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Preparation and Characterization of Waste PET and Sand Composites

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ABSTRACT

The amount of plastic waste, which is non-biodegradable and causes environmental pollution, generated in Nigeria is increasing, Polyethylene terephthalate (PET) is one of the most abundant waste plastics. In this study PET and sand were mixed to form PET sand composite. The structural, thermal, and flammability properties of the PET sand composite were investigated to assess their potential for applications. Fourier Transform Infrared Spectroscopy (FTIR), density and flammability analysis were conducted on the samples. FTIR analysis confirmed the presence of PET and silica, with characteristic absorption bands for ester (C=O), C-H bending, and Si-O-Si stretching. The results indicated minimal shifts in PET's functional groups upon sand incorporation, suggesting chemical stability. Density analysis revealed that increasing sand content enhances composite compactness, while flammability tests showed a reduction in the burning rate, indicating improved fire resistance. The findings demonstrate that PET sand composites possess favourable mechanical strength, thermal stability, and flame-retardant properties, making them suitable for sustainable material applications. This study highlights the potential of recycled PET and sand as viable raw materials for eco-friendly composite development.

Keywords: PETsand composites, FTIR analysis, flammability, thermal stability, sustainable materials

INTRODUCTION

As of 2017, global plastic production exceeded 380 million tonnes annually, leading to the widespread accumulation of plastic waste in many countries [1]. It is estimated that approximately 80% of ocean plastics originate from coastal developing nations due to inadequate waste management systems, which result in the unsustainable disposal of plastic materials into water bodies [2]. The increasing reliance on plastic products across various industries contributes significantly to municipal solid waste, with plastics accounting for over

12% of its total volume. Since plastics are non-biodegradable and do not readily re-enter the natural carbon cycle, they often accumulate in landfills and aquatic ecosystems [3].

Over the past decade, synthetic polymers have progressively replaced natural materials in diverse applications due to their functional advantages. According to a World Wide Fund for Nature (WWF) report, global plastic production is projected to increase by 4% by 2030 [4]. Consequently, managing plastic waste has become imperative to comply with environmental protection policies and energy conservation efforts. While certain plastics can be safely recycled, others remain non-recyclable and contribute to environmental pollution [2]. Recycled plastic waste has found utility in numerous civil engineering applications, such as a partial substitute for sand in concrete production, pavement construction, and as an insulator or conduit in buildings [5]. Studies have shown that composite boards can be effectively produced using *Swietenia macrophylla* wood dust and polyethylene plastic, highlighting the potential of plastic waste in material innovations [12].

Sand, an essential component in construction, significantly influences the strength, durability, weight, and shrinkage properties of concrete. By filling the pores in concrete, sand enhances its overall structural integrity [5]. Similarly, bricks, a commonly used building material, comprise 50–60% silica, 20–30% alumina, 2–5% lime, 2–5% iron oxide, and $\leq 7\%$ magnesia by weight [6]. However, improper plastic waste management poses significant environmental and economic challenges, such as clogging drainage systems, increasing flood risks, and facilitating stagnant water accumulation, which can negatively impact public health [3]. Additionally, the disposal of vast amounts of plastic waste in landfills demands extensive land resources and substantial financial investment, further straining national economies. The incineration of plastic waste also contributes to greenhouse gas emissions, particularly carbon dioxide, exacerbating climate change [1].

In spite of the increasing environmental concerns associated with plastic waste, there remains a gap in research on its potential applications. Recent research has explored the influence of additives on the interfacial bonding between cocoa fruit shell powder and polypropylene-based composites, demonstrating promising advancements in waste utilization [7]. This study aims to investigate the effect of key physical properties on composites formulated from varying ratios of polyethylene terephthalate (PET) waste plastics and sand, thereby exploring their feasibility for construction and engineering applications.

Gouasmi et al. [8] explored recycling polyethylene terephthalate waste from bottles to create a lightweight composite material by combining PET with siliceous sand. The process involves heat-treating the PET at 290 °C followed by step cooling, resulting in a composite with hardness comparable to natural rock. The research examines the structural characteristics of this material and assesses its performance when used as a partial replacement for natural aggregate in industrial screeds.

Sanches et al. [9] investigated the incorporation of sand particles into a recycled PET matrix to evaluate the resulting composite's mechanical properties and sustainability aspects. The study measured compressive strength and density of the composites. The results indicated that adding sand particles enhanced the strength and friction properties of the PET matrix, suggesting potential applications in construction materials.

The findings from this research suggest that this composite could be a viable alternative in construction applications, offering both economic and ecological benefits. This study aims to prepare and characterize the waste PET and sand composite obtained. The objectives of this research are to produce the PET/Sand composite, to test some physical properties of the composite, and to characterize the composite using FTIR

MATERIALS AND METHODS

Materials: Phenols, 1,1,2,2 tetrachloro ethane, weighing balance, and Pelkin Elmer 3000 MX FTIR spectrophotometer.

Preparation of hot resin of PET wastes

The small pieces of Polyethylene terephthalate waste plastics were dissolved in the solution prepared from phenol and 1,1,2,2-tetrachloroethane at the ratio 1:2.5. The solution was heated with continued steering on a hot plate at the temperature of 160-180 °C.

Preparation of PET sand composites

The composite mixture was made by varying the amount of PET from 5-20 g while sand remained constant (10 g). Another set of composites was prepared by varying the amount of sand while the PET remained constant. This procedure was repeated with the unused bottles, which is the reference composite [8]. Table 1 shows the sample compositions.

Table 1: Samples and their composition

Sample code	Composition (unit)
A	Sand A and waste PET
A1	Sand A and unused PET
B	Sand B and waste PET
B1	Sand B and unused PET
C	Sand C and waste PET
C1	Sand C unused PET

Water absorption of composites

A water absorption test of the composites was determined by immersion of the produced composites in distilled water at room temperature, 24 °C, for 24 h. Three specimens of each formulation were dried and immersed in distilled water for 24 h., The surface water was then wiped off using tissue`paper, and the wet weight values were determined. The percentage of water absorption was calculated using Equation 1 [9]:

$$M\ (\%) = (m_t - m_o)/m_o \times 100 \qquad (1)$$

Where m_o and m_t denote the oven-dry weight and weight after time t, respectively.

Flammability test of composites

A 40 mm mark was measured and marked out on each specimen. The specimen was clamped horizontally in a retort stand with the marked 40 mm distant from the clamp. The free end of the sample was ignited, and the time taken for the sample to ignite was recorded as the ignition (I_t). The sample was allowed to burn to the 40 mm mark (D_p). The relative rates of burning for the different samples were determined using Equation 2 [10]:

$$\text{Flame propagation rate (mm/s)} = D_p\,(\text{mm})/P_t(\text{sec}) - I_t(\text{sec}) \qquad (2)$$

Where D_p = Propagation distance measured in mm,

P_t = Flame propagation time measured in seconds

I_t = Ignition time measured in seconds.

Density test of composites

The densities of the composites were determined according to Gani et al [9]. The mass of each composite sample was determined using an analytical weighing balance, and the volume obtained via the dimensions of each side (length x breadth x width) was measured. The density of the samples was computed as the ratio of mass to volume (g/cm^3).

Fourier Transform Infrared Spectroscopy (FTIR) analysis

Fourier transform infrared spectroscopy analysis was performed on all the samples isolated to have a result regarding the biomineral. A few crystals were mixed with KBr (Merck for spectroscopy) and pulverized in an agate mortar to form a homogenous powder from which, under a pressure of 7 tons, the appropriate pellet was prepared. All spectra were recorded from 4000 to 400 cm^{-1} using the Pelkin Elmer 3000 MX spectrometer. Scans were 32 per spectrum with a resolution of 4 cm^{-1}. The IR spectra were analyzed using the spectroscopic software Win-IR Pro Version 3.0 with a peak sensitivity of 2 cm^{-1} [11].

RESULTS AND DISCUSSION

Effect of the amount of sand in composite on water absorptivity at constant temperature and time

Figure 1 illustrates the relationship between the amount of sand in the composite and its corresponding water absorption percentage. As the proportion of sand increases, the percentage of water absorption increased across all composite formulations. This indicates that sand plays a significant role in moisture retention within the composites. Among the different composite types analyzed, Sample A exhibits the highest water absorption, peaking at approximately 11%. This suggests that its composition may have a higher porosity, allowing for greater water penetration. Conversely, Sample B1 shows the lowest water absorption, indicating that it has better resistance to moisture compared to the other formulations. The remaining samples, including A1, B, B1 C, and C1, demonstrate intermediate water absorption levels with slight variations in trends.

The observed increase in water absorption with higher sand content can be attributed to the inherent properties of the materials used. Polyethylene terephthalate is a hydrophobic polymer that repels water [12, 13]. whereas sand is porous and tends to retain moisture. As the proportion of sand increases, the composite structure likely develops more voids, leading to increased water uptake [14]. Additionally, the variations in water absorption among different composites may be due to differences in PET-to-sand ratios, processing conditions, or the presence of additives that affect the interfacial bonding between the two materials.

Theoretically, composites with lower water absorption, such as Sample B1, may be more suitable for applications requiring high moisture resistance, such as outdoor construction, pavement materials, or areas exposed to frequent water contact. On the other hand, composites with higher water absorption (e.g., Sample A) may be less durable in humid environments due to potential degradation over time.

Overall, this analysis highlights the importance of optimizing PETsand composite formulations to achieve the desired balance between strength, durability, and moisture resistance, depending on their intended applications.

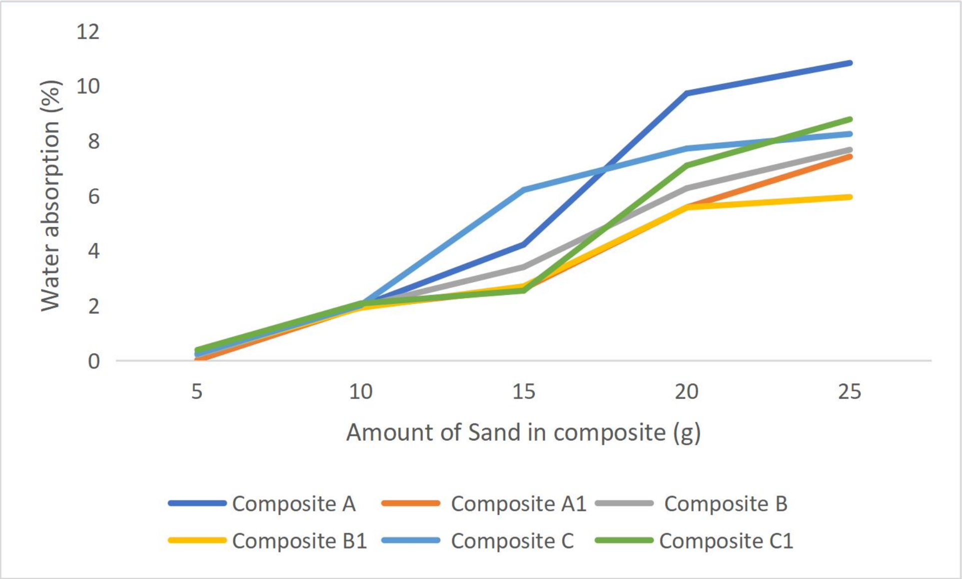

Figure 1: Effect of the amount of sand in composite on water absorption at constant time and temperature

Effect of the amount of PET in composite on water absorptivity at constant temperature and time

Figure 2 illustrates the relationship between the amount of PET in the composite and its water absorption percentage. Unlike the previous trend observed with sand, this graph shows a decreasing water absorption percentage as the PET content increases. At low PET content (5–10 g), water absorption is relatively high, reaching around 10% in Sample A, with other composites following a similar pattern. This suggests that when PET content is minimal, the composite remains more porous, allowing water to infiltrate more easily. However, as the PET content increases beyond 10 g, water absorption declines significantly across all composite formulations, approaching nearly 0% at around 15–25 g of PET. The reason for this trend can be attributed to the hydrophobic nature of PET. PET is a non-polar polymer that does not absorb water, meaning that higher PET content leads to a denser, less porous structure [15]. This improved water resistance is evident across all composite types, regardless of initial variations in water absorption.

Composites with higher PET content (≥15 g) exhibit superior water resistance, making them suitable for applications where exposure to moisture is a concern, such as outdoor furniture, pavement materials, and construction elements [16] Conversely, composites with low PET content may be more susceptible to degradation in humid environments due to their increased water absorption. Increasing the PET content in sand based composites enhances their resistance to water absorption, which could improve their durability and performance in wet conditions.

This finding underscores the importance of optimizing the PET-to-sand ratio when designing composite materials for various engineering applications.

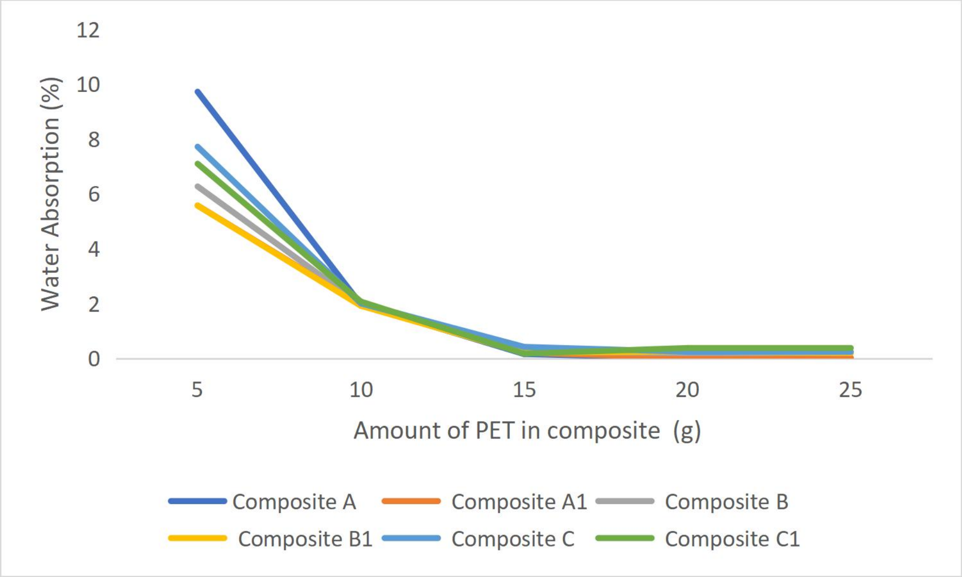

Figure 2: Effect of the amount of PET in composite on water absorption at constant time and temperature

Effect of the amount of PET in composite on the flammability of at constant temperature and time

Figure 3 presents the flammability behavior of the composites, showing a direct correlation between PET content and burning rate. The results demonstrate that as PET content increases, the burning rate of the composite also increases. This is because PET, being a thermoplastic polymer, readily burns under high temperatures. Research indicates that pure PET exhibits a high heat release rate (HRR) and a low ignition time, making it highly flammable [17]. The sand component in the composite serves as an inorganic filler, which helps to improve fire resistance. However, when PET content is high, the composite becomes more combustible, as PET is the dominant phase in the material matrix. A previous study [18] on PET/clay nanocomposites reported a similar trend, confirming that an increase in PET content directly enhances flammability.

This finding suggests that while PET improves water resistance, it also increases fire susceptibility, making fireproofing measures necessary for certain applications. Therefore, a balanced formulation of PET and sand is crucial in ensuring that the composite does not become excessively flammable. For construction applications, fire-retardant additives may be introduced to mitigate the high combustibility of PET-rich composites.

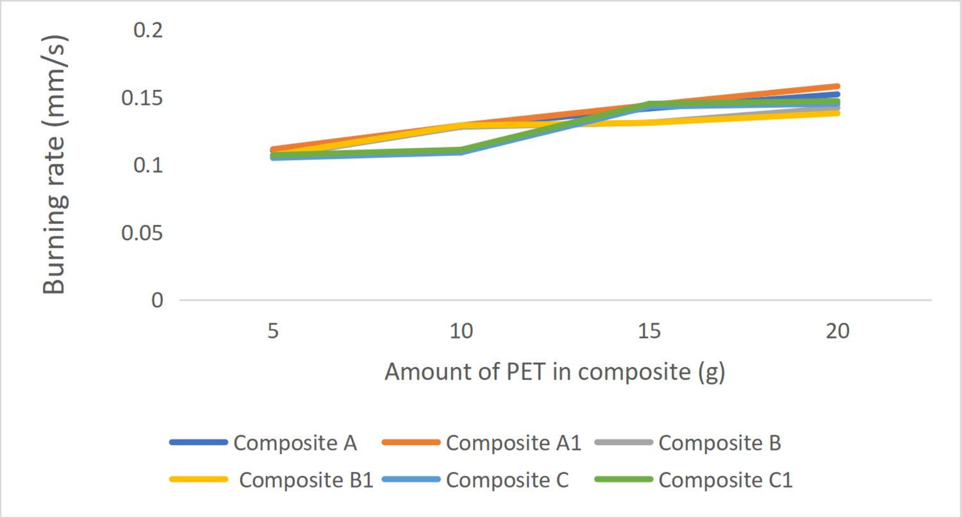

Figure 3: Effect of the amount of pet in composite on flammability at constant temperature and time

Effect of amount of sand in composite on flammability at constant temperature and time

Figure 4 illustrates the effect of sand concentration on the flammability of PET sand composites under constant time and temperature conditions. The results indicate that as the proportion of sand in the composite increases, the burning rate gradually decreases. This can be attributed to the non-combustible nature of sand, which acts as a flame retardant within the composite structure, thereby reducing its overall flammability. Sand, being an inorganic material, does not participate in combustion. Instead, it serves as a physical barrier that impedes flame propagation and lowers the heat release rate (HRR) of the composite. The steady decline in the burning rate observed across all tested composites suggests that a higher sand content enhances flame resistance. This observation aligns with previous studies [19], which established that polymer composites containing increased amounts of inorganic fillers, such as sand, exhibit improved fire resistance.

The mechanism behind this fire resistance can be explained through two primary factors. First, the heat shielding effect, where sand particles act as a protective layer, preventing direct exposure of PET to flames. This effect delays ignition and reduces the combustion rate, making the composite more resistant to fire [20]. Second, the reduction in polymer content, as PET is the primary flammable component in the composite. Increasing sand concentration effectively dilutes the PET content, thereby lowering the overall combustibility of the material. The steady decline in the burning rate across all composites confirms that increasing sand content significantly enhances fire resistance. This effect becomes particularly pronounced in high-sand-content composites, where flame inhibition is more evident. The presence of sand particles disrupts heat transfer within the composite and forms a protective char-like layer, further slowing down combustion. A similar study by Mahdi *et al.* [20] supports this observation, confirming that the incorporation of inorganic fillers like sand into polymer-based composites significantly reduces flammability. This highlights the effectiveness of sand as a fire-resistant additive, making PET/sand composites more suitable for applications where fire safety is a concern

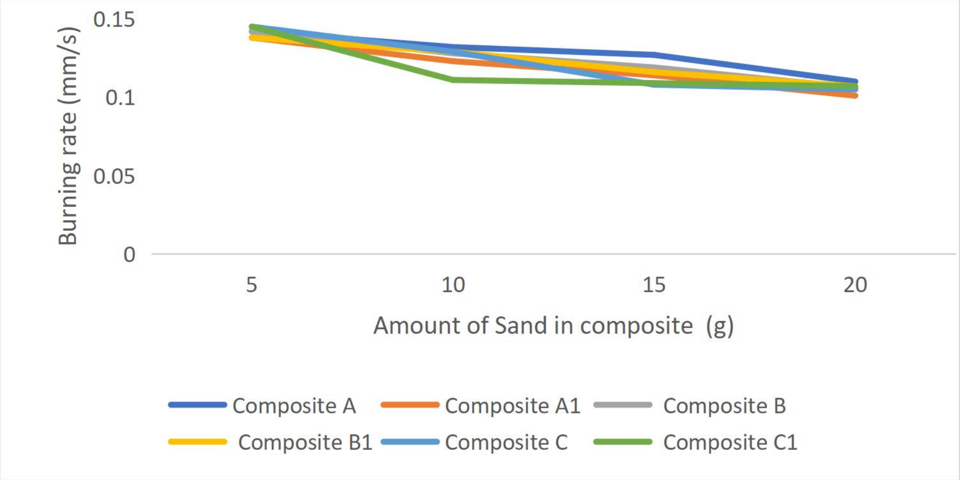

Figure 4: Effect of amount of sand in composite on flammability at constant time and temperature

Effect of amount of sand in composite on the density of at constant temperature and time

The effect of sand concentration on the density of PET/sand composites is illustrated in Figure 5. The results indicate a consistent increase in the density of the composites as the amount of sand increases. This trend suggests that sand, being a high-density inorganic material, significantly contributes to the overall density of the composite. As more sand is incorporated, the composite becomes denser due to the replacement of the lower-density PET matrix with the heavier sand particles. At lower sand concentrations, the composite exhibits a relatively lower density, which can be attributed to the dominance of PET, a polymer with a lower specific gravity compared to sand. However, as the proportion of sand in the composite increases, a steady rise in density is observed across all tested composites. This increase is due to the compact nature of sand particles, which not only add weight to the material but also reduces the presence of air voids, thereby enhancing the packing efficiency within the composite structure [18].

The observed trend aligns with previous research, which has demonstrated that incorporating inorganic fillers such as sand into polymer composites leads to an increase in density [19, 21]. This is because fillers with higher specific gravity tend to displace lighter polymer chains, resulting in a more compact and denser material. Furthermore, the uniformity in density values across different composite formulations suggests that the dispersion of sand within the PET matrix is relatively homogeneous, ensuring consistency in the composite's structural properties. In applications, the increase in density with higher sand content can have both advantages and limitations. On one hand, higher density can improve mechanical properties such as compressive strength and wear resistance, making the composite suitable for load-bearing applications. On the other hand, excessive density may impact lightweight applications where material weight is a critical factor. Therefore, optimizing the PET-to-sand ratio is essential to achieving a balance between density and functional performance [16].

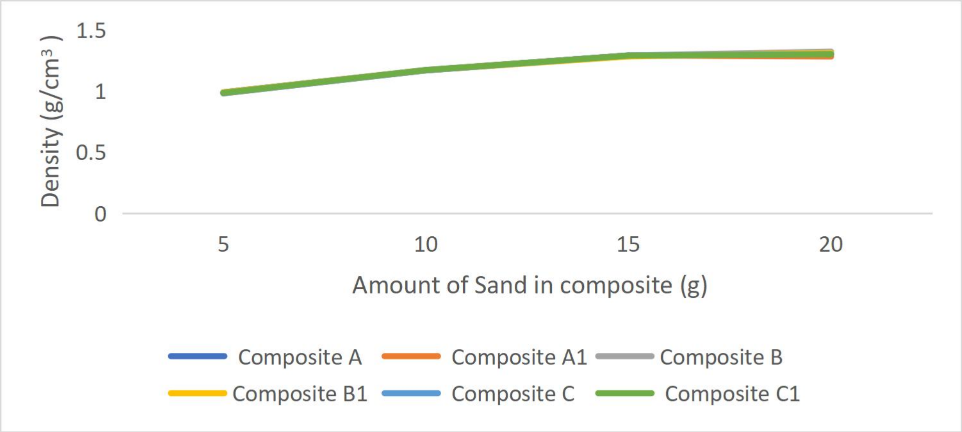

Figure 5: Effect of amount of sand in composite on the density at constant temperature and time

Effect of the amount of PET in composite on Density at constant temperature and time

Figure 6 shows the effect of the amount of PET in the composite on density at constant time and temperature. The result shows that the density of the composite formed decreased with an increase in the amount of PET. This could be due to the low value of the density of PET when compared to that of sand. A similar result was observed by Juki *et al*. [22] who reported that the density of the PET/Sand composite decreased progressively with the addition of more amount of PET. Juki et al [22] examined the use of recycled PET in concrete and found that increasing the PET content led to a reduction in the composite's density. The study attributed this reduction in density to the lower specific gravity of PET compared to conventional aggregates.

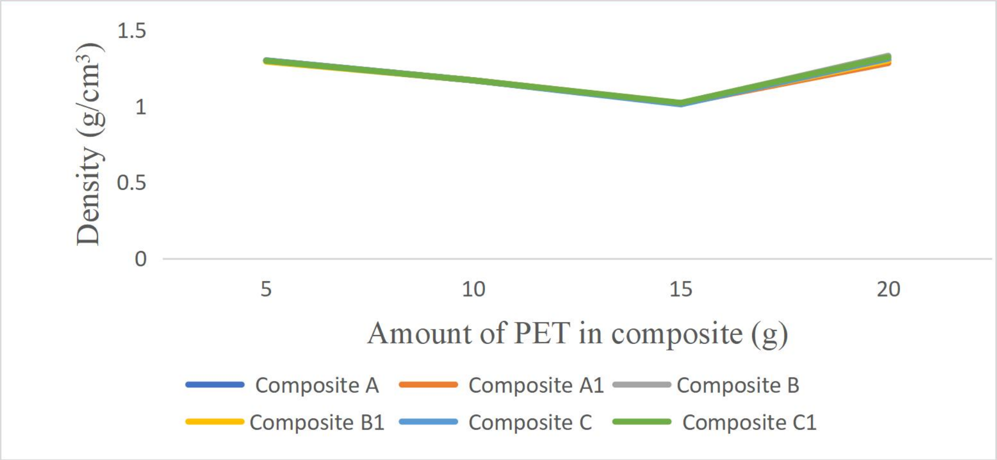

Figure 6: Effect of the amount of PET in composite on density at constant time

FTIR characterization of the composites

The FTIR spectrum of sample A, which represents the PET sand composite before modification, displays key absorption bands associated with PET. Figure 7 shows the prominent peaks observed around 1712 cm^{-1} corresponds to the carbonyl (C=O) stretching vibration, a distinctive feature of PET. Peaks around 1241 cm^{-1} and 1096 cm^{-1} are attributed to C-O stretching vibrations, further confirming the presence of ester groups in PET. Additionally, absorption in the 800–900 cm^{-1} range may be associated with aromatic ring bending, indicating the presence of benzene structures in PET. On the other hand, sample A1, which represents a modified or treated PET/sand composite, exhibits similar characteristic peaks but with variations in intensity and peak positions. The peaks around 1055–1013 cm^{-1} correspond to the Si-O-Si stretching vibrations, confirming the presence of silicate compounds from the sand component. The presence of these inorganic functional groups suggests a potential interaction between PET and sand particles [23].

Comparing the two spectra on Figure 7, a noticeable shift and intensity reduction in the carbonyl (C=O) stretching vibration at 1712 cm^{-1} is observed in sample A1, which may indicate interactions between PET and the silica-rich sand particles. This shift suggests a possible physical or chemical interaction between the organic and inorganic phases of the composite [24]. Additionally, the increased intensity of peaks in the 1000–1100 cm^{-1} range further supports the enhanced presence of silicate structures from sand.

The FTIR analysis confirms the coexistence of organic PET and inorganic sand within the composite structure [22, 25]. The characteristic absorption bands of PET are retained, while new peaks corresponding to silicate groups indicate the contribution of sand as a reinforcing filler. The changes in peak intensity and shifts suggest interactions between the polymer matrix and the inorganic filler, which may influence the material's mechanical and thermal properties [26].

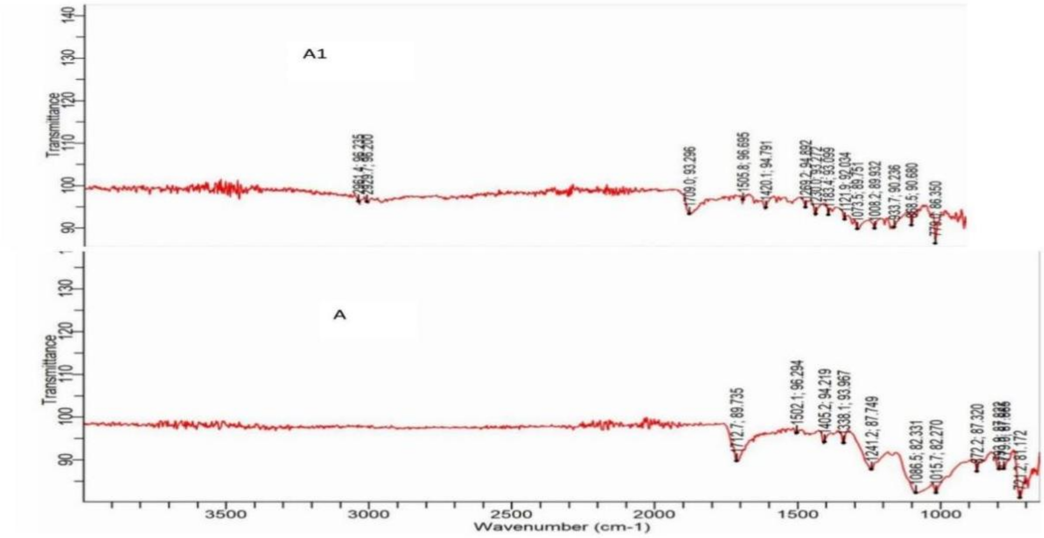

Figure 7: The FTIR analysis of the waste composite and reference A.

The FTIR analysis of the waste composite and Sample B

Figure 8 presents the FTIR spectra of waste Sample B and Sample B1, highlighting key functional groups present in their structures. The FTIR spectrum of waste Sample B reveals a distinct absorption peak at 1701.5 cm^{-1}, indicative of C=O stretching, which confirms the presence of ester groups derived from the PET component. Additionally, an absorption peak at 1408.9 cm^{-1}, corresponding to C-H vinyl stretching, is observed, further confirming the polymeric nature of the composite [27]. The presence of peaks at 1012.0 cm^{-1} and 775.3 cm^{-1} suggests Si-O-Si asymmetric and symmetric stretching vibrations, respectively, confirming the incorporation of silica into the composite [25].

This result aligns with the findings of a recent study [26], which observed similar spectral features in PET-based composites. The minimal presence of degradation-related peaks indicates that the PET component within the composite remains stable, suggesting limited structural deterioration.

The FTIR spectrum of the Sample B1 exhibits absorption at 1712.7 cm^{-1} and 1241.2 cm^{-1}, corresponding to strong C=O stretching and C-O stretching vibrations, respectively, which are characteristic of ester functional groups in PET. A peak at 721.2 cm^{-1} is attributed to C-H deformation in the benzene ring, reinforcing the presence of aromatic structures in the composite. Additionally, absorption at 1086.5 cm⁻¹ and 787.7 cm⁻¹ are associated with Si-O-Si asymmetric and symmetric stretching, confirming the presence of silica in the matrix.

These observations are consistent with the findings of Mahdi et al [23], who identified comparable peaks in their study of recycled PET/sand composites, particularly noting the strong carbonyl absorption at 1725 cm⁻¹ and the aromatic C-H bending at 725 cm⁻¹. A notable overlap occurs in the 1090–1100 cm⁻¹ region, where PET's C-O-C stretching and silica's Si-O-Si stretching contribute to absorption. This spectral overlap may complicate precise peak assignment, necessitating further characterization using additional techniques such as Raman spectroscopy for better differentiation [28].

The FTIR analysis confirms the structural integrity of PET in the composite while highlighting the presence of silica as a reinforcing filler. The observed spectral features suggest that the waste Sample B retains a stable chemical structure with minimal degradation, reinforcing its potential for further applications.

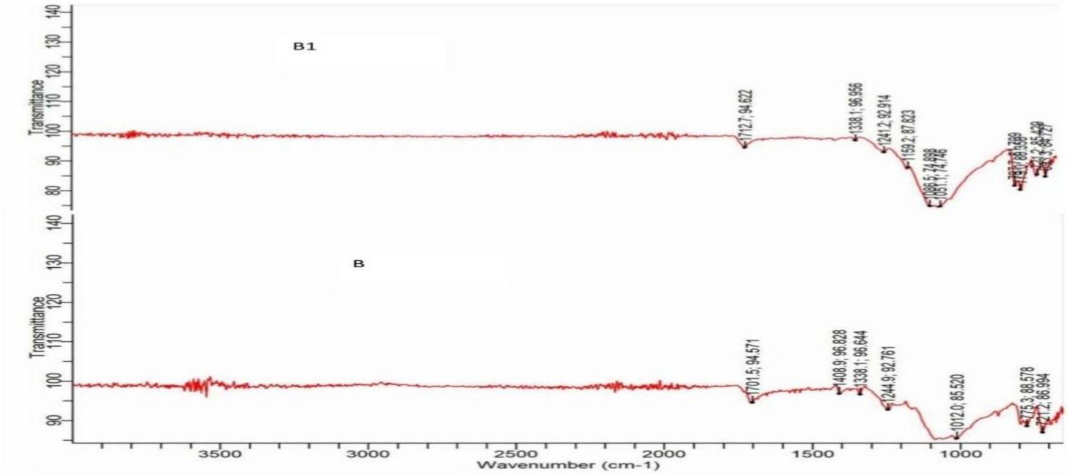

Figure 8: The FTIR Analysis of the waste composite and reference B

The FTIR Analysis of the waste composite and Sample C

Figure 9 presents the FTIR spectra of waste composite C and reference composite C, highlighting the key functional groups present in both materials. The FTIR spectrum of waste composite C exhibits a strong absorption band at 1716.4 cm⁻¹, corresponding to C=O stretching, which confirms the presence of ester functional groups derived from PET. Additionally, an absorption band at 1338.1 cm⁻¹ is attributed to C-H bending of methyne [29], while the peak at 1159.2 cm⁻¹ suggests C-O stretching vibrations, further confirming the presence of ester linkages. A peak at 728.7 cm⁻¹ represents C-H deformation in the benzene ring, which is characteristic of the aromatic structure in PET. Beyond the PET-related peaks, the spectrum also shows absorption at 1043.7 cm⁻¹, indicative of Si-O-Si asymmetric stretching, while the band at 775.3 cm⁻¹ corresponds to Si-O-Si symmetric stretching, confirming the presence of silica in the composite. These observations are consistent with the findings of Curtis et al [30], who reported that the incorporation of sand particles into PET/sand composites results in minimal shifts in PET's aromatic ring vibrations.

The FTIR spectrum of the reference composite C displays an absorption band at 1709.0 cm⁻¹, which corresponds to the carbonyl (C=O) stretching of the ester group in PET. Absorption at 1405.2 cm⁻¹ is associated with the C-H stretching of vinyl groups, while 1334.4 cm⁻¹ represents the C-H bending of methyne [24]. Additionally, the spectrum exhibits an absorption at 1237.5 cm⁻¹, corresponding to C-O stretching of ester groups, confirming the presence of PET in the composite. A peak at 721.2 cm⁻¹ is attributed to C-H deformation in the benzene ring, which aligns with previous observations by Mekindeche et al [28] for PET-based materials. The absorption at 1054.8 cm⁻¹ is assigned to Si-O-Si asymmetric stretching of silica [29], while the peak at 779.0 cm⁻¹ signifies Si-O-Si symmetric stretching, further supporting the presence of sand as a reinforcing filler.

The FTIR spectra confirm the presence of PET and silica in both waste composite C and reference composite C, with characteristic ester and silica absorption peaks appearing in both cases. The minimal shifts observed in PET's vibrational bands indicate that the incorporation of sand does not significantly alter its structural characteristics, further validating the material's stability and reinforcing its potential for sustainable applications.

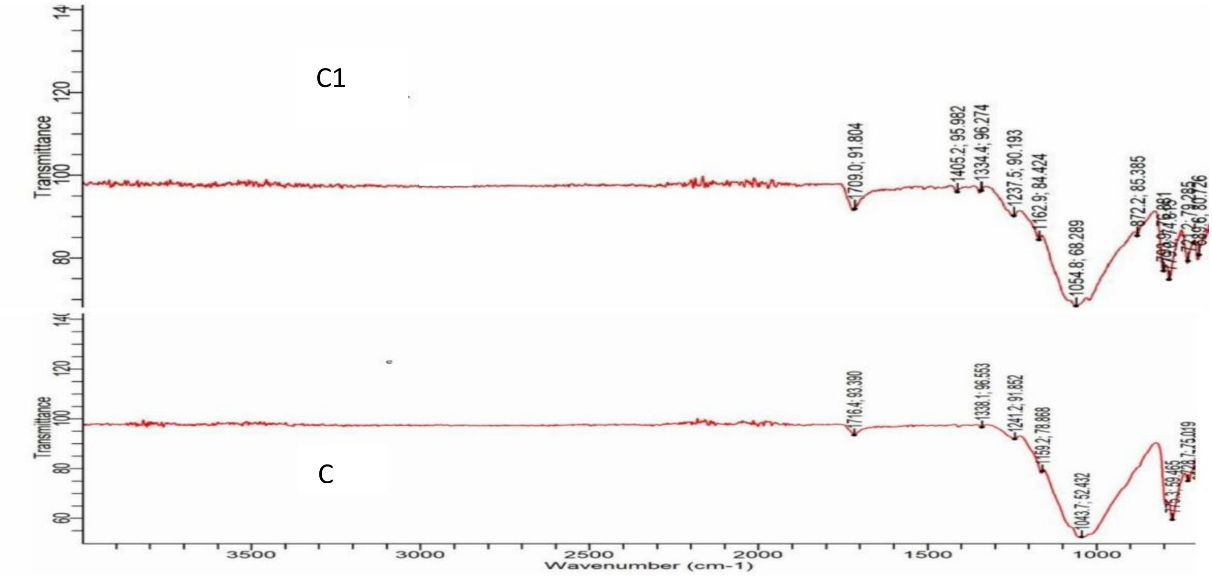

Figure 9: The FTIR Analysis of the waste composite and reference C

CONCLUSION

The analysis of PET and sand composites through FTIR spectroscopy, density evaluation, and burning rate assessments provided valuable insights into the structural integrity, thermal behavior, and stability of these materials. The FTIR spectra confirmed the presence of PET and silica in the composites, with characteristic absorption bands for ester (C=O), C-H bending, and Si-O-Si stretching. The incorporation of sand into the PET matrix leads to minimal shifts in PET's vibrational frequencies, indicating that the fundamental chemical structure remains largely intact. This suggests that the composites maintain good stability, making them viable for applications. The density analysis reveals that increasing sand content enhances the overall density of the composites. This trend suggests improved compactness and structural integrity, which is beneficial for applications requiring mechanical strength and durability. The burning rate analysis indicates a decline in flammability with increasing sand content. This implies that the incorporation of sand acts as a fire retardant, reducing the material's susceptibility to combustion. The findings suggest that PET and sand composites exhibit promising characteristics for various industrial applications, particularly in areas where enhanced thermal resistance, structural stability, and environmental sustainability are required. The study highlights the potential of utilizing recycled PET and sand to develop eco-friendly composite materials with improved performance, aligning with global efforts toward waste reduction and sustainable material development.

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