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Mechanical Performance of Recycled Polypropylene Composites Reinforced with Activated Carbon-Treated Clay as Concrete Aggregates

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ABSTRACT

The growing concern over plastic waste and the depletion of natural aggregates has spurred interest in sustainable construction materials. This study examines the mechanical and morphological performance of recycled polypropylene (rPP) composites reinforced with activated carbon (AC)-treated clay for use as lightweight concrete aggregates. The novelty lies in the hybrid filler system combining clay and AC within a recycled polymer matrix; an approach rarely explored for structural concrete applications. Composites were fabricated using a single-screw extruder at 185°C and 50 rpm, incorporating AC at 1, 3, 7, and 15 wt%. Mechanical testing revealed that 3 wt% AC achieved the highest tensile strength due to enhanced filler dispersion and interfacial bonding, while 15 wt% AC increased stiffness but reduced elongation due to agglomeration and brittleness. The highest yield strength at 7 wt% AC suggests a percolation threshold effect, improving load transfer efficiency. FESEM and EDX analyses confirmed better filler distribution and matrix-filler interaction at lower AC contents, aligning with mechanical results. These findings highlight rPP/clay/AC composites as eco-friendly, lightweight concrete aggregate alternatives with a balance of strength, stiffness, and flexibility. This study underscores the environmental benefits of repurposing plastic and carbon-based waste while recommending further investigation into their long-term durability and real-world performance.

Keywords:
Plastic Composite Aggregate, Plastic Waste, Hybrid Filler, Extrusion, Tensile Properties

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1. Introduction

The exponential growth in global plastic consumption, particularly in packaging and consumer goods, has led to a surge in plastic waste, posing significant environmental threats. Polypropylene (PP), one of the most widely used thermoplastics, contributes substantially to this problem due to its high production volume and resistance to degradation [1]. In parallel, the construction industry's increasing demand for natural aggregates used primarily in concrete has accelerated the depletion of non-renewable mineral resources [2]. To address these twin challenges of plastic waste accumulation and aggregate scarcity, recycled polypropylene (rPP) is being explored as a viable replacement for conventional aggregates in concrete composites [3-4]. As a lightweight, durable, and chemically resistant material, rPP offers potential for use in non-structural concrete components and lightweight construction panels [5], especially when reinforced to improve its mechanical limitations.

Numerous studies have investigated the reinforcement of rPP with various fillers such as clays, carbon black, and natural fibers to improve its mechanical and thermal properties [6-7]. Due to its layered silicate structure and high aspect ratio, clay enhances stiffness, tensile strength, and barrier performance by forming intercalated or exfoliated morphologies within the polymer matrix [8-9]. Meanwhile, Activated Carbon (AC), especially derived from biomass waste, has emerged as a sustainable additive [10] capable of improving interfacial adhesion and mechanical strength through its high surface area and porous structure [11-12]. However, most research has focused on individual fillers, and there is limited literature exploring the synergistic effect of combining AC-treated clay as a hybrid reinforcement system in rPP matrices, especially for applications as concrete aggregates.

Although promising developments have been made in recycling plastic into concrete aggregates using techniques like water-assisted melt compounding, previous studies have successfully optimized the process parameters of rPP/clay composite [3-4,13] but not the influence of hybrid reinforcement systems on mechanical and morphological properties. Additionally, the impact of AC when integrated with clay in rPP composites has not been systematically evaluated in terms of tensile strength, yield strength, elongation at break, and modulus of elasticity. There is also a lack of microstructural evidence linking filler dispersion to fracture behavior and mechanical outcomes. These gaps are particularly significant for concrete applications, where mechanical integrity and long-term performance under stress are critical. Therefore, this study aims to fill this knowledge void by integrating performance testing and microstructural analysis to determine the feasibility of these composites as lightweight concrete aggregates.

This research aims to investigate the mechanical and morphological performance of rPP composites reinforced with AC-treated clay for potential use as concrete aggregates. It focuses on evaluating the effect of varying wt% of AC on tensile strength, elongation at break, yield strength, and modulus of elasticity to determine the optimal filler content for enhanced performance. The study also analyzes the microstructure of the composites using field emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDX) to correlate filler dispersion and fracture morphology with mechanical behavior. Additionally, it assesses the feasibility of these composites as sustainable alternatives to traditional concrete aggregates, emphasizing their mechanical suitability, processing efficiency, and environmental contribution to reducing plastic and carbon waste.

2. Methodology
2.1 Raw Materials Preparation

Recycled polypropylene (rPP) (melting point: 130°C; density: 0.92 g/cm³) was sourced from San Miguel Yamamura Plastic Film Sdn. Bhd. Kaolin clay was provided by Edutech Supply & Service, and activated carbon (AC) was obtained from R&M Chemicals. The rPP pellets were manually mixed with 1% clay and varying weight percentages of AC, as detailed in Table 1. This rPP/clay/AC-X blend, where X represents the percentage of AC, was processed using a Cincinnati Extrusion GCE 30T single screw extruder at 185°C and a screw speed of 50 rpm, then cut using a palletizer. The resulting pellets were dried in an oven at 80°C for 24 hours. These dried pellets were then compressed using a hot press (Laboratory Press Model GT7014-A) at a molding temperature of 200°C and a pressure of 140 kg/cm² [3]. The hot press process took 60 minutes, including 15 minutes each for preheating and cooling and 30 minutes for compression. Finally, all samples were left at room temperature for at least 24 hours for conditioning before being subjected to further testing and analyses.

Table 1: Formulation table for rPP/clay/AC composite

Sample	rPP (wt%)	Kaolin clay (wt%)	Activated Carbon (wt%)
rPP/clay/AC0	99	1	0
rPP/clay/AC1	98	1	1
rPP/clay/AC3	96	1	3
rPP/clay/AC7	92	1	7
rPP/clay/AC15	84	1	15

2.2 Tensile Testing

The tensile testing of rPP/clay/AC composites was conducted using the Shimadzu AGS-X Series Universal Testing Machine, adhering to ASTM D638-03 Type 1 standards for dog-bone-shaped specimens. The machine featured a 20 kN load cell, and the crosshead speed was set at 50 mm/min. This test yielded essential mechanical properties, including the tensile modulus (Et), tensile strength (σb), and elongation at break (εb). Five specimens were tested for each formulation to ensure data reliability.

2.3 Field-Emission Scanning Electron Microscopy (FESEM) with Energy Dispersive X-Ray (EDX)

A Zeiss EVO 50 field-emission scanning electron microscope (FESEM) was employed to analyze the fracture morphology of the tensile test samples. The analysis was conducted at an accelerating voltage of 5 kV using the secondary electron mode, with images captured at a magnification of 300X and 1000X. Before SEM observation, the sample surfaces were sectioned and coated with a thin layer of gold to improve electron reflection and image quality. In addition to observing the surface morphology, Energy Dispersive X-ray Spectroscopy (EDX) was used with FESEM to analyze the elemental composition of the fractured samples. The EDX focused on identifying key elements like carbon (C), oxygen (O), and silicon (Si), which represent the rPP matrix, AC, and clay. This helped map how the fillers were distributed within the composite. FESEM and EDX clarified how filler dispersion, bonding, and structure affect the composite’s mechanical properties.

3. Results

3.1 Tensile Strength

The tensile strength of the rPP/clay/AC composites in Figure 1 demonstrates a relationship with increasing AC content. The composite containing 3 wt% AC (rPP/clay/AC3) exhibits the highest tensile strength among all formulations, significantly surpassing both the rPP/clay/AC15 and the unmodified control (rPP/clay/AC0). This enhancement is attributed to the reinforcing effect of AC, which, at moderate loading, enhances interfacial adhesion and stress transfer due to its high surface area and porous structure. The presence of AC promotes load distribution across the matrix-filler interface, improving the mechanical integrity of the composite [12-13]. However, at higher loadings (rPP/clay/AC15), tensile strength decreases, likely due to particle agglomeration, poor dispersion, and the resulting stress concentration points. These defects reduce load transfer efficiency and compromise tensile behavior, a common trend observed in carbon-based polypropylene composites [15]. Notably, while rPP/clay/AC3 excels in strength, it does not correspondingly achieve the highest yield strength, highlighting the distinct influence of AC on different deformation mechanisms.

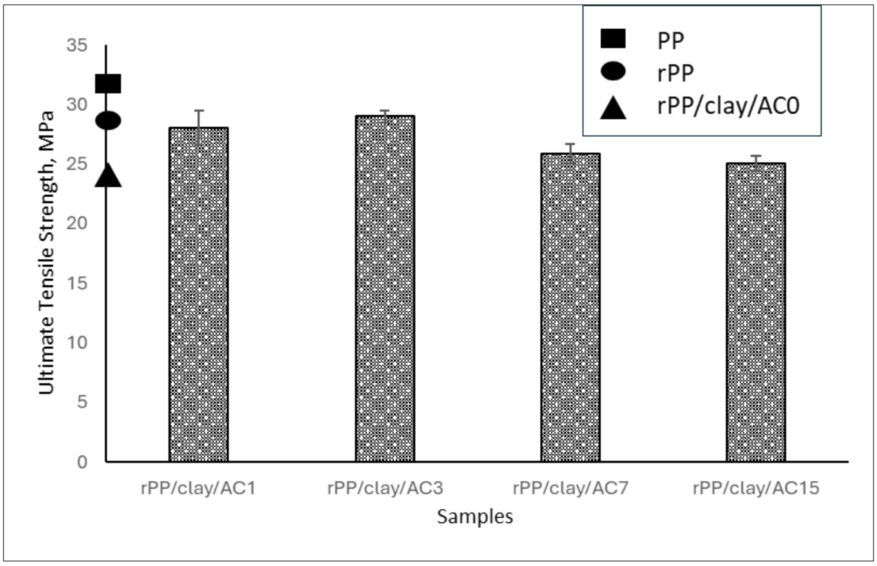

Fig. 1. Ultimate Tensile Strength for rPP/clay/AC composite

3.2 Elongation at Break

Elongation at break in Figure 2 generally decreases with increasing AC content, indicating a progressive loss of ductility. The rPP/clay/AC1 composite exhibits the highest elongation among the other composites, though still lower than the rPP/clay/AC0 reference. The reduction in elongation is attributed to the stiffening effect of AC particles, which restrict polymer chain mobility and increase the brittleness of the matrix. A previous study by Junaedi *et al.* [16]) observed that increasing short carbon fiber content in polypropylene composites led to a significant increase in stiffness and tensile modulus, which was accompanied by a sharp reduction in elongation at break. Specifically, a ductile-to-brittle transition was identified at higher filler loadings (12–13 wt%), attributed to restricted chain mobility and filler-induced rigidity, directly supporting that increased filler content such as activated carbon limits matrix flexibility and induces brittleness [16]. While low concentrations of AC (1–3 wt%) maintain better dispersion and interfacial compatibility, higher contents lead to agglomerates that serve as crack initiation sites and reduce the composite's ability to deform plastically under stress [17]. This trend is consistent with the observed inverse relationship between modulus and elongation at break of the composites with higher stiffness, such as rPP/clay/AC15, demonstrating markedly lower ductility. These findings suggest that while AC enhances strength and stiffness, it introduces a trade-off with flexibility, which must be carefully balanced depending on the target application.

These findings underscore a critical trade-off between strength and flexibility that must align with specific application demands. For instance, higher AC content can be advantageous due to improved stiffness and dimensional stability for rigid, load-bearing uses such as structural fillers or precast panels. In contrast, applications requiring impact resistance or energy absorption, such as lightweight concrete aggregates in seismic zones, will benefit from lower AC loadings of 1% to 3% that preserve ductility. Thus, balancing rigidity and deformability enhances the practical relevance of the elongation at break data and informs the design of rPP-based composites for targeted construction applications.

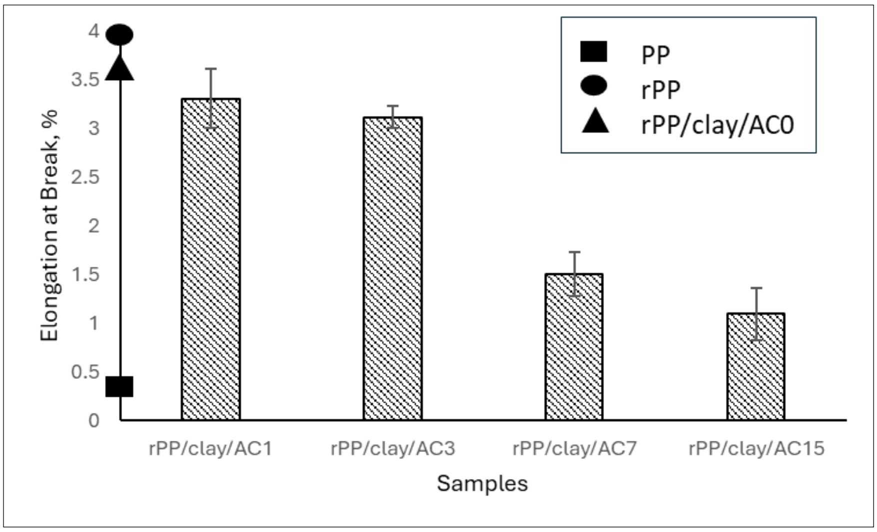

Fig. 2. Elongation at Break for rPP/clay/AC composite

3.3 Yield Strength

An interesting bar graph trend is observed in the yield strength values of the rPP/clay/AC composites in Figure 3. Contrary to expectations, the rPP/clay/AC7 composite achieves the highest yield strength among the other rPP/clay/AC composite. This peak performance at 7 wt% AC could be due to a percolation threshold effect, where an optimal filler network forms to resist initial plastic deformation without causing premature failure [18]. At this concentration, AC particles may be sufficiently dispersed to reinforce the matrix without inducing aggregation, maximizing the energy absorption prior to yielding. These findings suggest that AC plays a multifunctional role across different deformation stages of the composite. AC enhances yield strength in the early deformation phase by facilitating stress transfer and restricting localized plastic flow through mechanical interlocking and network formation. Despite high tensile strength, the lower yield strength at 3 wt% AC indicates that filler connectivity influences yield behaviour more than interfacial bonding alone. Conversely, at 15 wt% AC, excessive filler content leads to agglomeration and disrupted matrix continuity, promoting stress concentration and early failure. This underscores the importance of optimizing AC content to balance filler dispersion, interfacial interaction, and structural network formation for improved mechanical performance in rPP/clay/AC composites.

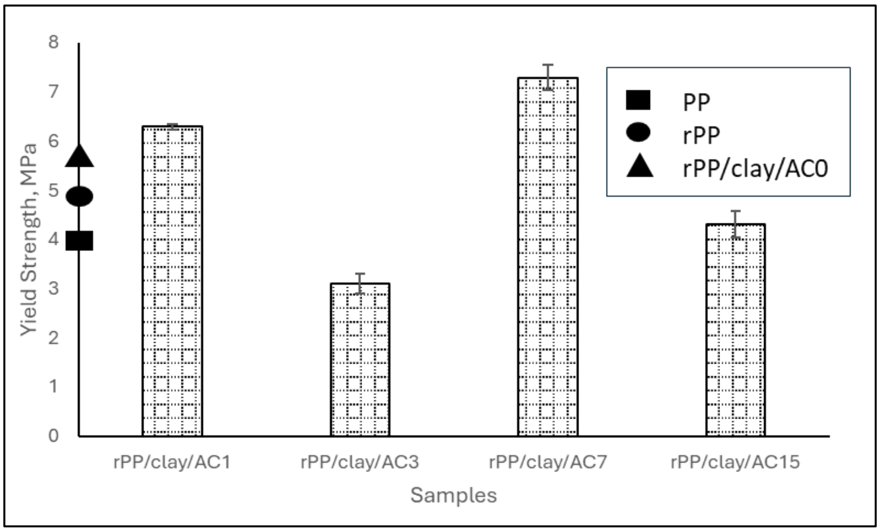

Fig. 3. Yield Strength of rPP/clay/AC composite

3.4 Modulus of Elasticity

The modulus of elasticity in Figure 4 increases consistently with AC content, with rPP/clay/AC15 exhibiting the highest stiffness among all samples. This trend is characteristic of polymer composites incorporating rigid carbon-based fillers, where increasing filler content elevates resistance to elastic deformation by creating a more rigid and interconnected filler network [19]. AC contributes to this enhancement by forming pathways that reduce the mobility of polymer chains, thereby increasing the load-bearing capacity under low-strain conditions. Despite the mechanical advantage in stiffness, this comes at the cost of reduced ductility and elongation, as seen in the corresponding decrease in elongation at break in Figure 2. Moreover, the high stiffness does not translate into superior tensile or yield strength, underscoring the importance of balancing modulus and toughness in the design of functional composite materials.

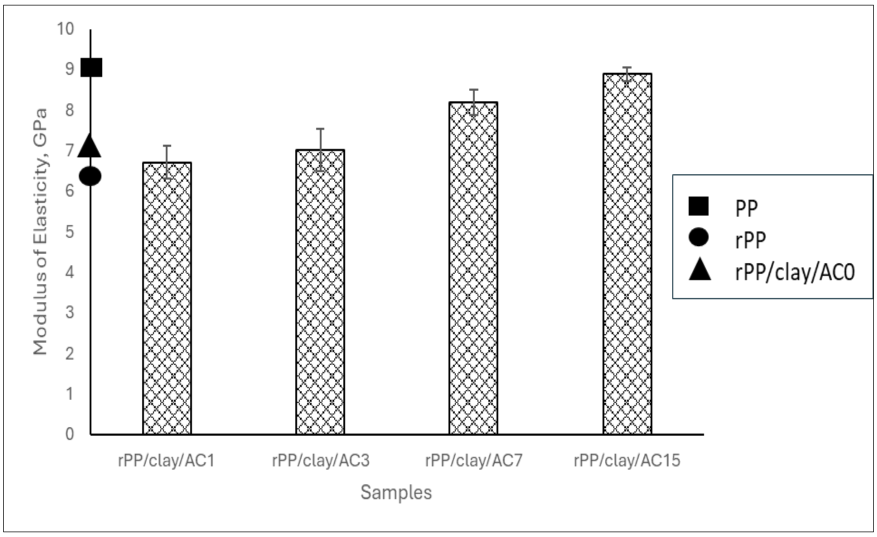

Fig. 4. Modulus of Elasticity of rPP/clay/AC composite

3.5 Morphological Analysis

The FESEM image of the control sample rPP/clay/AC0 in Figure 5 shows a relatively smooth fracture surface with aligned polymeric lamellae and limited evidence of filler particles. The lack of significant microvoids or reinforcing particle-matrix interaction corresponds with the lower mechanical performance across all tensile properties. The EDX spectrum confirms a high carbon content (85.0 wt%) with substantial oxygen (27.7 wt%) but no detectable silica (Si), indicating the absence of activated carbon and minimal clay content. This weak filler-matrix interaction explains the moderate tensile strength and elongation but relatively low stiffness and yield strength. The limited reinforcing phase explains the moderate tensile strength and elongation at break, lacking rigidity or strength enhancement due to weak interfacial load transfer [20].

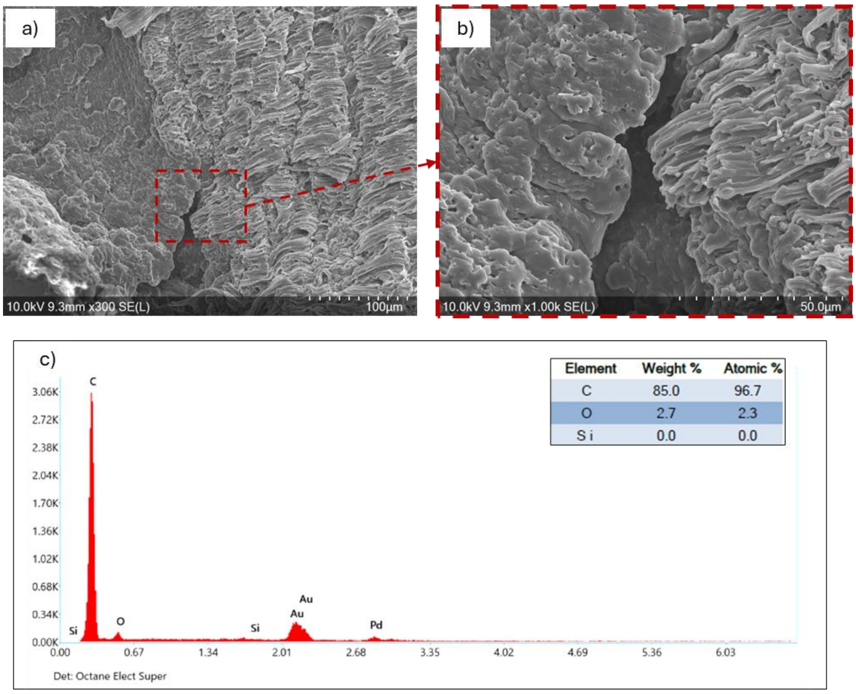

Fig. 5. FESEM image of a) rPP/clay/AC0 at 300x magnification, b) rPP/clay/AC0 at 1000x magnification, c) EDX of rPP/clay/AC0

In contrast, the rPP/clay/AC3 composite in Figure 6 displays a rough and fibrillated fracture surface under 1000× magnification, with visible embedded filler structures suggesting strong interfacial adhesion. This morphology indicates ductile failure and efficient energy dissipation mechanisms, which align with the highest tensile strength observed in mechanical testing. The corresponding EDX results confirm the presence of both C (82.8 wt%) and a trace of Si (0.2 wt%), indicative of well-dispersed AC and clay content. This optimal filler distribution enhances matrix-filler bonding and improves mechanical properties through stress transfer and crack pinning [21].

The FESEM-EDX analysis of the rPP/clay/AC7 composite in Figure 7 provides strong microstructural evidence supporting the observed mechanical behavior, particularly the peak yield strength in Figure 3 and moderate performance in other tensile properties. Figure 7(a) at 300× magnification and Figure 7(b) at 1000×, the fracture surface of rPP/clay/AC7 displays a relatively uniform filler distribution, with embedded and partially interconnected particles visible throughout the matrix. These structures are indicative of an emerging percolation threshold, where the filler content is sufficient to form load-bearing networks that enhance resistance to plastic deformation, reflected in the highest yield strength observed for this composite. The morphology captured in the higher magnification (Figure

7b) highlights intact filler-matrix interfaces and limited signs of agglomeration, supporting the idea of efficient stress transfer during the initial deformation stages. This structure effectively delays yielding by reinforcing the matrix locally while avoiding the brittleness typically introduced by excessive filler clustering. Such morphology is consistent with the percolation threshold effect, where an optimal filler concentration around 7 wt% AC promotes network formation without exceeding the critical volume fraction that would otherwise reduce ductility and tensile strength.

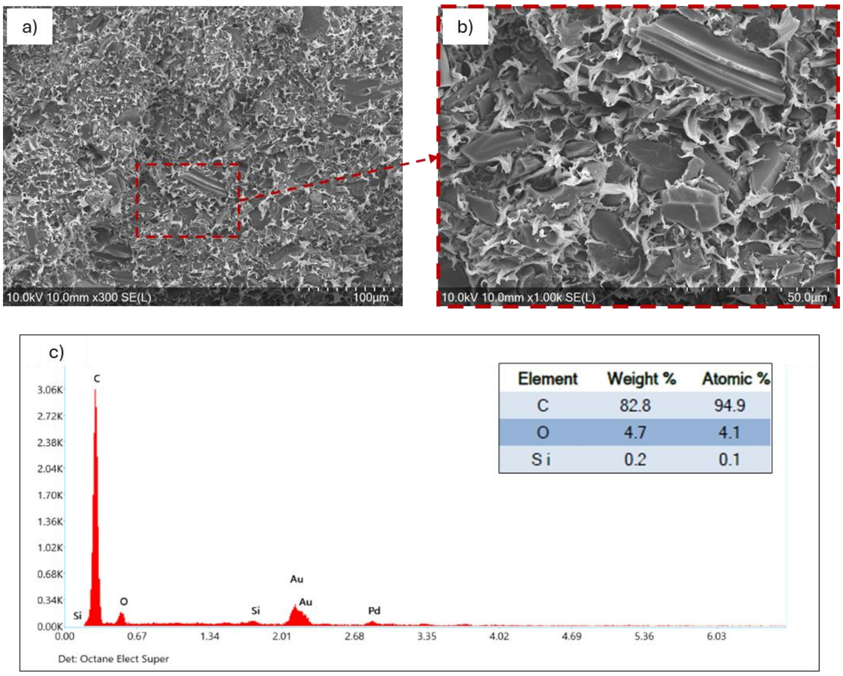

Fig. 6. FESEM image of a) rPP/clay/AC3 at 300x magnification, b) rPP/clay/AC3 at 1000x magnification, c) EDX of rPP/clay/AC3

The accompanying EDX spectrum in Figure 7(c) confirms the elemental composition of the fracture surface, with high C content (76.8 wt%, 95.0 at%) and low oxygen content (3.4 wt%, 3.2 at%), consistent with the dominant presence of the carbon-rich matrix and AC reinforcement. The lack of significant elemental impurities or void regions further supports the interpretation of good filler dispersion and matrix compatibility, correlating with the mechanical integrity observed in the yield strength in Figure 3.

On the other hand, the rPP/clay/AC15 composites in Figure 8 exhibits a fractured surface marked by large filler agglomerates, visible debonding, and voids. These microstructural defects indicate poor dispersion and interfacial weakening at high filler loadings, severely compromising the tensile strength and elongation at break, as the mechanical data support. The EDX results confirm a high C content (82.1 wt%) with no detectable Si, suggesting overloaded and poorly integrated AC within the matrix. This behavior is consistent with prior findings where excessive carbon filler led to particle clustering and premature crack initiation, ultimately degrading mechanical integrity despite improved stiffness [17].

The comparative analysis of FESEM and EDX results across rPP/clay/AC composites underscores the pivotal role of filler dispersion and interfacial bonding in determining mechanical performance. The rPP/clay/AC3 composite exhibited the most favorable morphology, with uniform filler distribution and strong matrix-filler adhesion, resulting in the highest tensile strength. In contrast, rPP/clay/AC0 showed limited filler interaction, correlating with lower reinforcement efficiency. The rPP/clay/AC7 sample revealed a semi-interconnected filler network characteristic of a system near the percolation threshold, which enhanced load transfer and yielded the highest yield strength. Meanwhile, the rPP/clay/AC15 composite displayed pronounced filler agglomeration and microstructural porosity, leading to reduced ductility and tensile performance despite increased stiffness. These findings confirm that optimal mechanical properties in rPP-based composites are achieved at moderate AC loadings (3–7 wt%), where filler distribution and interfacial compatibility are maximized.

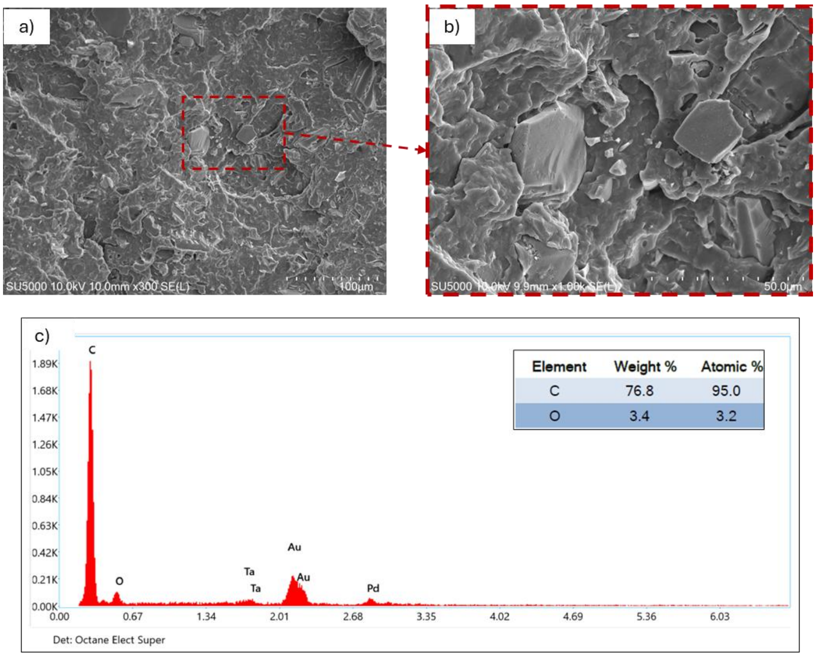

Fig. 7. FESEM image of a) rPP/clay/AC7 at 300x magnification, b) rPP/clay/AC7 in 1000x magnification, c) EDX of rPP/clay/AC7

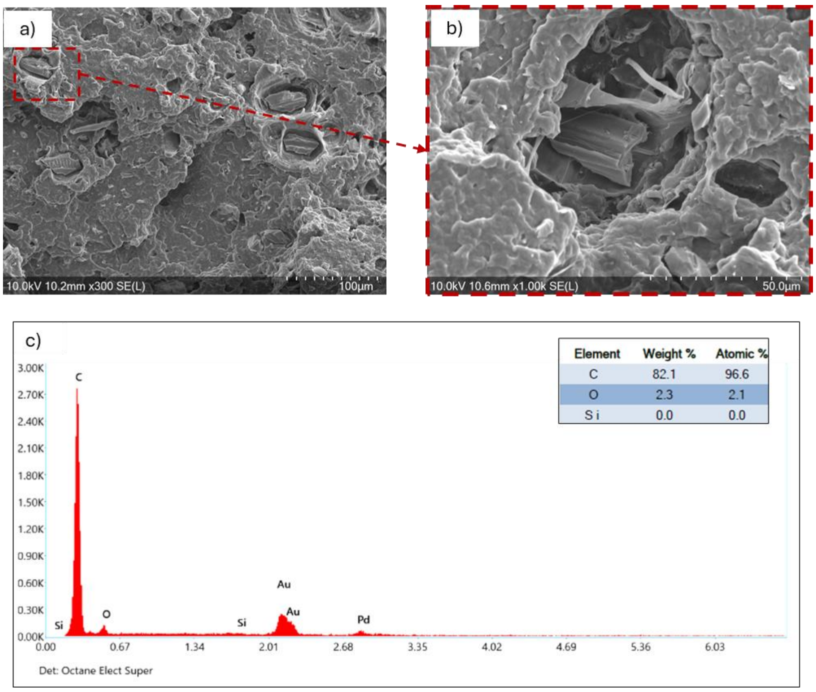

Fig. 8. FESEM image of a) rPP/clay/AC15 at 300x magnification, b) rPP/clay/AC15 at 1000x magnification, c) EDX of rPP/clay/AC15

4. Conclusions

This study successfully demonstrated that incorporating activated carbon (AC) into recycled polypropylene (rPP) composites reinforced with clay significantly enhances their mechanical and microstructural performance, fulfilling the research objectives. An optimal AC loading of 3 wt% yielded the highest tensile strength and improved interfacial bonding, as confirmed by FESEM and EDX analyses, while moderate AC content (1–3 wt%) improved stress transfer and preserved ductility. In contrast, excessive loading (15 wt%) led to agglomeration and embrittlement despite increased stiffness. These findings highlight AC's role as a multifunctional filler and its potential to fine-tune composite performance for use in lightweight, sustainable construction materials such as concrete aggregates. Additionally, the use of AC derived from bio-waste supports circular economy goals by promoting material upcycling. However, the study is limited to static mechanical testing; thus, future research should assess the dynamic durability of these composites under fatigue, impact, and thermal cycling to validate their long-term structural viability in real-world applications.

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References
[1] A. Alsabri, F. Tahir and S. G. Al-Ghamdi. "Environmental Impacts of Polypropylene (PP) Production and Prospects of Its Recycling in the GCC Region," Materials Today Proceedings 56 (2021): 2245–2251. https://doi:10.1016/j.matpr.2021.11.574

[2] L. Chen, M. Yang, Z. Chen, Z. Xie, L. Huang, A.I. Osman, M. Farghali, M. Sandanayake, E. Liu, Y.H. Ahn and A.A.H. Al-Muhtaseb, "Conversion of Waste into Sustainable Construction Materials: A Review of Recent Developments and Prospects," Materials Today Sustainability 27, (2024): 100930. https://doi:10.1016/j.mtsust.2024.100930

[3] N. Mohamad, A.A. Abd Ghani, M.A. Anen, J. Abd Razak, R.I. Raja Abdullah, M.A. Mohd Ali, H.E. Ab Maulod and S.M. Se, "Optimization of Recycled Polypropylene Concrete Aggregates Processing Using Water-Assisted Melt Compounding via Response Surface Methodology," In Springer Proceedings in Physics, (2022): 47–54. https://doi:10.1007/978-981-19-9267-4_6

[4] N. Mohamad, A.A. Abd Ghani, M.A.A. Amran, J. Abd Razak, R.I. Raja Abdullah, M.A. Mohd Ali, H.E. Ab Maulod and S.S. Meng, "Brief Review on Potential Production of Plastic Waste Concrete Aggregates Using Water-Assisted Melt Compounding," In Symposium on Intelligent Manufacturing and Mechatronics 25, (2022): 523–532. https://doi:10.1007/978-981-16-8954-3_50

[5] M.J. Islam, M. Shahjalal and N.M.A. Haque, "Mechanical and Durability Properties of Concrete with Recycled Polypropylene Waste Plastic as a Partial Replacement of Coarse Aggregate," Journal of Building Engineering 54, (2022). https://doi:10.1016/j.jobe.2022.104597

[6] M.H. Nazir, A.H. Al-Marzouqi, W. Ahmed and E. Zaneldin, "The Potential of Adopting Natural Fibers Reinforcements for Fused Deposition Modeling: Characterization and Implications," Heliyon 9, 4, (2023): 15023. https://doi:10.1016/j.heliyon.2023.e15023

[7] S.K. Satya and P.S.R. Sreekanth, "An Experimental Study on Recycled Polypropylene and High-Density Polyethylene and Evaluation of Their Mechanical Properties," Materials Today: Proceedings 27, (2020): 920–924. https://doi:10.1016/j.matpr.2020.01.259

[8] S. Lee, J. Yoo and J.W. Lee, "Water-Assisted Extrusion of Polypropylene/Clay Nanocomposites in High Shear Condition," Journal of Industrial and Engineering Chemistry 31, (2015): 317–322. https://doi:10.1016/j.jiec.2015.07.004

[9] B. Sarde, Y. Patil, B. Dholakiya and V. Pawar, "Effect of Calcined Kaolin Clay on Mechanical and Durability Properties of PET Waste-Based Polymer Mortar Composites," Construction and Building Materials 318, (2021): 126027.
https://doi:10.1016/j.conbuildmat.2021.126027

[10] M. Gayathiri, T. Pulingam, K.T. Lee and K. Sudesh, "Activated Carbon from Biomass Waste Precursors: Factors Affecting Production and Adsorption Mechanism," Chemosphere 294, (2021): 133764.
https://doi:10.1016/j.chemosphere.2022.133764

[11] M.I. Nuryanta, L.G. Aryaswara, R. Korsmik, O. Klimova-Korsmik, A.D. Nugraha, S. Darmanto, M. Kusni and M.A. Muflikhun, "The Interconnection of Carbon Active Addition on Mechanical Properties of Hybrid Agel/Glass Fiber-Reinforced Green Composite," Polymers 15, 11, (2023): 2411.
https://doi:10.3390/polym15112411

[12] Y. Yim and B. Kim, "Preparation and Characterization of Activated Carbon / Polymer Composites : A Review," Polymers 15, (2023): 1–14.
https://doi:10.3390/polym15163472

[13] N.A. Musa, N. Mohamad, H.E. Ab Maulod, J. Abd Razak , A.M.M Edeerozey, M.I. Shueb and A.M.M. Albakri, "Effect of Screw Speed of Water-Assisted Compounding on The Properties of Recycled Polypropylene-Reinforced Metakaolin Composite," Proceedings of International Innovative Research and Industrial Dialogue 24, (2024): 110–114.

[14] A. Gupta, H. Singh, and R. Swalia, "Hybrid Filler Composition Optimization for Tensile Strength of Jute Fibre-Reinforced Polymer Composite," Bulletin of Materials Science 39, 5, (2016):1223–1231.
https://doi:10.1007/s12034-016-1248-1

[15] A. Abdelhafeez, Y. Abdelrahman, M.E.S. Soliman and S.M. Ahmed, "Comparative Effects of Carbon Fiber Reinforcement on Polypropylene and Polylactic Acid Composites in Fused Deposition Modeling," Journal of Engineering Science 53, 1, (2025): 25–44.
https://doi:10.21608/jesaun.2024.334433.1381

[16] H. Junaedi, E. Albahkali, M. Baig, A. Dawood and A. Almajid, "Ductile to Brittle Transition of Short Carbon Fiber-Reinforced Polypropylene Composites," Advances in Polymer Technology 20, (2020): 6714097.
https://doi:10.1155/2020/6714097

[17] N.V. Stanciu, F. Stan, I.L. Sandu, C. Fetecau and A.M. Turcanu, "Thermal, Rheological, Mechanical, and Electrical Properties of Polypropylene/Multi-Walled Carbon Nanotube Nanocomposites," Polymers 13, 2, (2021): 1–22.
https://doi:10.3390/polym13020187

[18] Y. Zare, "An Approach to Study the Roles of Percolation Threshold and Interphase in Tensile Modulus of Polymer/Clay Nanocomposites," Journal of Colloid Interface Science 486, (2017): 249–254.
https://doi:10.1016/j.jcis.2016.09.080

[19] A. Bin Rashid, M. Haque, S.M.M. Islam and K.M.R. Uddin Labib, "Nanotechnology-Enhanced Fiber-Reinforced Polymer Composites: Recent Advancements on Processing Techniques and Applications," Heliyon 10, 2, (2024): 24692.
https://doi:10.1016/j.heliyon.2024.e24692

[20] S. Chong, T.C.K Yang, K.C. Lee, Y.F. Chen, J.C. Juan, T.J. Tiong, C.M. Huang and G.T. Pan, "Evaluation of the Physico-Mechanical Properties of Activated-Carbon Enhanced Recycled Polyethylene/Polypropylene 3D Printing Filament," Sadhana – Academy Proceedings in Engineering Sciences 45, 1, (2020): 10–15.
https://doi:10.1007/s12046-020-1294-7

[21] G. Wypych, "The Effect of Fillers on the Mechanical Properties of Filled Materials," (Handbook of Fillers, 5th Edition, 2021), 525–608.
https://doi:10.1016/b978-1-927885-79-6.50011-2