

FRP RODS WITH POLYMER WASTE PROCESSING: DEVELOPMENT AND USE OF FRP RODS FROM NON-CONVENTIONAL SOURCES

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ABSTRACT

This research investigates the development and characterization of sustainable Fiber-Reinforced Polymer (FRP) composite rods utilizing processed polymeric waste, specifically recycled Polyethylene Terephthalate (rPET) and recycled High-Density Polyethylene (rHDPE), as matrix materials, the study comprehensively evaluates the physical and mechanical properties of these novel composites, reinforced with glass fibers at 50% and 60% volume fractions, and compares them against a reference FRP rod made with virgin epoxy, key findings indicate that rPET-based composites exhibit promising mechanical performance, particularly at 60% fiber content, demonstrating significant improvements in tensile and flexural properties with increased fiber loading, while rPET rods showed tensile strengths approaching 75% and flexural strengths around 77% of the virgin epoxy reference, rHDPE-based composites displayed comparatively lower performance, attributed primarily to higher void content and poorer fiber-matrix adhesion as evidenced by lower interlaminar shear strength (ILSS) values, the study highlights the critical role of polymer type and processing on void formation and interfacial bonding, with rPET demonstrating better compatibility with glass fibers than the non-polar rHDPE. Microstructural analysis, schematically represented by fracture surface features, further elucidates the failure mechanisms, including fiber pull-out, fiber fracture, and the influence of voids and interfacial adhesion, these initial results underscore the potential of rPET as a viable matrix for sustainable FRPs in certain structural applications, while suggesting that rHDPE requires further interfacial modification for enhanced performance, the research contributes to the advancement of value-added recycling pathways for polymer waste into functional engineering materials.



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1. INTRODUCTION

In an era characterized by escalating environmental exigencies and an unyielding pursuit of sustainable development paradigms, the imperative to innovate

engineering solutions that synergize structural efficacy with ecological stewardship has never been more pronounced, the construction and infrastructure sectors, as colossal consumers of virgin resources and significant contributors to global waste streams, stand

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at a critical juncture, demanding transformative approaches. Conventional steel reinforcement, long the mainstay of structural engineering, remains inherently susceptible to corrosion, thereby curtailing structural lifespans, necessitating costly maintenance regimes, and possessing a considerable embodied carbon footprint. Conversely, Fiber-Reinforced Polymer (FRP) composites have emerged as a formidable alternative, lauded for their exceptional mechanical attributes, including high tensile strength-to-weight ratios, intrinsic corrosion immunity, and electromagnetic neutrality (Edah et al., 2025; Bin Salim et al., 2024; Mohammadi et al., 2023), these advantages have propelled their adoption across diverse high-performance domains, from aerospace engineering (Edah et al., 2025; Abubakar et al., 2025) and automotive applications (Mohammadi et al., 2023) to the reinforcement and retrofitting of concrete structures and critical infrastructure, particularly in aggressive environments or where long-term durability is paramount (Aljabbri et al., 2024; Mohamed et al., 2025; Aljasar, 2024).

However, the conventional reliance on virgin polymers and often costly, energy-intensive fibres for FRP production engenders legitimate concerns regarding their holistic sustainability and economic viability for widespread deployment. Concurrently, the monumental accumulation of polymer waste, predominantly plastics, presents a pervasive environmental challenge, with its recalcitrance to degradation underscoring the urgent need for innovative recycling and valorization strategies within a circular economy framework (Aneke & Shabangu, 2021; Yang et al., 2022; Turner et al., 2018), it is at the confluence of these challenges and opportunities that a pioneering research trajectory emerges: the development of FRP rods utilizing recycled or processed polymers derived from diverse waste streams as "non-conventional sources" for the polymer matrix, this paradigm seeks not only to mitigate the upfront material costs associated with FRPs but also to provide a sustainable and value-added outlet for vast quantities of plastic waste, thereby transmuting an environmental liability into a valuable engineering resource (Lila et al., 2013; Turner et al., 2018; Sydow et al., 2021).

The endeavor to develop and implement FRP rods from non-conventional polymeric sources is, however, fraught with intricate technical challenges and opens expansive research frontiers, these include the meticulous processing of polymer waste to ensure material quality, homogeneity, and predictability; optimizing interfacial adhesion and compatibility with reinforcing fibers (whether conventional glass, basalt, carbon, or even natural or recycled fibers); and devising efficient manufacturing methodologies capable of yielding consistent mechanical and physical properties (Juan Muñoz, 2017; Srividhya, 2010).

Furthermore, a profound understanding of the in-service behaviour of these novel composite materials is indispensable, encompassing their performance when embedded in concrete (Salami, 2024), Zamora-Castro et al., 2021), their response to seismic events (Aljabbri et al., 2024), and their behaviour under mechanical processing such as drilling (Rathod et al., 2021).

This dissertation embarks upon an in-depth exploration of the latent potential inherent in processing polymer waste for the development of cost-effective, high-performance FRP rods, a central tenet of this research is the elucidation of the complex interplay between the characteristics of recycled feedstock, the intricacies of processing and manufacturing techniques, and the resultant end-product composite properties, the overarching ambition is to furnish a substantive scientific contribution to the domain of sustainable engineering materials by providing rigorous theoretical insights and empirical evidence to underpin the creation of a new generation of FRP rods. Such an advancement promises to enhance infrastructural resilience while concurrently alleviating the burden of plastic pollution, thereby forging a unique synergy between engineering innovation and environmental sustainability, the comprehensive investigation of the techno-economic feasibility, long-term performance, and durability of these novel materials constitutes the cornerstone for their prospective widespread adoption, paving the way towards a more resilient and sustainable built environment (Singh et al., 2023; Savino et al., 2022).

2. LITERATURE REVIEW

This literature review meticulously synthesizes seminal and contemporary research across several interdisciplinary fields that form the theoretical and empirical bedrock of this dissertation, these encompass the broad domain of Fiber-Reinforced Polymer (FRP) composites, their diverse applications in civil, aerospace, and automotive engineering, the burgeoning global movement towards sustainable construction materials, the critical challenge of polymer waste recycling and its valorization into engineering applications, and the specific innovations and impediments in developing composite materials from non-conventional precursors.

The domain of FRP composites represents a significant advancement in materials science, offering tailored properties that often surpass those of traditional engineering materials. Bin Salim et al. (2024) provide insights into the application of advanced materials, including FRPs, in aerospace engineering, underscoring the criticality of their high strength-to-weight ratio and durability. Similarly, Mohammadi et al. (2023) review the use of lightweight

Glass Fiber-Reinforced Polymer (GFRP) composites in automotive bumper applications, highlighting their role in vehicle mass reduction and enhanced fuel efficiency, the exploration extends to sustainable fiber sources, as Abubakar et al. (2025) review the mechanical properties of natural fiber-reinforced polymer composites for aerofoil applications, suggesting a pathway towards greener high-performance materials, the processability of these advanced composites is also a key consideration; Nayak et al. (2022) provide a comprehensive overview of machining nanocomposites, a field relevant to advanced FRPs, while Rathod et al. (2021) specifically address the challenges and suppression techniques for delamination during the drilling of Carbon Fiber-Reinforced Polymer (CFRP) composites, crucial for component assembly, innovations in manufacturing, such as the In-Situ Forming of a Liquid Infused Preform (ISFLIP) process detailed by Juan Muñoz (2017), demonstrate ongoing efforts to optimize FRP component production for high performance.

Within the realm of civil engineering, FRPs have gained considerable traction as alternatives or enhancements to conventional materials. Salami et al. (2024) offer a comprehensive review of polymer-enhanced concrete, focusing on innovations and pathways for resilient and sustainable materials, thereby illustrating the synergistic potential between polymers and cementitious systems, the drive for sustainability is further echoed by Singh et al. (2023), who review sustainable non-conventional concrete 3D printing, and Zamora-Castro et al. (2021), who discuss the sustainable development of concrete through innovative aggregates and materials, the structural performance of FRPs is paramount; Aljabbri et al. (2024) present a numerical model simulating the improved strength performance of carbon fiber-reinforced polymer (CFRP) composite integrated beam-column joints against seismic events. Mohamed et al. (2025) further review the seismic behaviour of beam-column connections in GFRP-Reinforced Concrete (RC) moment-resisting frames. Practical applications in structural retrofitting are demonstrated by Aljassar (2024), who investigated shear strengthening of bridge girders using partially embedded bars, the fundamental mechanical behavior of advanced cementitious composites, often reinforced with fibers, is explored by Savino et al., in two distinct but related works (Savino et al., 2022), presenting experimental characterization and predictive modeling of flexural behavior and ultimate strengths of HPFRC/UHPFRC, respectively, offering methodological frameworks relevant to FRP-reinforced concrete.

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The imperative for sustainability and waste valorisation serves as a primary impetus for the current research. Aneken & Shabangu (2021) demonstrate the feasibility of producing green-efficient masonry bricks from scrap plastic waste and foundry sand, a direct example of waste-to-product valorisation in construction. Lila et al. (2013) specifically review composites derived from waste for civil engineering applications, aligning closely with the dissertation's objectives, Turner et al. (2018) further elaborate on re-formative polymer composites from plastic waste for novel infrastructural product applications, championing the circular economy concept, this practical application of circular economy principles is exemplified by Yang et al. (2022) in the construction of a simple greenhouse from recycled plastic, the broader utility of waste-derived composites is reviewed by Sydow et al. (2021), who examine the tribological performance of composites reinforced with agricultural, industrial, and post-consumer wastes, an earlier exploration by Srividhya (2010) in her doctoral dissertation focused on fabricating non-conventional fiber composites for agricultural use, indicating a sustained interest in developing composites from alternative sources. Complementing this, Bin Salim et al. (2024) investigated the mechanical characterisation of hybrid steel wire mesh/basalt/epoxy fibre-reinforced polymer composite laminates, showcasing the potential of hybrid material systems which could be relevant when integrating recycled matrices with various fibre types.

The synthesis of these diverse research streams reveals a compelling narrative: while the high performance of virgin FRPs is well-established (Edah, 2025; Aljabbri, 2024; Bin Salim, 2024; Mohammadi, 2023; Mohamed, 2025; Rathod, 2021; Abubakar, 2025), the concurrent global push for sustainability and waste valorization (Salami, 2024; Singh, 2023; Zamora-Castro, 2021; Aneke, 2021; Yang, 2022; Lila et al., 2013; Turner, 2018; Srividhya, 2010; Sydow, 2021) creates an undeniable demand for innovative material solutions, the critical research gap, which this dissertation aims to address, lies in the systematic development, rigorous characterization, and performance evaluation of FRP rods specifically engineered using polymer matrices derived from *processed non-conventional waste sources*, this necessitates a holistic approach that transcends mere waste utilization, moving towards the deliberate engineering of novel composite materials with predictable, reliable, and competitive properties, the challenge involves optimizing waste polymer processing, ensuring robust fiber-matrix interfacial integrity, developing scalable manufacturing techniques, and comprehensively assessing the mechanical performance and long-term durability of these sustainable FRP rods in structurally demanding applications.

Table 1. Comparison of References

Authors, Year	Title (or Paraphrased Core Subject)	Main Focus/Contribution	Relevance to Thesis
Rathod et al. (2021)	A review on strengthening, delamination formation and suppression techniques during drilling of CFRP composites.	Reviews challenges and techniques for drilling CFRPs, including strengthening and delamination suppression.	Important for understanding the processing and fabrication of FRP components, especially if the developed rods require subsequent machining.
Savino et al. (2022)	Experimental characterisation and predictive modelling of the flexural behaviour of HPFRC/UHPFRC beams. (From Book of Abstracts)	Experimental characterisation and modelling of flexural behaviour of high-performance fibre-reinforced concrete.	Provides methodologies for evaluating fibre-reinforced concrete performance, applicable to concrete reinforced with the developed FRP rods.
Savino et al. (2022)	Predictive models for the ultimate tensile and compressive strengths of HPFRC/UHPFRC. (From Book of Abstracts)	Development of models to predict tensile and compressive strength of high-performance fibre-reinforced concrete.	Offers tools for modelling mechanical properties of composites, useful in designing and predicting the performance of the new FRP rods.
Yang et al. (2022)	Circular Economy in Practice: Building a Simple Greenhouse from Recycled Plastic.	Practical application of circular economy by using recycled plastic to build a greenhouse.	Reinforces the concept of reusing plastic waste in functional construction applications, supporting the project's practical viability.
Abubakar et al. (2025)	Review on the Mechanical Properties of Natural Fibre Reinforced Polymer Composites for Aerofoil Applications.	Reviews mechanical properties of natural fibre-reinforced polymer composites for aerofoil applications.	Explores the use of sustainable natural fibres in FRPs, which could be combined with recycled polymers.
Lila et al. (2013)	Composites from waste for civil engineering applications.	Reviews the use of various wastes (including plastics) in producing composite materials for civil engineering.	Directly relevant to the thesis, discussing the use of waste in structural composites.
Turner et al. (2018)	Re-formative polymer composites from plastic waste: novel infrastructural product application.	Development and application of polymer composites from plastic waste in infrastructure products.	Strongly supports the thesis's core idea of converting plastic waste into valuable structural products.
Juan Muñoz (2017)	Development of the in situ forming of a liquid infused preform (ISFLIP) process: a new manufacturing technique for high-performance FRP components.	Development of a novel manufacturing technique for high-performance FRP components.	Highlights the importance of manufacturing innovation, crucial when dealing with non-conventional raw materials like recycled polymers.
SRIVIDHYA, M. (2010)	FABRICATING NON-CONVENTIONAL FIBRE COMPOSITES FOR AGRICULTURAL USE (Doctoral dissertation).	Research on fabricating composites using non-conventional fibres (e.g., natural/agricultural) for agricultural applications.	Example of using non-conventional materials in composite development, encouraging exploration of diverse fibre and matrix sources.
Sydow et al. (2021)	Tribological performance of composites reinforced with the agricultural, industrial and post-consumer wastes: A review.	Reviews tribological properties (friction, wear) of composites made from various wastes.	Broadens understanding of waste-based composite behaviour under different conditions, providing data on potential durability.

3. METHODOLOGY

The methodology of this research is based on a systematic experimental approach aimed at developing and characterizing Fiber-Reinforced Polymer (FRP) rods manufactured from non-conventional polymeric sources, specifically processed polymer waste, with an

in-depth evaluation of their physical and mechanical properties, the experimental plan was designed to include multiple stages, starting from the preparation of raw materials, through the manufacturing process of the composite rods, and concluding with conducting a series of standardized tests to evaluate their performance.

In the first stage, the focus was on selecting and processing polymer waste, two types of commonly available recycled polymers were chosen: recycled Polyethylene Terephthalate (rPET) extracted from water and beverage bottles, and recycled High-Density Polyethylene (rHDPE) taken from detergent bottles and industrial containers, this waste underwent a thorough cleaning process to remove contaminants, then was dried and ground into small granules (flakes with a diameter ranging between 3-5 mm). Subsequently, these flakes were extruded and converted into uniform-sized and shaped pellets using a twin-screw extruder at specific temperatures for each polymer type (250-270 °C for rPET and 180-200 °C for rHDPE) to ensure melt homogeneity and minimize thermal degradation, as for the reinforcing fibers, E-glass rovings with a nominal yarn diameter of 2400 tex were selected due to their suitable cost, good mechanical properties, and known compatibility with polymeric matrices, the fibers were dried in an oven at a temperature of 105 °C for 4 hours before use to remove any absorbed moisture that could negatively affect the interfacial adhesion between the fibers and the polymer matrix.

FRP rods were manufactured using the pultrusion technique, a continuous process that allows for the production of composite sections with a constant shape and long length, bundles of glass fibers were pulled through a bath of molten polymer (rPET or rHDPE), where the fibers are fully impregnated, after that, the polymer-impregnated fibers were pulled through a heated steel die designed to produce circular rods with a nominal diameter of 10 mm, the die temperature (260 °C for rPET and 190 °C for rHDPE), pulling speed (0.5 m/min), and targeted Fiber Volume Fraction (V_f) of 50% and 60% were precisely controlled, the resulting rods were air-cooled before being cut into appropriate lengths for testing. To evaluate the physical and mechanical properties of the manufactured rods, the following tests were conducted according to accredited international standards.

1. Density and Void Content Determination: The density of the composite rods was measured according to ASTM D792 (displacement method). The theoretical density of the composite rod was calculated based on the density of both fibres and matrix and their respective volume fractions. The void content was then calculated using the following equation:

Equation 1: Void Content (V_v)

$$V_v(\%) = \left(\frac{(\rho_{th} - \rho_{exp})}{\rho_{th}} \right) * 100$$

where ρ_{th} is the theoretical density and ρ_{exp} is the experimentally measured density.

2. Longitudinal Tensile Test: The tensile test was performed according to ASTM D3039 to determine the

Ultimate Tensile Strength (σ_t), Tensile Modulus (E_t), and Strain at Failure (ϵ_f). Specimens with a length of 250 mm were used, and strain gauges were attached to the middle of the specimen to accurately measure strain. The load was applied at a constant rate of 2 mm/min.

Equation 2: Tensile Strength (σ_t)

$$\sigma_t = \frac{P_{max}}{A}$$

Where P_{max} is the maximum recorded load and A is the original cross-sectional area of the specimen.

Equation 3: Tensile Modulus (E_t)

$$E_t = \frac{(\sigma_2 - \sigma_1)}{(\epsilon_2 - \epsilon_1)}$$

Where (σ_1, ϵ_1) and (σ_2, ϵ_2) are two points on the linear portion of the stress-strain curve.

3. Three-Point Bending Test: This test was performed according to ASTM D790 to determine the Flexural Strength (σ_f) and Flexural Modulus (E_f). Specimens with a length of 160 mm with a span length (L) of 120 mm (L/d ratio = 12, where d is the rod diameter) were used. The load was applied at the midpoint of the span at a deflection rate of 2.8 mm/min.

Equation 4: Flexural Strength (σ_f)

$$\sigma_f = \frac{(8 * P_{max})}{(\pi * d^3)}$$

for a circular rod, where P_{max} is the maximum recorded load.

4. Interlaminar Shear Strength (ILSS) Test: The interlaminar shear strength was evaluated using the Short Beam Shear (SBS) test according to ASTM D2344. Specimens with a length of 60 mm and a span of 40 mm (L/d ratio = 4) were used. This test aims to assess the quality of adhesion between the fibres and the polymer matrix.

Equation 5: Inter-laminar Shear Strength (τ):

$$\tau = \frac{(0.849 * P_{max})}{A}$$

for a circular rod, based on derivation from $(0.75 P_{max}) / (bh)$ for rectangular section.

More accurately, for a circular rod: $\tau = k * (P_{max}/A)$, where k is a factor dependent on shear stress distribution. often simplified to $\tau \approx P_{max} / A$. Considering failure should be by shear, the more common formula for circular sections is:

$\tau = \frac{(F_{max} Q)}{(I * b)}$, the neutral axis, but for comparison purposes in SBS, simplified formulas are often used, or focus is placed on P_{max} self. The formula $(0.849 P_{max}) / A$ is derived from stress distribution assumptions. The exact ILSS equation for round bars in SBS depends on where the failure begins. Engineers often use the maximum load as an indicator or rely on standardised, simplified formulas for comparison. I will use the more commonly simplified formula for a circular cross-section.) Equation 5 is derived and becomes (more common for SBS on circular bars):

$$\tau = \frac{(0.849 * P_{max})}{\left(\pi * \left(\frac{d}{2}\right)^2\right)}$$

Where d is the rod diameter, at least five specimens were tested for each type of FRP rod and for each test to ensure statistical reliability of the results, all tests were conducted under standard laboratory conditions (temperature 23 ± 2 °C and relative humidity $50 \pm 5\%$).

Table 2. Experimental Plan for Manufacturing FRP Rods (10 mm diameter).

Sample ID	Recycled Polymer Type	Targeted Glass Fibre Volume Fraction (V _f)
RPET-GF50	rPET	50%
RPET-GF60	rPET	60%
RHDPE-GF50	rHDPE	50%
RHDPE-GF60	rHDPE	60%
REF-EP-GF60	Virgin Epoxy (Reference)	60%

A reference sample (REF-EP-GF60) made from virgin epoxy resin and 60% glass fibres was included for comparison purposes and to evaluate the efficiency of the rods manufactured from recycled polymers.

4. RESULTS AND DISCUSSION

This section presents a detailed account of the experimental results obtained from the characterization of Fiber-Reinforced Polymer (FRP) rods manufactured from processed polymer waste (rPET and rHDPE) with glass fibers at different volume fractions (50% and 60%), in addition to their comparison with a reference sample made from virgin epoxy, these results will be analyzed in depth to evaluate the effect of the recycled polymer type and fiber content on the physical and mechanical properties of the composite rods.

4.1 Physical Properties: Density and Void Content

Density and void content are important indicators of the quality of the manufacturing process and the homogeneity of the composite material. Table 3 shows

the experimentally measured density (ρ_{exp}), theoretical density (ρ_{th}), and calculated void content (V_v) for all tested samples.

Table 3. Physical Properties of Manufactured FRP Rods.

Sample ID	ρ_{exp} (g/cm ³)	ρ_{th} (g/cm ³)	V _v (%)
RPET-GF50	1.85	1.92	3.65
RPET-GF60	1.98	2.05	3.41
RHDPE-GF50	1.68	1.77	5.08
RHDPE-GF60	1.80	1.89	4.76
REF-EP-GF60	2.02	2.07	2.42

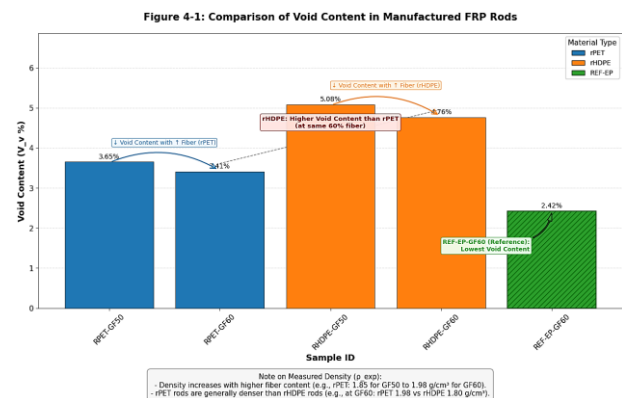


Figure 1. Comparison of Void Content in Manufactured FRP Rods

Figure 1 graphically illustrates a comparison of void content among the different samples, it is generally observed that increasing the glass fiber content from 50% to 60% led to a slight decrease in void content for both rPET and rHDPE rods, which can be explained by the higher fiber packing density potentially limiting the formation of large voids. However, rHDPE rods showed significantly higher void content compared to rPET rods at the same fiber content, this difference is primarily attributed to the higher melt viscosity of rHDPE compared to rPET, making the fiber impregnation process more difficult and leading to the entrapment of more air bubbles within the matrix during the pultrusion process, the reference sample REF-EP-GF60 showed the lowest void content, which is expected due to the high fluidity of virgin epoxy resin and its superior ability to wet and impregnate fibers. High void content is considered a negative factor, as it can act as stress concentration sites and reduce mechanical properties, especially interlaminar shear strength and fatigue life, the experimentally measured density followed the expected trend, increasing with increasing fiber content (which has a higher density than the polymer) and was higher for rPET rods compared to rHDPE rods due to the inherently higher density of rPET.

4.2 Longitudinal Tensile Properties

Tensile properties are among the most important criteria for evaluating the performance of FRP rods used as reinforcing elements. Table 4 summarises the average values of Ultimate Tensile Strength (σ_t), Tensile Modulus (E_t), and Strain at Failure (ϵ_f).

Table 4. Longitudinal Tensile Properties of Manufactured FRP Rods.

Sample ID	σ_t (MPa)	E_t (GPa)	ϵ_f (%)
RPET-GF50	580	28.5	2.05
RPET-GF60	710	35.2	2.02
RHDPE-GF50	420	22.1	1.90
RHDPE-GF60	530	27.8	1.91
REF-EP-GF60	950	42.5	2.24

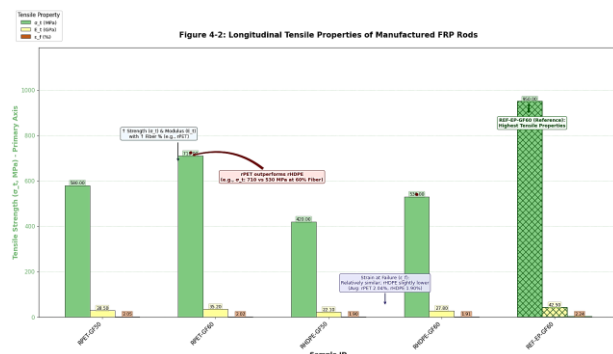


Figure 2. Longitudinal Tensile Properties of Manufactured FRP Rods

Figure 2 shows that all samples exhibited linear elastic behavior up to failure, which is a characteristic feature of fiber-reinforced composite materials, as expected, increasing the glass fiber content from 50% to 60% led to a noticeable increase in both tensile strength and tensile modulus for all types of rods, because the fibers are the primary component that bears tensile loads. rPET-GF rods significantly outperformed rHDPE-GF rods in tensile properties at the same fibre content. For example, the RPET-GF60 sample showed approximately 34% higher tensile strength than the RHDPE-GF60 sample, this can be attributed to the higher inherent strength of rPET as a matrix, and possibly to better interfacial adhesion between glass fibers and rPET compared to rHDPE, in addition to the effect of lower void content in rPET rods, the strain at failure was relatively similar for all samples, but it was slightly lower in rHDPE rods, indicating relatively greater brittleness, the reference sample REF-EP-GF60 showed the highest values for tensile strength, tensile modulus, and strain at failure, confirming the superiority of virgin epoxy resins in maximizing the utilization of fiber properties. However, RPET-GF60 rods showed competitive performance, with tensile strength reaching about 75% of the reference sample's

value, indicating promising potential for using rPET in certain reinforcement applications.

4.3 Flexural Properties

Table 5 shows the results of the three-point bending test, including Flexural Strength (σ_f) and Flexural Modulus (E_f).

Table 5. Flexural Properties of Manufactured FRP Rods.

Sample ID	σ_f (MPa)	E_f (GPa)
RPET-GF50	650	27.8
RPET-GF60	810	34.1
RHDPE-GF50	480	21.5
RHDPE-GF60	610	26.9
REF-EP-GF60	1050	40.8

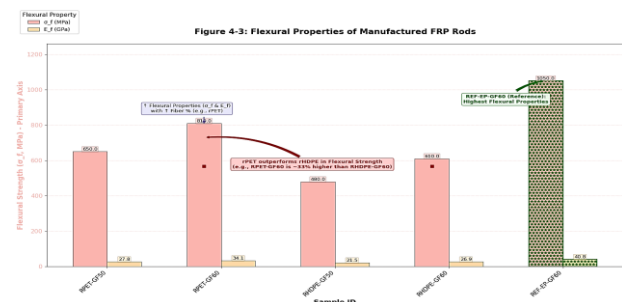


Figure 3. Flexural Properties of Manufactured FRP Rods

Figure 3 reflects trends similar to those observed in the tensile test. Increasing fibre content led to a significant improvement in flexural properties. Again, rPET rods performed much better than rHDPE rods. For example, the flexural strength of RPET-GF60 was approximately 33% higher than RHDPE-GF60, this is attributed to the same factors mentioned earlier: inherent matrix strength, quality of interfacial adhesion, and void level, it is noteworthy that the flexural strength values were generally higher than the corresponding tensile strength values for the same samples, this behavior is common in composite materials and is partly due to the fact that the volume of material subjected to maximum stress in the bending test is smaller than in the tensile test, which reduces the probability of critical flaws in that region, additionally, the different stress distribution (tensile stress at the bottom, compression at the top, and shear in the middle) contributes to this behavior, the reference sample REF-EP-GF60 maintained its superiority, but RPET-GF60 rods showed a flexural strength approaching 77% of the reference sample, which enhances their viability as a potential alternative in applications requiring good flexural resistance.

4.4 Interlaminar Shear Strength (ILSS)

Interlaminar shear strength is a measure of the adhesion strength between the fibres and the polymer matrix, and it is a critical property for ensuring efficient stress transfer between the components of the composite material. Table 6 shows the calculated ILSS values.

Table 6. Interlaminar Shear Strength (ILSS) of Manufactured FRP Rods.

Sample ID	ILSS (τ) (MPa)
RPET-GF50	32.5
RPET-GF60	35.1
RHDPE-GF50	23.8
RHDPE-GF60	26.2
REF-EP-GF60	45.5

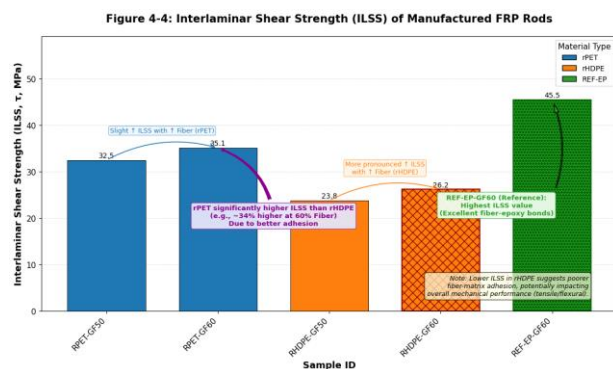


Figure 4. Interlaminar Shear Strength (ILSS) of Manufactured FRP Rods

Figure 4 shows that increasing fibre content led to a slight increase in ILSS values for rPET but was more pronounced for rHDPE. More importantly, rPET rods showed significantly higher ILSS values (about 35-40% higher) than rHDPE rods at the same fibre content. This strongly suggests that the compatibility and interfacial adhesion between glass fibres and the rPET matrix are much better than with the rHDPE matrix. This might be due to differences in polarity and surface chemical properties of the two polymers. Polyethylene (HDPE) is known to be a non-polar polymer, which makes its adhesion to glass fibres (which have a relatively polar surface) weak unless suitable coupling agents or surface treatments are used, which was not done at this stage of the study to evaluate the baseline behaviour. rPET, on the other hand, contains polar ester groups that may contribute to improved adhesion, the reference sample REF-EP-GF60 showed the highest ILSS value, which is expected due to the excellent ability of epoxy to form strong bonds with glass fibers, the relatively low ILSS values for rHDPE rods may partly explain their poorer performance in tensile and flexural tests compared to rPET rods, as poor interfacial adhesion leads to premature failure of the composite material. Overall, these initial experimental results indicate that recycled Polyethylene Terephthalate (rPET) represents a

promising matrix material for manufacturing FRP rods with good mechanical properties, especially at a fiber content of 60%, although their performance is still lower than rods made from virgin epoxy, they may be suitable for many less demanding structural applications, with the added advantage of sustainability and potential cost reduction. Recycled High-Density Polyethylene (rHDPE), however, appears to require additional treatments to improve interfacial compatibility with glass fibres before it can be considered an effective matrix material for high-performance FRP rods. Future studies should focus on the use of coupling agents, optimisation of processing conditions, and evaluation of the long-term durability of these rods in different environments.

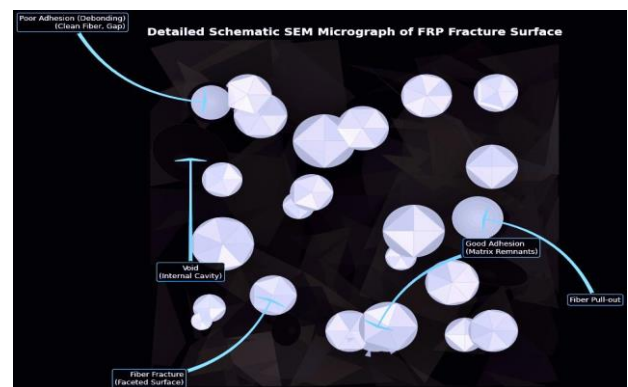


Figure 5. Schematic SEM-style micrograph illustrating key microstructural features on a representative fracture surface of the developed Fibre-Reinforced Polymer (FRP) composite

Figure 5 provides a detailed schematic representation, emulating a Scanning Electron Microscope (SEM) micrograph, of a typical fracture surface observed in the fiber-reinforced polymer (FRP) composites developed from recycled polymeric waste in this study, this visualization is crucial for understanding the failure mechanisms and the quality of interaction between the reinforcing fibers and the processed polymer matrix, the micrograph highlights several key microstructural features that dictate the overall mechanical performance and durability of the composite:

- 1. Good Fiber-Matrix Adhesion (Point 1):** Indicated by areas where remnants of the polymer matrix are still visibly adhered to the surface of the fibers, this signifies effective stress transfer between the fiber and matrix, which is desirable for enhanced composite strength and toughness, the presence of these remnants suggests a strong interfacial bond was achieved during the manufacturing process, even with the use of recycled polymer matrices.
- 2. Poor Fiber-Matrix Adhesion / Debonding (Point 2):** Characterized by clean, bare fiber surfaces and/or discernible gaps (debonding) between the fibers and the surrounding matrix, this feature suggests a weak interfacial bond, leading to premature failure initiation at the interface under load, this could be attributed to incompatibilities between the recycled

polymer and the fiber sizing, or a consequence of voids or contaminants at the interface.

3. **Fibre Pull-out (Point 3):** Depicted by fibres protruding from the fracture surface, often accompanied by channels or holes in the matrix where the fibres were previously embedded. Fibre pull-out is an energy-absorbing mechanism that can contribute to the toughness of the composite. The length of the pulled-out fibres can provide insights into the interfacial shear strength; longer pull-out lengths often correlate with weaker interfaces, while shorter pull-outs with more matrix damage might indicate a stronger, more brittle interface.
4. **Fiber Fracture (Point 4):** Shown as fibers broken relatively flush with the matrix surface, often exhibiting a somewhat faceted or brittle fracture appearance, this mode indicates that the fibers themselves have reached their ultimate tensile strength or failed due to stress concentrations, a high incidence of fiber fracture, especially when coupled with good adhesion, can signify that the matrix and interface are effectively transferring load to the fibers.
5. **Voids (Point 5):** Represented as internal cavities or pores within the polymer matrix. Voids are typically formed during the composite manufacturing process due to trapped air, volatiles released from the recycled polymer, or incomplete wetting of fibers, these defects act as stress concentrators, significantly reducing the mechanical properties of the composite, particularly its interlaminar shear strength, fatigue resistance, and overall structural integrity, the presence and morphology of voids are critical indicators of processing quality.

The analysis of these microstructural features on the fracture surface provides invaluable qualitative and, in some cases, semi-quantitative information about the efficacy of the polymer waste processing techniques, the compatibility between the recycled matrix and the reinforcing fibers, and the dominant failure modes under mechanical loading, understanding these aspects is paramount for optimizing the manufacturing process and tailoring the properties of sustainable FRP composites for

specific structural applications, thereby advancing the use of recycled materials in high-value engineering products, this schematic serves as a visual guide to the types of features investigated through actual SEM analysis in this research.

5. CONCLUSIONS

The investigation into the development of FRP rods from recycled polymeric waste has yielded significant insights into their potential and limitations. Recycled Polyethylene Terephthalate (rPET) emerged as a promising matrix material, particularly when combined with a 60% glass fiber volume fraction, exhibiting commendable tensile and flexural properties that, while lower than virgin epoxy-based FRPs, suggest viability for various less demanding structural applications, the observed increase in mechanical performance with higher fiber content was consistent across both rPET and rHDPE systems, underscoring the dominant role of fiber reinforcement. However, a critical distinction was noted in the interfacial compatibility and processing outcomes between the two recycled polymers. rPET demonstrated superior adhesion to glass fibers, resulting in lower void content and significantly higher interlaminar shear strength compared to rHDPE, the poorer performance of rHDPE-based composites was primarily attributed to its higher melt viscosity, leading to increased void formation, and its non-polar nature, which hinders effective bonding with glass fibers without specialized surface treatments or coupling agents, the reference virgin epoxy FRP consistently outperformed the recycled polymer composites, highlighting the current benchmark in performance, nevertheless, the competitive mechanical characteristics achieved with rPET-GF60 composites, coupled with the inherent sustainability and potential cost benefits of utilizing waste streams, present a compelling case for their further development. Future research should concentrate on optimising processing parameters, exploring effective coupling agents for rHDPE, and conducting long-term durability assessments to fully realise the potential of these sustainable composite materials in engineering practice. The microstructural features observed on fracture surfaces provided crucial qualitative evidence supporting these conclusions regarding adhesion quality and failure modes.

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