture, its excessive inclusion can introduce additional voids, thereby increasing the potential for water ingress. Therefore, the correct balance between SG and sand is essential to achieve optimum moisture resistance and structural performance [6], [21]. The systematic application of Response Surface Methodology and the agreement between graphical and statistical analyses demonstrate the reliability and adequacy of the developed model. The results confirm that the combination of PET, SG, and sand can be effectively optimised to achieve high water resistance, providing a validated pathway for the development of durable and sustainable composite materials.

3.5 Regression Model

The predictive regression equation developed for the water absorption of polyethylene terephthalate (PET) composite boards was obtained using the Central Composite Design within the Response Surface Methodology framework. The quadratic model represents the main, interaction, and second-order effects of the independent variables and is expressed as:

$$WA = 0.175302 + 0.037865A - 0.002924\text{B} - 0.000018\text{AB} - 0.000671A^2 - 8.48 \times 10^{-6}B^2 \quad (2)$$

where A and B denote the coded levels of PET and spent garnet (SG) content, respectively. The model provides a reliable statistical representation of how variations in PET and SG influence the water absorption behaviour of the composite boards.

The positive coefficient of PET indicates that an increase in PET content corresponds to a slight rise in water absorption when other variables remain constant. This finding agrees with Jaskowska-Lemańska et al. (2022) and Coviello et al. (2023), who reported that excessive polymer content can increase matrix porosity and promote water penetration when filler integration is insufficient [4], [5]. In contrast, the negative coefficient of SG confirms its effectiveness as a water-resistant filler, as higher SG levels are associated with reduced water absorption. This result supports the findings of Lăzărescu et al. (2023) and Budiea et al. (2022), who concluded that dense mineral fillers with angular shapes decrease pore connectivity and restrict moisture flow [18], [25]. The negative quadratic coefficients for both PET and SG indicate diminishing returns at higher concentrations, implying that beyond certain limits, further increases do not significantly improve water resistance. This behaviour aligns with the non-significant lack of fit observed in the analysis of variance and confirms that the model is well calibrated within the studied range without significant higher-order effects [28].

The slightly negative interaction term between PET and SG suggests a minor synergistic effect where simultaneous increases of both components marginally reduce water absorption. Although not a dominant influence, this interaction supports the concept proposed by Phang et al. (2022) and Smaoui et al. (2023) that appropriate filler and binder balance enhances composite impermeability [3], [21]. The derived regression model demonstrates both predictive and interpretative value, allowing accurate estimation of water absorption across different compositions and providing insight into the underlying material behaviour. The analysis confirms that the strategic inclusion of SG relative to PET content is the principal factor controlling moisture resistance in the developed composites. The model also highlights the importance of multivariate approaches such as Response Surface Methodology for complex systems where multiple interactions occur simultaneously.

These results are consistent with the observations of Zhang and Zhai (2021), Amsalu Fode et al. (2024), and Smaoui et al. (2023), who found that statistically validated models are critical for process control and for scaling up the production of high-performance sustainable materials [3], [8], [12]. The close agreement between predicted and experimental results further validates the reliability of the model and demonstrates the effectiveness of the Central Composite Design as a robust optimisation tool. Overall, the regression model not only serves as an empirical predictor but also as a scientific guide for the rational formulation of PET composite boards. Its successful application confirms the feasibility of using recycled polymers and industrial by-products such as spent garnet to develop sustainable construction materials with improved water resistance.

4 Conclusions

This study systematically investigated the optimisation of water absorption in polyethylene terephthalate (PET) composite boards by incorporating spent garnet (SG) and sand as fillers using the Central Composite Design within the Response Surface Methodology framework. The integration of post-consumer PET as a thermoplastic binder with varying proportions of SG and sand produced composite formulations with enhanced water resistance. The results demonstrated that increasing SG content while maintaining an appropriate sand balance significantly reduced water absorption, achieving an optimum value of 0.30%. This value is notably lower than the typical values exceeding 0.50% reported for PET composites without filler optimisation [4], [5].

The developed regression model exhibited strong statistical validity, with a high coefficient of determination ($R^2 = 0.97$), low residual error, and consistent diagnostic indicators. These results confirm the reliability of the predictive model in optimising filler proportions. The pronounced interaction effect between SG and sand, as indicated by the analysis of variance and surface plots, emphasises the critical role of synergistic filler integration in reducing moisture absorption. This finding addresses a gap identified in earlier research, where the influence of industrial by-product fillers on water absorption was not fully understood [18], [25]. The utilisation of spent garnet as a functional filler demonstrates both technical and environmental benefits. Converting waste materials such as PET and SG into high-performance construction composites supports circular economy principles and contributes to sustainable material development [1], [2]. The approach adopted in this research diverts waste from landfills while enhancing the durability and performance of construction materials. Moreover, the Response Surface Methodology provided a systematic and resource-efficient framework for optimising material composition [3], [8].

Although this study focused primarily on water absorption as a key performance indicator, the relationship between binder and filler content also affects other important properties such as compressive strength, flexural strength, and thermal conductivity. The outcomes of this work establish a foundation for future studies to apply multi-objective optimisation methods that simultaneously improve mechanical and durability performance. Further research is recommended to evaluate long-term durability under cyclic wetting and drying exposure and to perform microstructural characterisation to elucidate the mechanisms responsible for moisture resistance. In conclusion, this study contributes to the advancement of sustainable composite materials by demonstrating that the optimisation of PET, spent garnet, and sand compositions can effectively minimise water absorption while enhancing material performance. The findings provide valuable insights for the large-scale production and application of waste-derived, durable, and environmentally responsible composite boards in construction.

4.1 Recommendation

Based on the substantial improvement in water resistance achieved through the optimisation of polyethylene terephthalate (PET), spent garnet (SG), and sand proportions, several directions for further research and practical application are proposed. Future studies should extend the current optimisation framework to include additional performance criteria such as compressive strength, flexural behaviour, and thermal conductivity. Multi-objective optimisation methods that incorporate advanced statistical or machine learning techniques are recommended to design composite boards with specific performance targets suitable for various construction applications [3], [8].

Long-term durability evaluations should be conducted to assess the performance of the optimised PET composite boards under realistic environmental conditions. Tests involving cyclic wetting and drying, freeze and thaw cycles, and chemical exposure would provide essential data for predicting service life and compliance with relevant building standards [1], [25]. Microstructural studies using scanning electron microscopy or X-ray computed tomography are also encouraged to examine the internal morphology of the composites, particularly the distribution of fillers and the interfacial bonding with the PET matrix [18]. For industrial application, pilot-scale production and life cycle assessment studies should be undertaken to evaluate the scalability, economic feasibility, and environmental footprint of the developed composites. These investigations will facilitate the transition from laboratory research to practical implementation and support the broader adoption of sustainable materials in construction. Such work will strengthen the role of PET and spent garnet composites in promoting circular economy practices through waste minimisation and resource efficiency [2], [24].

4.2 Limitations

Although this study provides valuable insights into the optimisation of water absorption in polyethylene terephthalate (PET) composite boards, several limitations should be acknowledged. The experimental programme was restricted to a specific range of PET, spent garnet (SG), and sand contents as determined by the Central Composite Design. Therefore, the results may not represent behaviour outside this compositional range, and further investigation is recommended to determine the full performance limits of the material [28].

The current study was limited to short-term water absorption testing under controlled laboratory conditions. The potential effects of temperature variation, sustained mechanical loading, and cyclic environmental exposure were not examined and may influence long-term performance in practical applications. Moreover, the absence of detailed microstructural analysis restricts direct correlation between physical observations and internal morphological changes. Future research should include microstructural characterisation to provide a deeper understanding of filler distribution and the mechanisms contributing to water resistance [21]. Finally, while this study concentrated on water absorption as the main response variable, other key material properties such as fire resistance, acoustic performance, and environmental impact were not explored. These parameters are essential for comprehensive performance evaluation and should be incorporated into future assessments of PET composite boards intended for sustainable construction applications [4], [5].

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CRediT authorship contribution statement

Mat Nawi, Burhanudin; Kamarudin: study conception and design. **Mat Nawi**: data collection. **Mat Nawi, Burhanudin:** analysis and interpretation of results. **Mat Nawi, Burhanudin, Md Noh, Kamarudin:** draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

Conflicts of Interest

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

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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