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Harnessing PET Waste for High-Performance Composite Boards in Green Building Applications

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Abstract

This study investigates the compressive and tensile properties of PET composite boards made from post-consumer plastic waste (PET), spent garnet, and sand for application in green building technology. Laboratory tests were conducted to evaluate the composites' mechanical performance, particularly in optimising the binder-to-filler ratio and filler composition. The results indicate that increasing PET content significantly enhances compressive strength, with Mixes 12 and 13 achieving the highest compressive strength (12-16.5 MPa). Tensile strength ranged from 2.63 MPa to 8.58 MPa and was more influenced by filler composition. Regression models for both strengths revealed significant dependence on the binder-to-filler ratio and filler composition. ANOVA analysis confirmed the significance of these factors in enhancing mechanical performance. Diagnostic plots validated the regression models, indicating good data fit. Despite these promising results, the PET composites demonstrated relatively low tensile strength, indicating the need for further reinforcement, such as fibre inclusion. Additionally, the study did not address long-term durability under environmental stressors, highlighting a critical area for future research. Recommendations include exploring fibre reinforcement, evaluating long-term performance, and conducting lifecycle analysis to assess the environmental impact. This research contributes to developing sustainable construction materials by optimising the composition of PET composite boards, with potential application in non-structural building elements.

1. Introduction

Polyethylene terephthalate (PET) is one of the most extensively produced and utilised thermoplastics worldwide, predominantly serving in packaging applications such as beverage bottles, food containers, and synthetic fibres [1]. Global PET production has surged to nearly 30 million tonnes annually as of 2020, driven by increasing consumer demand and industrial applications [1]. Despite this vast production, the management of PET post-consumer waste remains a significant environmental challenge. Current estimates indicate that only around 29% of PET waste is recycled globally, with the remainder predominantly subjected to landfilling, incineration, or, alarmingly, improper disposal [2]. This mismanagement exacerbates plastic pollution, contributing an estimated 8 million tonnes of plastic debris into marine environments each year, with devastating consequences for biodiversity and ecosystem stability [3].

The environmental persistence of PET is a direct consequence of its non-biodegradable polymeric structure, which enables accumulation in both terrestrial and aquatic habitats [4]. Over time, PET debris undergoes fragmentation into microplastics, a phenomenon that facilitates their infiltration into food chains and raises concerns regarding potential adverse human health effects [5]. Unregulated waste disposal practices, including open dumping and inefficient collection systems, further compound these impacts [6], [7]. Such practices accelerate pollutant dissemination, promote greenhouse gas emissions through anaerobic decomposition in landfills, and generate toxic pollutants from uncontrolled incineration, thereby intensifying the environmental footprint of PET waste [2]. These challenges underscore the urgency for innovative and sustainable PET waste management strategies to mitigate their ecological and societal repercussions [8].

Within the circular economy framework, recycling and valorisation of PET waste into high-value products have emerged as promising approaches to alleviate the environmental burden of plastic pollution [9], [10]. Specifically, the conversion of PET waste into composite building materials capitalises on the polymer's inherent properties while diverting substantial waste volumes from landfill and reducing dependence on conventional construction materials characterised by high embodied carbon, such as concrete and steel [11], [12]. The utilisation of recycled PET composites aligns with global sustainability imperatives by fostering resource efficiency, reducing greenhouse gas emissions, and encouraging green innovation in construction sectors [13], [14], [15].

Nonetheless, while PET-based composites present environmental and economic advantages, their widespread adoption in construction is hindered by challenges related to mechanical performance optimisation and durability assurance [16]. Previous research has indicated that PET composites offer competitive compressive strengths but often exhibit relatively lower tensile properties, a limitation that must be addressed to meet structural application standards [11], [12]. The mechanical behaviour of such composites is strongly influenced by the binder-to-filler ratio and the nature of filler materials, with inorganic fillers like sand and spent garnet demonstrating potential to enhance compressive strength through improved matrix cohesion [17], [18]. Conversely, irregular particle shapes of certain fillers may weaken tensile properties due to suboptimal bonding with the polymer matrix, highlighting the inherent trade-offs in composite design [19].

Moreover, the long-term durability of PET composites under environmental stressors, including moisture ingress, ultraviolet radiation, and temperature variations, remains insufficiently explored, particularly concerning real-world applications [20]. Addressing these gaps is critical to advancing PET composite boards from laboratory-scale innovations to reliable, sustainable building materials. The present study builds upon this foundation by systematically investigating the compressive and tensile properties of PET composite boards with varying binder-to-filler ratios and filler compositions. Through rigorous mechanical testing and statistical modelling, this work aims to elucidate the optimal material formulations that maximise structural performance while considering durability implications. By advancing the understanding of PET composite behaviour under diverse loading and environmental conditions, the study contributes to the evolving landscape of sustainable construction materials and waste valorisation technologies.

In summary, this research seeks to bridge critical knowledge gaps surrounding PET-based composites by offering a comprehensive assessment of their mechanical strengths and highlighting pathways to enhance durability and applicability in green building contexts. The insights gained are anticipated to inform material optimisation strategies and promote the broader integration of recycled PET composites in construction, thereby supporting waste reduction and sustainable development objectives.

2. Materials and Methods

2.1 Materials

The raw materials used in producing the PET composite board include PET, SG, and sand, each contributing distinct functions to the final product, as shown in fig. 1. PET, a polymer obtained from discarded plastic bottles, is the composite material's binder. The bottles are collected from dustbins, thoroughly cleaned, and cut into pieces with a size range of 10 to 15 mm. SG, a by-product of industrial processes, has a particle size that passes through a 0.6 mm sieve. This material was sourced from Boustead Naval Shipyard Sdn Bhd, located in Lumut, Perak. SG acts as a filler, providing additional strength and structural integrity to the composite. Sand, passing through a 1.18 mm sieve, was sourced from the UTHM Advanced Materials Laboratory and functions as a filler. It contributes to the composite's texture and enhances its overall stability. Sourcing these materials from specific locations ensures consistency and quality in production [21], [22].

(a) **(b)** **(c)**

Fig. 1 *Raw materials (a) PET; (b) Spent Garnet; (c) Sand*

2.2 Design Mix Proportion

The table outlines the experimental mixtures used in a study that employs CCD under RSM. The study investigates three primary components: PET, SG, and sand, across thirteen distinct mixture runs (M1 to M13). CCD is a highly effective method for exploring the interaction effects between multiple variables, in this case, the proportions of PET, SG, and sand [23], [24]. Compared to conventional methods, CCD offers a more efficient approach by allowing the simultaneous evaluation of linear, quadratic, and interaction effects [23], [25]. This is accomplished with fewer experimental runs than would be required by a full factorial design, making the method both time- and resource-efficient.

Table 1 *Design mix proportion*

Mix	PET (%)	PET (kg)	SG (%)	SG (kg)	Sand (%)	Sand (kg)
M1	29.00	0.0217	0.00	0	71.00	0.0843
M2	23.50	0.0176	19.13	0.0227	57.38	0.0681
M3	34.50	0.0258	16.38	0.0194	49.13	0.0583
M4	40.00	0.0299	30.00	0.0356	30.00	0.0356
M5	29.00	0.0217	35.50	0.0421	35.50	0.0421
M6	29.00	0.0217	35.50	0.0421	35.50	0.0421
M7	29.00	0.0217	35.50	0.0421	35.50	0.0421
M8	29.00	0.0217	35.50	0.0421	35.50	0.0421
M9	29.00	0.0217	35.50	0.0421	35.50	0.0421
M10	18.00	0.0135	41.00	0.0486	41.00	0.0487
M11	34.50	0.0258	49.13	0.0582	16.38	0.0194
M12	23.50	0.0176	57.38	0.068	19.13	0.0227
M13	29.00	0.0217	71.00	0.0842	0.00	0

A key advantage of CCD is the inclusion of centre-point replicates, as seen in mixtures M9 to M13, which provide valuable information for estimating pure experimental error and ensuring the reproducibility of results [12]. This feature enhances the reliability and robustness of the findings, making the method particularly suitable for studies where precision and accuracy are paramount [26]. Overall, using CCD in this study strengthens the experimental design by providing a detailed and efficient means of exploring complex relationships between the selected materials [23]. The results of this study contribute to the development of robust statistical models capable of optimising mixture compositions, ultimately offering valuable insights into the material properties under investigation [26].

2.3 Sample Preparation

The manufacturing process of PET composite boards involves seven essential steps, as illustrated in fig. 2. The initial process begins with material preparation, ensuring all original materials achieve preferred dimensions to eliminate experimental measurement effects. PET bottles are cut into 10-15 mm pieces to create uniform mixing conditions during processing. The sand material and spent garnet undergo dry sieving, producing 1.18 mm and 0.6 mm sieved particle sizes, respectively.

The second essential operation involves accurately weighing all materials according to the designated mix proportions specified in table 1. Each component is measured precisely to maintain consistency across all samples. The weighed materials are then introduced into the mixing system, which heats materials to 250°C for 30 to 40 minutes to achieve comparable testing conditions for all samples. Gradual stirring of the mixture occurs during this period to attain homogeneous blending between components. The mould inside the compaction machine undergoes a 10-minute preheating process at 180°C to establish consistent moulding procedures.

Moulding the sample begins by pouring the blended mixture into the preheated casting mould for each test batch. The compression step at 180°C, over 10 minutes within the mould helps shape and create the desired item dimensions. After compression, the sample must rest at room temperature for at least twenty minutes before removing it from the mould. The samples prepared need a clean storage container to prevent damage before additional testing begins. This systematic method standardises all processes, producing dependable experimental findings with uniform sample preparation results.

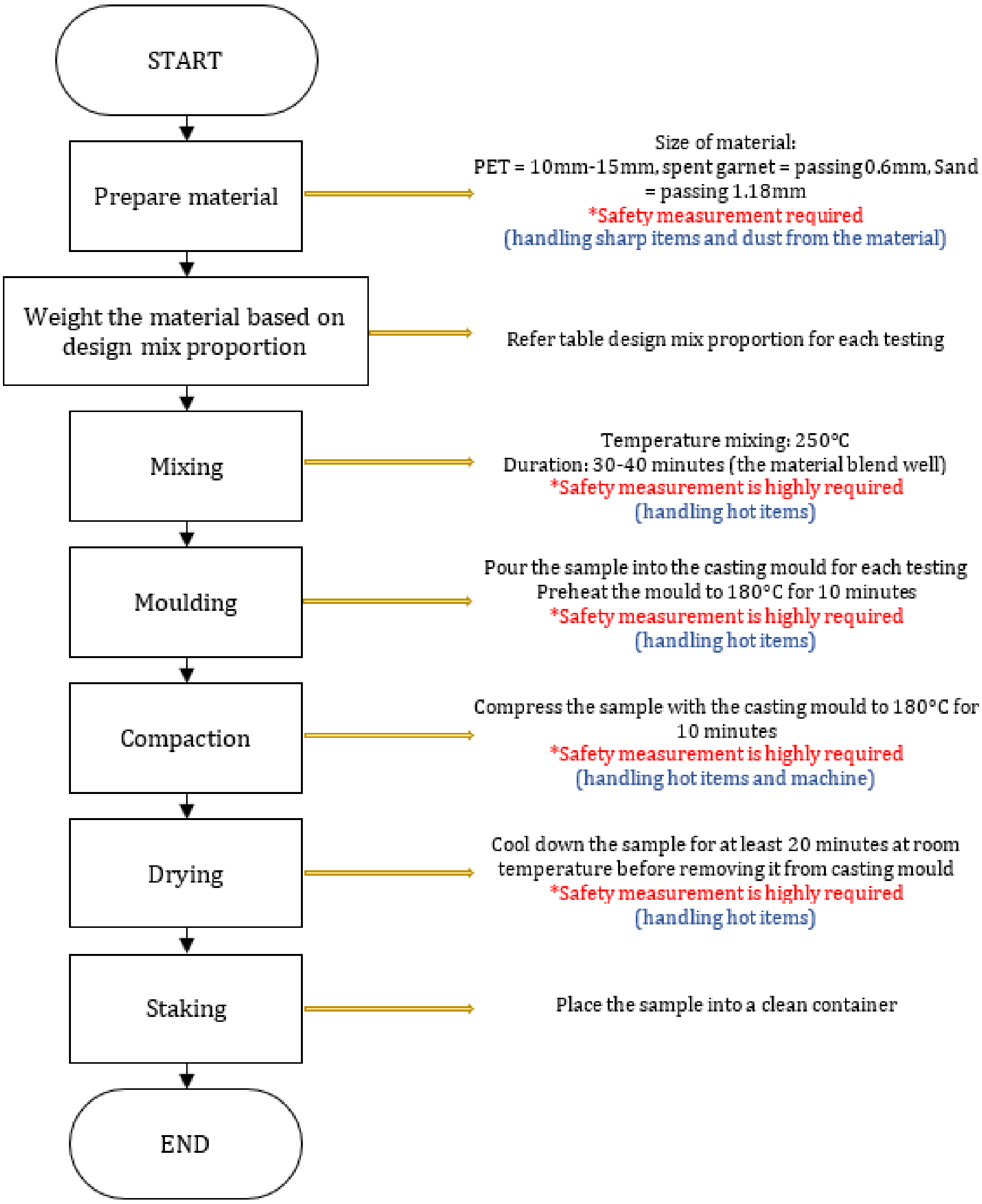

Fig. 2 *The processing of PET composite board*

2.4 Compressive Strength Testing

Following the approach detailed by ASTM D3410 [27], a compressive strength test was conducted on a PET composite board containing varying proportions of spent garnet. Three samples of each PET composite board mix were tested using the Universal Testing Machine (UTM INSTRON) to ascertain the average compressive strength, as shown in fig. 3(a). The sample size used for this testing is 140 mm x 25 mm x 10 mm. A formula can calculate the compressive strength of the PET composite board.

$$F_{cu} = \frac{P}{A} \tag{1}$$

Where:
F_{cu} is the compressive strength (N/mm^2)
P is the ultimate compressive load (N)
A is the surface area in contact with the plates (mm^2)

2.5 Tensile Strength Testing

The 250 mm x 25 mm x 10 mm test samples were placed in the grips of a mechanical testing apparatus and put under tension while the load was being recorded. The material's ultimate strength was calculated using the maximum load handled before failure. Three samples of each PET composite board mix were tested on a Universal Testing Machine (UTM INSTRON) as shown in fig. 3(b) to determine the average tensile strength. The tensile strength was estimated using the required equation in ASTM D3039 [28].

$$F_{tu} = \frac{P}{A} \tag{2}$$

Where:
F_{tu} is the tensile strength (N/mm^2)
P is the ultimate compressive load (N)
A is the surface area in contact with the plates (mm^2)

(a) **(b)**

Fig. 3 *Universal Testing Machine (UTM INSTRON) (a) Compressive strength testing; (b) Tensile strength testing*

3. Results and Discussion

3.1 Physical Properties

The tabulated parameters of the raw materials used in producing PET composite boards, namely PET, spent garnet, and sand, offer critical insight into their influence on compressive strength are presented in table 2. Density and specific gravity are particularly important physical properties in this context, as they directly affect the composite matrix's packing density and interfacial bonding [18], [29]. PET, with a density of 1426 kg/m^3 and specific gravity of 1.426, is considerably lighter than spent garnet (2258 kg/m^3; 2.258) and sand (2261 kg/m^3; 2.261). As a low-density thermoplastic polymer, PET serves primarily as a binder, while the denser spent garnet and sand function as fillers to enhance mechanical performance [30], [31].

The density and particle size contrast between PET (10–15 mm) and the fillers (spent garnet passing 0.6 mm; sand passing 1.18 mm) plays a significant role in achieving optimal compaction and stress transfer within the composite. Previous studies, such as those by Huseien *et al.* (2019) and Muttashar *et al.* (2017) have highlighted that finer filler materials like spent garnet, due to their angularity and high specific gravity, facilitate better interlocking and packing, which in turn contributes to higher compressive strength [17], [18]. Sand, with slightly coarser grading than garnet, complements this by filling voids and enhancing matrix uniformity. When optimally proportioned with PET, these combinations improve the load-bearing capacity of the composite by promoting densification and minimising porosity [11].

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 (°C)	220	-	-
Size (mm)	10-15	0.6	1.18

Moreover, the melting point of PET (approximately 220°C) indicates its thermal stability during composite processing, ensuring it can effectively coat and bind the finer filler particles without premature degradation. This thermal compatibility enhances adhesion and contributes to a more homogenous composite structure, essential for maximising compressive strength. Aneke *et al.* (2021) also demonstrated that PET-based composites exhibited superior compressive strength when appropriate binder-to-filler ratios and particle gradations were maintained [11]. Therefore, the synergistic use of lightweight PET and dense fillers like spent garnet and sand, as reflected in their physical parameters, plays a crucial role in enhancing the compressive strength of the composite board [32], [33].

3.2 Properties of PET Composite Board

The compressive strength results of the PET composite board, as shown in fig. 4, highlight significant variation across the 13 different mixes. The compressive strength of the composite material ranged from 4.5 MPa to 16.5 MPa. Mixes 12 and 13 exhibited the highest compressive strengths, approaching 16.5 MPa, while Mix 1 demonstrated the lowest strength, around 4.5 MPa. This variation strongly suggests that the binder-to-filler ratio plays a crucial role in determining the structural integrity of the composite.

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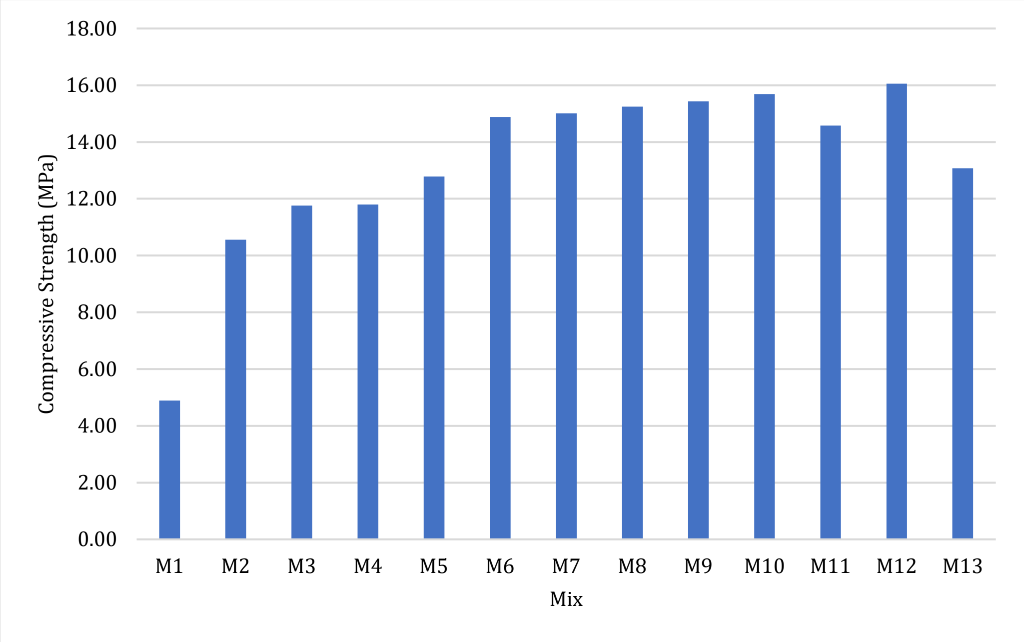

Fig. 4 *Compressive strength of PET composite board*

In line with prior research, including post-consumer PET as a binder enhances the compressive strength of composite materials [34]. As observed, the increases in PET content relative to the filler material, particularly spent garnet and sand, appear to elevate the compressive strength. Specifically, mixes 12 and 13, which contained higher PET content, show a clear improvement in compressive strength. This observation is consistent with studies that reported that an increased binder ratio leads to a denser and more cohesive composite structure, improving its ability to withstand compressive forces [35], [36].

It is important to note that the higher compressive strength in Mixes 12 and 13, which involved elevated PET content, contrasts with the findings in Mix 1, where an excess of filler materials, such as sand and garnet, reduced strength. This trend echoes the findings, which argued that while high binder content can enhance the material's compressive strength, excessive filler materials may reduce cohesion, thus weakening the composite [37]. Additionally, this trend suggests an optimal binder-to-filler ratio, where the material’s performance is maximised.

The tensile strength values, depicted in fig. 5, demonstrate a different trend compared to compressive strength. Tensile strength values ranged from 2.63 MPa to 8.58 MPa, with Mix 12 again achieving the highest value of approximately 8.58 MPa. Mix 1, which had the lowest compressive strength, demonstrated the lowest tensile strength. This suggests a complex relationship between the binder-to-filler ratio and the material's mechanical properties, where the addition of PET as a binder positively impacts tensile performance, although to a lesser degree than its impact on compressive strength.

These results confirm that polymer-based composite materials typically show stronger compressive performance than tensile [34]. This observation highlights the different mechanical mechanisms underlying these two properties. Compressive strength is more directly influenced by the material’s bulk density and cohesion. In contrast, tensile strength depends on the material’s ability to resist elongation, which is often more sensitive to the arrangement and bonding of the fillers.

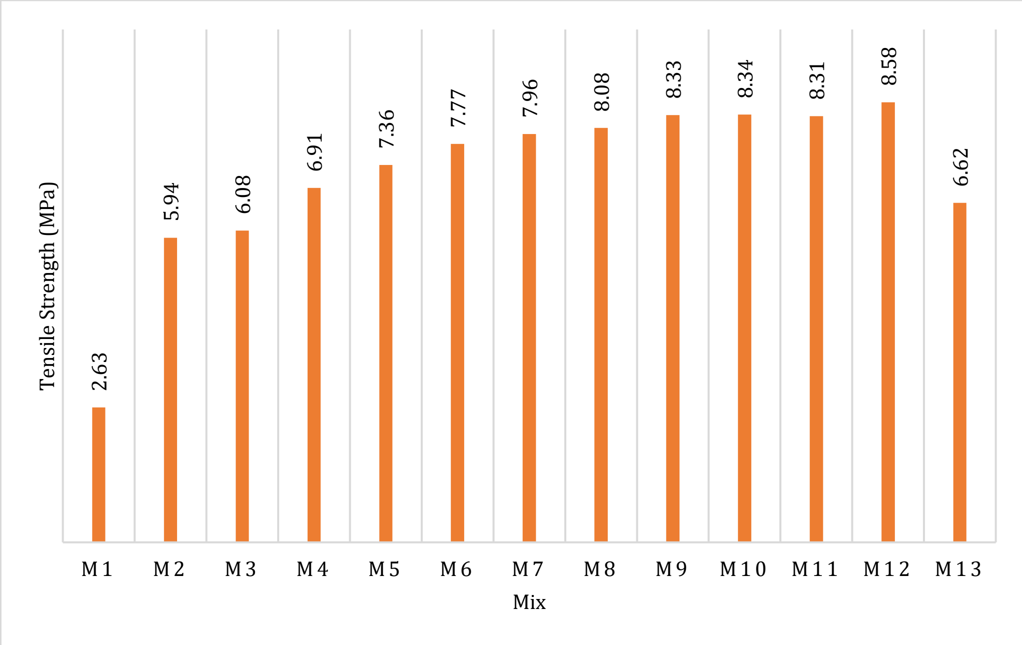

Fig. 5 *Tensile strength of PET composite board*

Compared to other commercial composite materials, the generally lower tensile strength in the PET composite boards can be explained by the material's inherent composition and the specific arrangement of the filler materials. Polymer composites may exhibit inferior tensile properties compared to materials such as fibre-reinforced plastics, which offer superior tensile performance due to the alignment and bonding of reinforcing fibres [37].

Comparing fig. 4 and fig. 5 reveals an interesting inverse relationship between compressive and tensile strengths in the PET composite boards. While the compressive strength generally improves with an increase in binder content, the tensile strength does not follow the same pattern. The positive correlation between binder content and compressive strength suggests that increasing PET content leads to improved resistance to axial load, enhancing the material's capacity for compressive stress. However, the tensile strength is more sensitive to the microstructure of the composite, particularly the distribution and interaction of fillers, suggesting that excessive binder material may reduce the composite's ability to resist stretching.

The results from this study are consistent with those of previous research on polymer-based composites, which have identified the optimal balance between binder and filler material as a critical factor in determining the mechanical properties of composites [12]. The role of PET as a binder in this study and the varying influence of filler types (spent garnet and sand) suggest that careful optimisation of these material proportions is essential to achieve the desired mechanical performance. The performance of the composite materials in tensile testing, while lower than in compressive strength testing, still demonstrates potential for non-structural applications in the construction industry, where the composite material may be used in panels or other applications where tensile stress is less of a concern.

In conclusion, the compressive and tensile strength results underscore the importance of a balanced binder-to-filler ratio in developing PET composite materials. While the material shows promise for non-structural applications, further optimisation and exploration of reinforcement strategies are necessary to enhance its tensile performance and overall mechanical properties. The findings of this study align with the ongoing search for sustainable, waste-derived materials in construction. However, they also highlight the need for more in-depth investigations into long-term durability and environmental performance under varied conditions.

3.3 ANOVA Analysis

The results presented in table 3 offer an in-depth statistical analysis of the compressive strength of PET composite boards, focusing on the influence of different factors and their interactions. The analysis uses the commonly employed analysis of variance (ANOVA) technique to assess the effect of the binder-to-filler ratio (A-B-F), filler composition (B-SG-Sand), and their interactions on compressive strength. The model demonstrates high statistical significance, as indicated by the p-value of less than 0.0001, confirming that the model effectively captures the key variables influencing the compressive strength of the composite material.

From the data, the individual contributions of the factors are notable. The binder-to-filler ratio (A-B-F) significantly affects the compressive strength, with a p-value of 0.0838 and an F-value of 3.90. While this suggests a moderately significant relationship, the proportion of spent garnet and sand (B-SG-Sand) has the most substantial impact, as evidenced by an F-value of 478.39 and a highly significant p-value of less than 0.0001. These results underscore the importance of filler content in determining the strength of PET composite materials. Previous studies have similarly noted the significant role of fillers in enhancing compressive properties, where the inclusion of inert fillers improved the load-bearing capacity of polymer composites [34].

The interaction term between binder and filler ratio (AB) also significantly affects compressive strength, with an F-value of 16.78 and a p-value of 0.0046. This suggests that the binder and filler content relationship is crucial in determining the material's compressive properties. The squared terms (A^2 and B^2) further highlight the complexity of the relationship, with both showing highly significant effects (p-values less than 0.0001). The observed non-linear effects indicate that while increasing the binder and filler content can improve compressive strength, there is a diminishing return as these components increase beyond an optimal level, aligning with findings in the literature [33].

Regarding fit statistics, the model's R^2 value of 0.9933 and the adjusted R^2 value of 0.9886 suggest that the model explains over 99% of the variability in compressive strength, making it highly reliable for predicting material performance. The coefficient of variation (C.V.%) of 2.47% also indicates a low level of variability in the data, further validating the robustness of the model.

In conclusion, the ANOVA analysis of compressive strength confirms that the binder-to-filler ratio and the filler composition are critical factors in determining the material's mechanical properties. The high significance of the filler composition and the interaction terms suggests that careful optimisation of these components is essential to achieve the desired compressive strength. Further research could focus on refining the mix ratios to enhance the material's performance in construction applications.

Table 3 *ANOVA analysis of compressive strength for PET composite board*

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	111.01	5	22.20	209.07	< 0.0001	significant
A-B-F	0.4144	1	0.4144	3.90	0.0888	
B-SG-Sand	50.80	1	50.80	478.39	< 0.0001	
AB	1.78	1	1.78	16.78	0.0046	
A^2	12.39	1	12.39	116.71	< 0.0001	
B^2	55.88	1	55.88	526.28	< 0.0001	
Residual	0.7433	7	0.1062			
Lack of Fit	0.3228	3	0.1076	1.02	0.4709	not significant
Pure Error	0.4205	4	0.1051			
Cor Total	111.75	12				
			Fit Statistics			
Std. Dev.	0.3259		**R^2**	0.9933		
Mean	13.21		**Adjusted R^2**	0.9886		
C.V. %	2.47		**Predicted R^2**	0.9722		
			Adeq Precision	49.5772		

Table 4 presents the results of the ANOVA analysis for tensile strength, providing insights into how different factors influence the material's resistance to tensile forces. Like compressive strength analysis, the model for tensile strength shows high statistical significance, with a p-value of less than 0.0001. The findings suggest that the factors considered in the study, namely the binder-to-filler ratio (A-B-F) and filler composition (B-SG-Sand), play a significant role in determining the tensile strength of the PET composite boards.

The filler composition (B-SG-Sand) is the most influential factor for tensile strength, with an F-value of 556.12 and a highly significant p-value of less than 0.0001. This highlights the critical role of the type and proportion of fillers in enhancing the material's ability to resist stretching and elongation. However, unlike the compressive strength analysis, the binder-to-filler ratio (A-B-F) does not exhibit as strong an influence on tensile strength, as evidenced by an F-value of 4.74 and a p-value of 0.0659, which is not significant at the conventional 0.05 level. This indicates that the tensile properties of the composite material are less sensitive to variations in the binder-to-filler ratio. This finding contrasts with the results for compressive strength. This may be since tensile strength is typically governed by the distribution and bonding of the filler materials rather than the binder content [37].

Table 4 *ANOVA analysis of tensile strength for PET composite board*

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0017	5	0.0003	134.15	< 0.0001	significant
A-B-F	0.0000	1	0.0000	4.74	0.0659	
B-SG-Sand	0.0014	1	0.0014	556.12	< 0.0001	
AB	1.000E-06	1	1.000E-06	0.3949	0.5497	
A^2	0.0000	1	0.0000	16.10	0.0051	
B^2	0.0003	1	0.0003	108.26	< 0.0001	
Residual	0.0000	7	2.532E-06			
Lack of Fit	2.927E-06	3	9.757E-07	0.2637	0.8489	not significant
Pure Error	0.0000	4	3.700E-06			
Cor Total	0.0017	12				
			Fit Statistics			
Std. Dev.	0.0016		**R^2**	0.9897	**Std. Dev.**	0.0016
Mean	0.0458		**Adjusted R^2**	0.9823	**Mean**	0.0458
C.V. %	3.48		**Predicted R^2**	0.9715	**C.V. %**	3.48
			Adeq Precision	40.0820		

The interaction term (AB) for tensile strength is statistically insignificant, with a p-value of 0.5497, indicating that the combined effect of binder and filler on tensile strength is minimal. This suggests that, unlike compressive strength, the tensile properties of PET composite boards are primarily influenced by the individual components, particularly the filler composition, rather than their interaction. The squared terms for binder-to-filler ratio (A^2) and filler composition (B^2) exhibit significant effects (p-values less than 0.05), indicating that, as with compressive strength, there are non-linear relationships at play. These effects suggest that excessively high levels of binder or filler content may lead to suboptimal tensile properties, as observed in other polymer composites [1], [38], [39].

The model's fit statistics for tensile strength show an R^2 value of 0.9897 and an adjusted R^2 value of 0.9823, indicating that the model explains approximately 99% of the variability in tensile strength. This high level of explanatory power, coupled with a low C.V. % of 3.48%, suggests that the model is robust and reliable in predicting the material's tensile performance. The relatively low residual sum of squares (2.927e-06) further indicates a strong fit, reinforcing the model's validity.

In conclusion, the ANOVA analysis of tensile strength confirms that filler composition is dominant in determining the material's tensile performance. At the same time, the binder-to-filler ratio has a lesser influence. The non-significance of the interaction terms and the non-linear effects observed for both factors suggest that further optimisation of the material composition is necessary to improve tensile properties. Future studies could explore alternative filler combinations or the incorporation of fibre reinforcements to enhance the material's tensile strength and broaden its applicability in construction.

3.4 Diagnostics Plot

The normal plot of compressive strength, as shown in fig. 6(a), is essential in assessing the distribution of residuals for the data. The data points along the diagonal line indicate that the residuals follow a normal distribution, confirming that the assumptions of normality required for ANOVA and regression modelling are satisfied. This is a critical diagnostic check, as the validity of inferential statistics relies on the normality assumption [40]. The data's normality is in line with the significant results obtained in the ANOVA table, which showed that the compressive strength model was highly significant (p < 0.0001). This suggests that the linear regression model used in this analysis is both reliable and robust, and the results obtained can be trusted for making inferences about the material's performance under compression.

In fig 6(b), the predicted versus actual plot for compressive strength further supports the robustness of the regression model. The scatter of points around the red line (representing perfect predictions) shows a high degree of alignment, indicating that the predicted values are close to the experimental results. The lack of substantial deviation between the actual and predicted values highlights that the model is well-calibrated, with the predictor variables (binder-to-filler ratio and filler composition) accurately explaining the variation in compressive strength. This is consistent with the high R^2 value (0.9933) and adjusted R^2 value (0.9886) reported in the ANOVA table, further validating the accuracy and effectiveness of the model in predicting the material's compressive strength.

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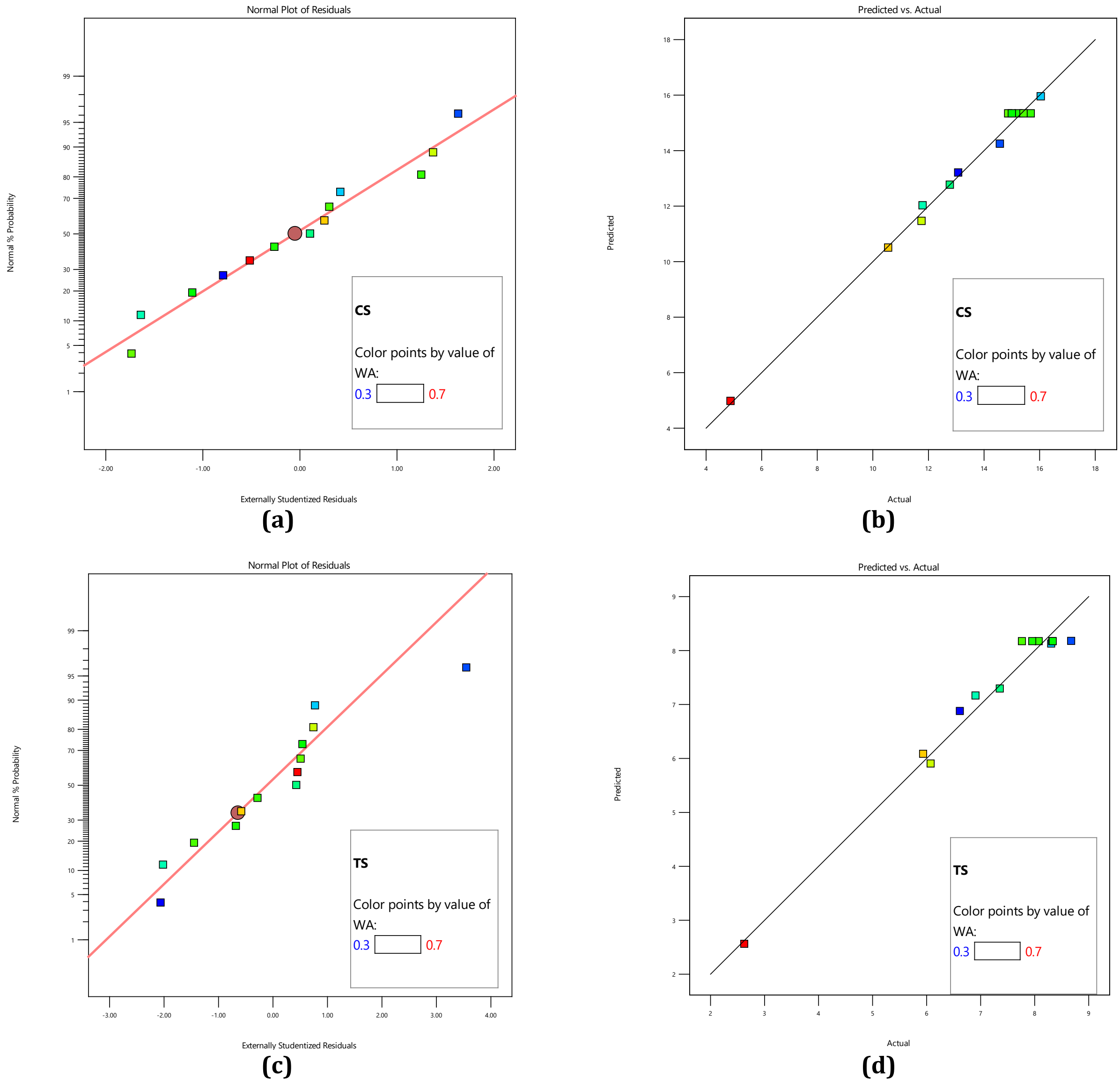

Fig. 6 *Diagnostics plot of PET composite board (a) Normal plot of CS; (b) Predicted vs actual of CS; (c) Normal plot of TS; (d) Predicted vs actual of TS*

Similar to the compressive strength data, the normal plot for tensile strength fig. 6(c) suggests that the residuals follow a normal distribution, confirming the validity of the assumptions underpinning the tensile strength regression analysis. The alignment of the data points along the diagonal further suggests that the residuals are symmetrically distributed around the mean, which is a positive indicator of the model's predictive capability. The fact that the residuals are normally distributed in compressive and tensile strength analyses ensures that the model's statistical tests are valid and reliable, making it possible to generalise the results of this study to a wider population of PET composite materials.

The predicted versus actual plot for tensile strength fig. 6(d) shows a similar trend to the compressive strength plot, with most of the points clustered around the red line, indicating that the predicted tensile strength closely matches the experimental data. However, a slight deviation was observed in some of the data points, which could indicate minor inconsistencies in the model's predictions for tensile strength. Despite these slight deviations, the overall alignment between predicted and actual values suggests that the model is generally reliable, consistent with the R^2 value (0.9897) and adjusted R^2 value (0.9823) from the ANOVA table. These high values suggest that the model explains a large portion of the variation in tensile strength, thus providing a sound basis for analysing the material's performance under tensile loads.

The contour plot in fig. 7(a) illustrates the relationship between the binder-to-filler ratio (Factor A) and the sand-to-spent garnet ratio (Factor B) in determining the compressive strength of PET composite boards. The plot clearly shows that higher values of both factors lead to an increase in compressive strength, with the highest values observed at the peak of the contour. This aligns with the regression and ANOVA results, where the interaction between the binder-to-filler ratio and filler composition significantly affected compressive strength. The contour plot provides a clear visual representation of the material's behaviour, demonstrating that optimal ratios of binder and filler result in maximum compressive strength, further reinforcing the critical role of these two factors in composite board performance.

The contour plot for tensile strength, fig. 7(b), shows a different pattern from compressive strength. Here, the tensile strength decreases as the binder-to-filler ratio increases, particularly at higher levels of the binder content. This inverse relationship suggests that increasing the binder content enhances the material's compressive strength and may reduce its ability to resist tensile stresses. This result aligns with previous studies indicating that polymer composites often exhibit trade-offs between compressive and tensile strengths, with binder content playing a key role in both properties [34]. The optimal mixture of fillers (sand and spent garnet) is also evident in this plot, where the sand content influences tensile strength more significantly than compressive strength.

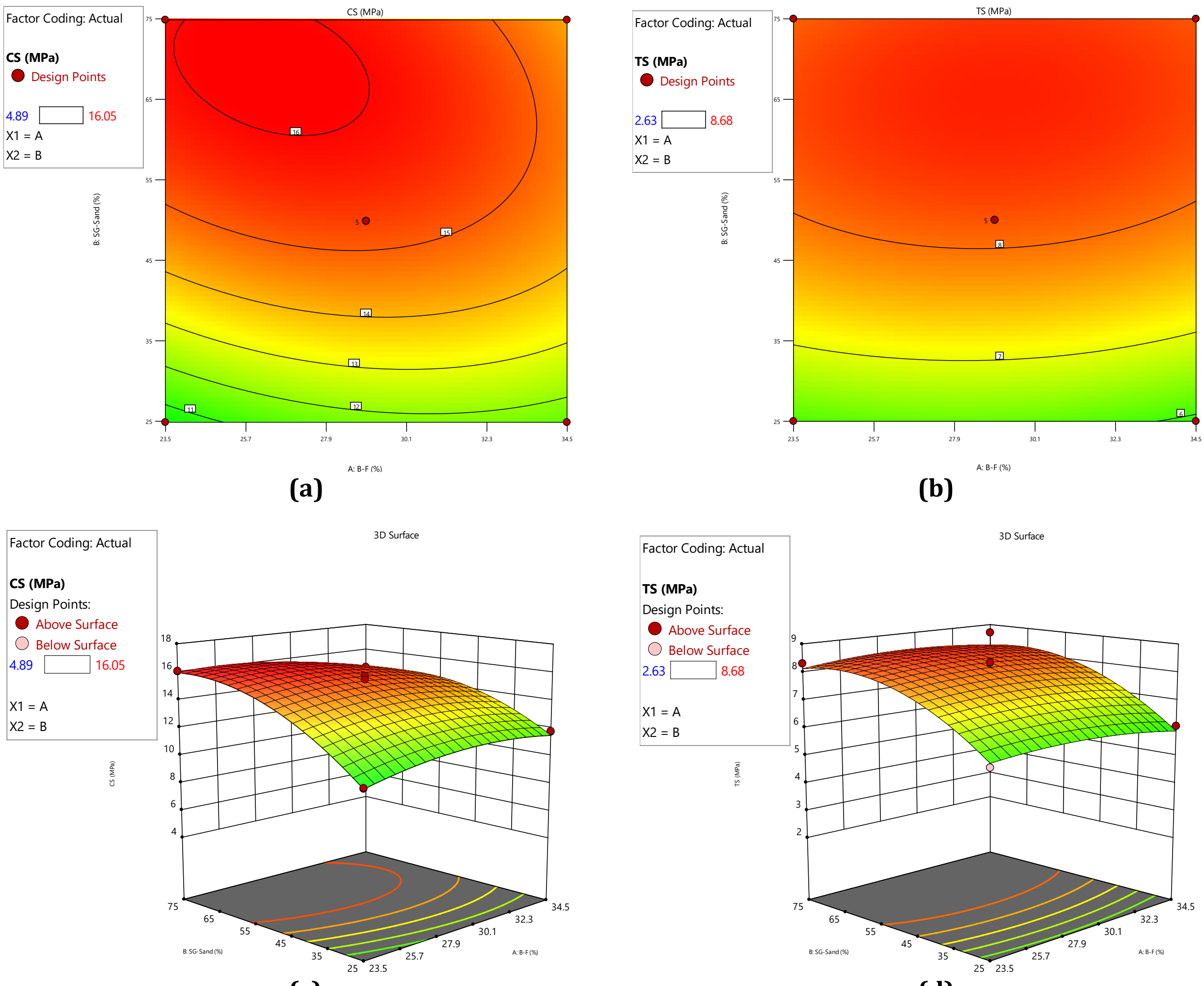

Fig. 7 *Graphical plot of PET composite board (a) Contour plot of CS; (b) Contour plot of TS; (c) 3D surface of CS; (d) 3D surface of TS*

Fig. 7(c) provides a three-dimensional surface plot of compressive strength, further illustrating the relationship between the binder-to-filler ratio and the sand-to-spent garnet ratio. The 3D surface shows that increasing both factors leads to a peak in compressive strength, confirming the contour plot and regression analysis findings. The surface plot offers a more detailed view, showing that the highest compressive strength occurs when the binder content and the proportion of spent garnet are at their maximum. This reinforces the idea that a balanced composition of binder and filler is essential to achieving optimal mechanical properties in the composite material.

The 3D surface plot for tensile strength fig. 7(d) highlights the non-linear relationship between the binder-to-filler ratio and the sand-to-spent garnet ratio, where tensile strength peaks at lower binder content and higher sand content. This reinforces the conclusion drawn from the contour plot, suggesting that excessive binder content may hinder the material's ability to resist tensile stresses. The surface plot adds depth to the analysis by visually demonstrating how material composition variations can influence the composite board's tensile

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performance. This is crucial for understanding how to optimise PET composite boards for specific applications with critical tensile strength.

The diagnostics plots presented here, including normal plots, predicted vs. actual plots, and contour and 3D surface plots, all provide valuable insights into the mechanical behaviour of PET composite boards. The consistency across these diagnostics confirms that the regression models for both compressive and tensile strengths are statistically reliable and well-calibrated. The findings from the ANOVA and regression analyses are visually supported by the diagnostic plots, which reveal the complex interactions between the binder-to-filler ratio and filler composition. These results provide a comprehensive understanding of the factors influencing the performance of PET composite boards, highlighting the potential for optimising their mechanical properties for construction applications. Future studies may build upon these findings by exploring the environmental durability of these composites and the potential for incorporating fibre reinforcement to improve tensile properties.

3.5 Regression Model

The regression models for compressive strength (CS) and tensile strength (TS) provide critical insight into the relationship between the material's composition and mechanical properties. These models help quantify the influence of the binder-to-filler ratio (A) and the sand-to-spent garnet ratio (B) on the material's performance. The regression model for compressive strength is given by:

$$CS = -21.53509 + 1.61906A + 0.472954B - 0.004855AB - 0.024312A^2 - 0.002499B^2 \quad (3)$$

This equation models the compressive strength (CS) of PET composite boards based on two primary factors: the binder-to-filler ratio (A) and the sand-to-spent garnet ratio (B). The positive coefficients for both A and B suggest that increasing the binder content (PET) and the amount of spent garnet relative to sand contribute to enhanced compressive strength. In particular, the binder-to-filler ratio (A) has a stronger effect on compressive strength than the sand-to-spent garnet ratio (B, coefficient = 0.472954), as evidenced by the higher coefficient (1.61906 for A versus 0.472954 for B).

The negative quadratic terms (A^2 and B^2) indicate diminishing returns, meaning that further increases in either the binder or the filler content may lead to less efficient packing or potentially detrimental effects on compressive strength. This observation is consistent with existing literature that suggests an optimal balance between binder and filler for maximum material performance. The negative interaction term (AB)indicates that when both factors are increased together, their combined effect slightly reduces compressive strength, suggesting that the ideal mixture may require careful optimisation of both parameters to avoid the negative interactions between them.

The model provides a robust mathematical framework for understanding how the binder-to-filler ratio and filler composition affect compressive strength, with a high R^2 value (0.9933) and an adjusted R^2 value (0.9886), indicating that over 99% of the variability in compressive strength is explained by the model. These results are consistent with previous studies on polymer-based composites, where material strength was shown to be highly influenced by the binder content. The regression model for tensile strength is expressed as:

$$TS = -3.21696 + 0.425083A + 0.169150B + 0.000418AB - 0.007791A^2 - 0.001381B^2 \quad (4)$$

This equation describes the tensile strength (TS) of PET composite boards, considering the same two factors: the binder-to-filler ratio (A) and the sand-to-spent garnet ratio (B). Like the compressive strength model, the positive coefficients for A and B suggest that increased binder content and spent garnet proportion positively contribute to tensile strength. However, the coefficients for A (0.425083) and B (0.169150) are lower than the compressive strength model, suggesting that the binder content has a less significant impact on tensile strength than on compressive strength. This aligns with the observation that tensile strength is generally more sensitive to the distribution and alignment of fillers within the composite matrix than the binder content.

The negative quadratic terms for A2 and B2 indicate that further increases in the binder or the filler may reduce tensile strength. This suggests a need to carefully balance the material's composition to avoid excessive binder content, which could lead to brittleness, as seen in other studies on polymer composites. The small positive interaction term (AB) indicates a slight synergy between the binder and filler components, where an optimal combination of these two factors may lead to marginal improvements in tensile strength.

The regression model for tensile strength also has a high R^2 value (0.9897) and adjusted R^2 value (0.9823), indicating that the model explains nearly 99% of the variation in tensile strength. The robust nature of the model is further validated by its predictive capability, as evidenced by the low standard deviation (0.0016) and coefficient of variation (C.V. = 3.48%), which suggests that the model provides consistent and reliable predictions for tensile strength across the experimental conditions.

The regression models for compressive and tensile strengths highlight the critical role of the binder-to-filler ratio and the sand-to-spent garnet ratio in determining the mechanical performance of PET composite boards. These models are highly significant, with the ANOVA results confirming the importance of these factors in influencing the material properties (tables 3 and 4). The findings are consistent with previous studies that have emphasised the need to carefully optimise binder-to-filler ratios to achieve desirable mechanical properties in composite materials [12].

While the compressive strength is more sensitive to changes in binder content and filler composition, the tensile strength relies more on the distribution of fillers, particularly the proportion of sand relative to spent garnet. This inverse relationship between compressive and tensile strengths is a typical characteristic of polymer-based composite materials, where the matrix's ability to resist axial loads is often more easily controlled than its ability to resist stretching or elongation. These findings support the notion that PET composites can be optimised for specific applications, depending on whether compressive or tensile strength is prioritised.

The non-linear relationships observed in the regression models suggest an optimal range for the binder content and filler proportions, beyond which the material properties may deteriorate. This highlights the importance of material design and suggests that future work should further explore the impact of other processing factors, such as curing time and temperature, to optimize PET composite boards' mechanical properties.

The regression models developed for compressive and tensile strengths of PET composite boards offer valuable insights into the material's behaviour under different compositional conditions. These models provide a strong foundation for understanding how variations in the binder-to-filler ratio and filler composition affect the mechanical properties of the composite material. While both models are highly significant and explain a large proportion of the variability in the data, further optimisation of the material's composition is necessary to achieve the desired balance of strength and flexibility. Future research should prioritise refining material formulations and evaluating the incorporation of fibre reinforcement to enhance tensile properties, making PET composite boards a more viable option for sustainable construction applications.

3.6 Application in Green Building

The experimental results of this study demonstrate the considerable potential of PET composite boards as sustainable alternatives for non-structural applications within the green building sector. The mechanical performance characterised by compressive strengths ranging from 4.5 MPa to 16.5 MPa and tensile strengths between 2.63 MPa and 8.58 MPa suggests that optimised PET composites can fulfil the mechanical demands required for applications such as wall panels, insulation boards, and ceiling tiles, where high tensile load-bearing capacity is less critical [11], [12]. Notably, the highest compressive strength values achieved by mixes with elevated PET binder content and spent garnet fillers align with previous studies emphasising the importance of matrix cohesion and filler interlocking in enhancing load resistance [17], [18]. These characteristic positions PET composites favourably for roles that require resistance to compressive stresses and dimensional stability [41].

From an environmental perspective, incorporating recycled PET into composite boards contributes to significant waste diversion from landfills and reduces reliance on virgin materials with inherently high embodied carbon footprints, such as concrete and steel [11]. The utilisation of industrial by-products like spent garnet further reinforces circular economy principles by valorising secondary raw materials, thereby fostering resource efficiency and reducing extraction pressures on natural resources [12]. These advantages are paramount in green building practices, which prioritise sustainability, waste minimisation, and carbon footprint reduction [9].

However, the comparatively lower tensile strength observed in PET composites particularly in formulations with higher filler content indicates a limitation for structural applications where tensile loads are predominant [42]. This tensile performance gap, which is consistent with the known behaviour of polymer-based composites, underscores the necessity for supplementary reinforcement strategies, such as fibre incorporation or hybrid composite designs, to broaden the applicability of PET boards within building envelopes that may experience multidirectional stresses [43]. Additionally, tensile strength sensitivity to filler distribution highlights the critical role of microstructural control in manufacturing processes, necessitating further research into optimised processing parameters to enhance matrix-filler adhesion [44].

Beyond mechanical properties, the sustainability credentials of PET composite boards extend to their potential thermal and insulation capabilities [45]. Although not the primary focus of the present study, the physical characteristics of PET and associated fillers, combined with their low thermal conductivity relative to conventional materials, suggest that these composites could contribute to improved building energy efficiency by providing enhanced thermal insulation, a core objective of green building design. The relatively low density of PET composites also offers benefits in reducing the overall mass of building components, which can translate into decreased transportation emissions and ease of installation [46].

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Nonetheless, successful integration of PET composites in green building applications mandates rigorous evaluation of long-term durability under environmental stressors, including moisture ingress, ultraviolet radiation, and temperature fluctuations [20]. Current findings and prior literature reveal gaps in understanding how these factors influence composite longevity, particularly with respect to degradation mechanisms and material performance retention [11]. Therefore, while PET composites exhibit promising mechanical and environmental profiles, their durability performance must be comprehensively characterised to assure compliance with building codes and standards, thereby facilitating market acceptance.

In conclusion, the study's findings substantiate the feasibility of PET composite boards as sustainable, eco-friendly materials suitable for green building applications that demand moderate mechanical performance and enhanced environmental credentials. The demonstrated ability to tailor mechanical properties through binder and filler composition optimisation provides a pathway for developing bespoke materials aligned with specific functional requirements. Future research should prioritise advancing composite formulations with enhanced tensile properties and conducting comprehensive lifecycle assessments to validate environmental benefits. This approach will ensure that PET composites not only meet performance expectations but also contribute meaningfully to the advancement of sustainable construction and circular economy objectives.

3.7 Comparative Analysis

The mechanical performance of PET composite boards, as revealed by this study, positions them as a competitive alternative to conventional building materials such as wood-based panels, medium-density fibreboard (MDF), and polyvinyl chloride (PVC) composites. The compressive strength range of 4.5 to 16.5 MPa for PET composites aligns with the lower to mid-range values reported for wood-based materials, indicating suitability for non-structural applications like wall panels and insulation boards [11], [12]. This performance is particularly notable considering the environmental benefits associated with using recycled PET, contrasting with the resource-intensive production of traditional materials.

Compared to PVC composites, which often provide higher tensile strengths and excellent moisture resistance, PET composites currently exhibit lower tensile performance, as demonstrated in this study with values ranging from 2.63 to 8.58 MPa. This discrepancy can largely be attributed to the microstructural challenges associated with filler dispersion and binder-filler interfacial bonding, especially given the irregular shape of spent garnet particles used as fillers [18], [47]. While PET composites show promising compressive characteristics, their tensile limitations indicate the need for further reinforcement strategies, such as fibre incorporation, to match or surpass PVC's mechanical and durability properties.

Economically, PET composite boards offer distinct advantages due to their utilisation of post-consumer waste, potentially lowering raw material costs and supporting circular economy principles. The diversion of PET from landfills and oceans not only mitigates environmental pollution but also reduces dependence on virgin raw materials with high embodied energy, such as timber and petrochemical-derived polymers [2].However, scaling production while maintaining consistent quality remains a critical challenge that influences cost-effectiveness and market competitiveness.

Lifecycle assessments comparing PET composites to traditional materials underscore their lower carbon footprint and energy consumption during manufacture, reinforcing their appeal within green building frameworks [11]. Nonetheless, uncertainties persist regarding their long-term performance and recyclability at end-of-life, areas where established materials currently have clearer pathways and regulatory frameworks. Thus, comprehensive environmental and economic evaluations integrating durability and circularity metrics are necessary to substantiate PET composites' advantages over incumbent materials.

In summary, PET composite boards represent a viable and sustainable alternative to several conventional building materials, especially where compressive strength is prioritized. Their adoption will benefit from targeted material optimisation to improve tensile properties and long-term durability, alongside addressing manufacturing scalability. By bridging the gap between performance and sustainability, PET composites have the potential to contribute significantly to green construction practices, provided ongoing research and policy support facilitate their integration into mainstream building applications.

3.8 Challenges and Limitations

Despite the promising mechanical performance demonstrated by PET composite boards, several challenges constrain their widespread adoption in construction applications. A primary limitation is the relatively low tensile strength compared to compressive strength, which restricts the use of these composites to non-structural elements unless reinforced by fibres or alternative materials. The irregular particle morphology of fillers such as spent garnet can impair binder-filler adhesion, leading to microstructural weaknesses under tensile loading. This inherent trade-off between compressive strength and tensile flexibility underscores the complexity of optimising polymer composite formulations for balanced mechanical properties [12], [18].

Durability concerns present another critical limitation. PET composites' long-term resistance to environmental stressors such as moisture, ultraviolet radiation, and thermal cycling remains inadequately characterised. These factors can induce material degradation, embrittlement, or delamination over time, thereby compromising performance and safety in real-world settings. The paucity of accelerated ageing and field exposure studies limits confidence in their service life predictions, which is essential for building regulatory approval and industry acceptance [11], [43]. Addressing durability through protective coatings, stabilisers, or improved matrix-filler interfaces is a necessary avenue for future research.

From a processing perspective, the variability inherent in recycled PET feedstock poses challenges for maintaining consistent composite quality at scale [48]. Variations in contamination levels, molecular weight distribution, and prior thermal history can affect melt flow properties and binder performance during fabrication, potentially resulting in heterogeneous mechanical behaviour [48]. Additionally, the optimisation of compounding parameters such as temperature, mixing duration, and pressure requires careful control to ensure uniform dispersion of fillers and reproducible properties, complicating large-scale manufacturing efforts.

Finally, market acceptance and regulatory compliance remain significant hurdles. Although the environmental benefits of PET composites are clear, building codes and certification standards are still evolving to accommodate recycled polymer materials [13], [49]. The construction industry's inherent conservatism, driven by safety concerns and liability risks, necessitates rigorous testing protocols and long-term validation data to build stakeholder confidence. Furthermore, cost competitiveness with established materials such as wood, MDF, and PVC composites must be demonstrated to incentivise adoption [50]. Collaborative efforts among researchers, industry, and policymakers are essential to overcome these multifaceted challenges and realise the potential of PET composite boards in sustainable construction.

4. Conclusion

This study comprehensively evaluated the mechanical performance of PET composite boards synthesised from post-consumer PET waste combined with spent garnet and sand fillers. The experimental results indicated that the binder-to-filler ratio and filler composition substantially influence both compressive and tensile strengths. Compressive strength exhibited a positive correlation with increasing PET binder content and spent garnet proportion, achieving values up to 16.5 MPa, which aligns with prior research highlighting PET's efficacy as a binder in enhancing composite cohesion and load-bearing capacity [11], [12]. Conversely, tensile strength showed more nuanced behaviour, peaking at 8.58 MPa but remaining constrained by the inherent brittleness and filler distribution within the polymer matrix, reflecting limitations noted in polymer composites lacking fibre reinforcement [4], [18]. The developed regression models and ANOVA analyses elucidated these complex interactions, revealing non-linear effects that underscore the necessity of compositional optimisation for tailored mechanical properties.

From a waste management perspective, the utilisation of post-consumer PET in composite boards exemplifies a pragmatic approach to mitigating plastic pollution. By diverting significant volumes of PET waste from landfills and incineration pathways, which contribute to environmental degradation and greenhouse gas emissions, this strategy supports circular economy objectives and resource efficiency [2]. The transformation of waste into value-added construction materials addresses both environmental imperatives and socio-economic drivers, fostering green innovation while potentially reducing dependence on high-embodied carbon materials such as concrete and steel [11].

Within the construction industry, these findings suggest that PET composite boards have promising applications in non-structural elements such as cladding, insulation, and partitioning, where compressive strength is critical but tensile demands are lower. Nevertheless, the lower tensile strength and unresolved questions regarding long-term durability under environmental stressors—including moisture ingress, UV exposure, and temperature fluctuations limit broader structural applications without further material enhancement and validation [4], [43]. The industry's adoption of such composites will also necessitate stringent compliance with building codes and standards, as well as performance benchmarking against incumbent materials.

Policy implications emerging from this research highlight the need for regulatory frameworks that incentivise the incorporation of recycled plastics into construction materials while ensuring product safety and performance. Policymakers should encourage investment in standardisation protocols, support innovation in recycling technologies, and facilitate partnerships across waste management and construction sectors to scale sustainable materials deployment [9]. Additionally, lifecycle assessment mandates could help quantify environmental benefits, reinforcing evidence-based decisions that promote sustainable building practices.

Future research must prioritise the development of hybrid composite systems that integrate fibre reinforcements or interfacial modifiers to ameliorate tensile properties and enhance toughness, thereby expanding potential applications [12]. Scaling up manufacturing processes while maintaining material consistency and cost-effectiveness remains a critical challenge, warranting comprehensive techno-economic analysis. Moreover, long-term environmental durability studies, including accelerated ageing and field testing, are essential to establish service life predictions and validate performance under realistic conditions [11]. A holistic environmental impact assessment encompassing cradle-to-grave lifecycle analyses will further substantiate the sustainability credentials of PET-based composites.

In summary, this study contributes significant empirical evidence and predictive modelling tools that advance the understanding of PET composite materials for green building applications. The results affirm the material's potential to contribute meaningfully to waste reduction and sustainable construction, provided that compositional and durability challenges are addressed. Bridging laboratory-scale insights with industrial scalability and regulatory acceptance is imperative to unlocking the full environmental and economic benefits of PET composite boards in the circular economy.

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Mat Nawi, Burhanudin;* ***data collection:*** *Mat Nawi;* ***analysis and interpretation of results:*** *Mat Nawi, Burhanudin, Md Noh, Kamaruddin;* ***draft manuscript preparation:*** *Mat Nawi, Burhanudin. All authors reviewed the results and approved the final version of the manuscript.*

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