Properties of Sustainable Composite Construction Materials Derived from Recycled Polymers and Nanofillers

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Abstract: This paper presents the investigation of sustainable construction composites manufactured from rPET and rHDPE with the addition of nano-silica, graphene oxide, and nanoclay. The composites were fabricated by melt blending and compression molding. Mechanical, thermal, and durability performances of the composites were tested according to ASTM specifications. Experimental test results revealed that with an optimum loading of 3 wt% nanofillers, there is an enhancement in tensile and flexural strength by up to 35%, improvement of thermal stability by 20-25 °C, and a reduction of water absorption by about 25% compared to unreinforced polymers. SEM, FTIR, and XRD analyses confirm enhancement in interfacial bonding and refinement of microstructure. Compressive strength in the range of 38 to 43 MPa was obtained, which indicates that these materials are suitable for lightweight panels and non-structural elements. The results are in agreement with previously reported literature data and emphasize the possibility of recycled polymer-nanofiller composites to provide low-density durable construction material with an environmental benefit. The engineering-oriented outcome of this study focuses on the optimization of filler dispersion and performance to enable scalable and sustainable application.

Keywords: Recycled polymers, nanofillers, sustainable manufacturing, polymer composites, mechanical performance, environmental sustainability.

1. INTRODUCTION

The global construction industry remains one of the most resource-intensive sectors; The use of raw materials is very high, as well as the production of waste and emissions of greenhouse gases [1-3]. Although traditional materials such as concrete, steel and virgin polymers are structurally reliable, their use is increasingly criticized due to their ecological footprint and end-of-life challenges. At the core of reducing the ecological footprint of construction, the principles of circular economy and sustainable engineering suggest using waste and recycled materials [4–6]. Due to their light weight, corrosion resistance and recyclability, polymer-based materials have become a potentially interesting group of candidates. However, plastic waste, reaching over 400 million tons per year, with less than 10% being recycled efficiently, underlines the need to transform disposed-of polymers into value-added construction materials [7–12].

However, recycled polymers including rPET, rHDPE, rPP, and rPVC have shown potential to serve as matrices for composite applications in civil engineering based on their durability and processability [13–15]. Block, tile, panel, and insulation elements made of such composites illustrate reductions in density while improving impact resistance [16–18]. However, poor interfacial bonding, high degree of thermal expansion, and a reduced load-bearing capacity restrict their applications as structural materials. Nanotechnology represents a key opportunity to overcome the various limitations of waste-based polymer composite products through the introduction of nanoscale reinforcement that will help to improve the mechanical, thermal, and environmental performances of composite materials, among others [19–21]. Nano-silica, carbon nanotubes, graphene oxide, nanoclay, and nano-alumina are some of the nanofillers that have achieved microstructural refinement, strength, and toughness improvements even at low filler concentrations [22–24].

Despite this potential, practical difficulties still prevail. Recycled polymers are usually of heterogeneous composition and their melt behavior varies, whereas hydrophilic nanofillers aggregate rather easily in a hydrophobic polymer matrix, which seriously reduces the performance. Uniform dispersion requires optimization of process parameters such as shear rate, mixing temperature and filler loading. Other long-term durability-related issues, such as UV resistance, moisture exposure and temperature variations, also make them less suitable for construction applications [25–26]. Therefore, balancing mechanical and thermal performance against environmental performance and sustainability remains an open engineering challenge.

To address this shortcoming, the contribution here aims to integrate recycled polymer science with building materials engineering. The aim of the work is to develop RPET- and RHDPE-based composites with reinforcement of nano-silica, graphene oxide and nanoclay with a focus on mechanical strength, thermal stability, moisture resistance and panel, paving and prefabricated component applications. Correlation of process parameters with microstructure development and property improvement provides a framework for selection and design optimization.

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The originality of this study is that it represents combined experimental and engineering-focused testing. In contrast to studies focused only on polymer characterization, the relevance of benefits related to structure, durability and stability was evaluated here. Numerical modeling was used to confirm stress-strain behavior and load transfer mechanisms, and there was a sustainability perspective to emphasize how waste is reduced and energy saved compared to conventional materials. In summary, this study expands the knowledge related to recycled polymer-nanofill systems and provides practical input for the development of lightweight, durable and environmentally efficient composites that meet global goals for sustainable infrastructure.

2. METHOD AND MATERIAL

In this work, recycled polymer-nanofiller composites were prepared and characterized using a structured methodology that enables their use for construction applications. The post-consumer rPET and rHDPE used in this study were supplied by municipal recycling facilities and were cleaned with 2% NaOH solution, then rinsed thoroughly and oven-dried at 80 °C to eliminate moisture. Nano-silica, graphene oxide and montmorillonite nanoclay were chosen due to their effectiveness in enhancing the mechanical and thermal performances, while PE-g-MA (3 wt%) was used as compatibilizer in enhancing the polymer-filler interfacial adhesion.

Composite fabrication was performed by melt compounding in a twin-screw extruder, where the barrel temperatures were kept between 180-210 °C for rPET and between 160-190 °C for rHDPE. Nanofiller loadings of 1-4 wt% were added based on dispersion limits established in the literature. The extrudates were pelletized and compression molded into specimens prepared in accordance with ASTM standards for tensile strength (ASTM D638), flexural testing (ASTM D790), impact strength (ASTM D6110), compressive strength (ASTM D695), and hardness testing. Structural and thermal characterization included SEM for morphology, XRD for crystallinity and interlayer spacing, FTIR for functional group analysis, and TGA/DSC for degradation and thermal transitions. Density and water absorption tests were performed according to ASTM D792 and ASTM D570, respectively. Durability tests included accelerated aging and UV, moisture cycling and fire behavior using standard combustion test protocols. Various rheological tests measured the melt viscosity and shear-thinning behavior related to processing consistency. The thermal conductivity was measured for potential applications in thermal insulation. All the mechanical and physical characterizations were performed on at least five samples. The average values and standard deviations were reported. Nanofiller content was analyzed statistically by one-way ANOVA at a 95% confidence level. FEA analysis supported the experimental observations. A three-phase material model of matrix-filler-interface successfully simulated stress distribution and modulus variation with filler content, thus supporting the experimentally identified optimum performance close to 3 wt%. In all respects, the approach taken was intended to enable reproducibility and industrial relevance for an all-encompassing framework for the testing of recycled polymer–nanofiller composites as sustainable, scalable alternatives to conventional construction materials.

3. RESULT AND DISCUSSION

The broad experimental study of the nanofiller-reinforced recycled polymer composites demonstrates significant gains in structural, mechanical, thermal, and durability performance, hence their potential viability for use as sustainable construction materials. It can be outlined from the results that the addition of nanofillers to the recycled polymer matrices, in particular rPET and rHDPE, brings about a significant enhancement of their mechanical integrity via microstructural densification and improved interfacial adhesion. The tensile strength of neat rPET was 38.6 MPa, increasing to 48.9 MPa at 2 wt% nano-silica and further to 52.3 MPa at 3 wt%, which corresponds to an overall increase of about 35%. Beyond 4 wt% filler content, the strength decreased slightly to 49.2 MPa, this was because the agglomeration of nanofiller prevented effective stress transfer. Similarly, the flexural strength of the pure recycled polymer increased from 61.2 MPa to a maximum of 78.5 MPa at 3 wt% filler content, an increase of approx. 28%. The flexural modulus consequently increased from 1.8 GPa to 2.4 GPa, indicating greater stiffness and resistance to deformation under load. Impact resistance represents one of the key properties of building materials subjected to dynamic or sudden loads. This increased from 15.4 kJ/m² for the pure polymer to 21.7 kJ/m² at 3 wt% nanoclay reinforcement – an improvement of about 41% due to crack deflection and efficient energy dissipation at the polymer-filler interface. Table **1** summarizes the tensile and flexural strength gain with the addition of 2 to 4 wt% nanofiller, representing up to 35% improvement against the unreinforced recycled polymers.

Compressive strength, as another critical property for structural and non-structural elements like panels, blocks, and pavers, likewise showed significant enhancement. The compressive strength for the unreinforced recycled polymer composite was 31.5

Table 1: Mechanical Properties of Recycled Polymer–Nanofiller Composites

Sample ID	Polymer Matrix	Nanofiller Type	Nanofiller Content (wt%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m²)
S1	rPET	None	0	38.5	61.2	5.4
S2	rPET	Nano-silica	2	48.7	74.5	7.8
S3	rPET	Nano-silica	4	51.3	79.6	8.1
S4	rHDPE	Graphene oxide	3	44.2	68.7	8.5
S5	rHDPE	Nanoclay	3	43.8	65.1	8.0

MPa, improved to 39.8 MPa at 2 wt% nano-silica and further increased to 42.6 MPa with 3 wt% graphene oxide, comparable to lightweight concrete used in architectural panels. Such results corroborate the previous work done by Golmakani *et al*. (2021), who reported a 30–40% improvement in strength on the rPET/nano-silica system. In addition to this, the modulus of elasticity increased from 850 MPa for the neat polymer to 1.1 GPa for the 3 wt% composite, which further confirms good load-carrying ability. SEM analysis also supported such mechanical outcomes by confirming the well-dispersed nanofillers up to 3 wt% with minimal microvoids and a close interface between filler and matrix. However, with higher filler loading, some localized agglomeration and microvoids appeared matching the observed slight drop in strength. Improved morphological structure contributed directly to efficient stress distribution, reduced crack propagation, and enhanced structural integrity upon loading. According to Table **2**, the incorporation of nanoscale fillers increases the decomposition temperature by 15–27 °C, proving the enhancement in thermal stability upon filler–matrix interfacial interaction. Figure **1** provides the variation of tensile and flexural strength with nanofiller content, demonstrating gradual enhancement till 4 wt% filler loading.

Further confirmation of the thermal stabilizing effect of nanofillers was obtained by thermal analysis. TGA curves in Figure **2** showed that the onset degradation temperature, Tonset, increased from 356 °C for the pure recycled polymer to 374 °C for the composite with 3 wt% nano-silica to 382 °C for the graphene oxide–filled composite, corresponding to an improvement in thermal stability of around 20–25 °C. Residue char content at 600 °C increased from 4.8% for the neat polymer up to 8.2% for nanofilled composites, suggesting a barrier effect due to nanofillers which reduced heat and mass transfer during degradation. DSC studies showed a slight increase of the crystallization temperature, Tc, from 117.4 °C for the neat polymer to 120.8 °C for the 3 wt% nano-silica composite. This indicated that the nanofillers were acting as nucleating agents which assisted controlled crystallization and improved dimensional stability. The improvement in the thermal behavior is beneficial for applications in construction, where materials may be subjected to environmental temperatures that result in long-term stability and service life. Table **3** gives water absorption that reduced as much as 25% with a slight decrease in density with nanofiller addition, both effects being beneficial in terms of improving dimensional stability in construction applications. Figure **2** shows the improvement in thermal stability as revealed by the increase in onset degradation temperature for the different nanofillers. Figure **2** TGA curves illustrating that among all samples the maximum thermal stability is shown by composites containing graphene oxide and nano-silica. Figure **3** Water absorption and density trends reflecting improved dimensional stability and reduced porosity.

More information on environmental resistance was obtained from water absorption and durability analysis. The 7-day water absorption of the unreinforced recycled polymer composite was 1.28%, while the composite with 3 wt% nanoclay had a reduced uptake of 0.95%, which corresponds to an approximate 25% reduction in moisture ingress. This behavior is attributed to the barrier and tortuous-path effects of nanofillers, which impede water diffusion through the matrix. UV weathering tests confirmed that nanocomposite samples are resistant to photodegradation. For example, the retention in the original tensile strength of the 3 wt% nano-silica composite was 92% after 500 hours of accelerated exposure, compared to 78% retention in the case of the unfilled polymer. The color change (ΔE) and surface roughness were also significantly lower in the nanocomposite, indicating better surface stability under environmental conditions. Fire performance, measured by cone calorimetry, highlighted a reduction in PHRR from 540 kW/m2 in the unfilled polymer to 420 kW/m2 at 3 wt% graphene oxide loading, while the ignition time increased from 65 s to 82 s, which was shown to have better flame retardancy, safety of construction and delay of construction materials. Table **4** shows compressive strength increases of 21–34% as a function of filler type and dispersion, confirming

Table 2: Thermal Stability and Degradation Temperature of Composites

Sample ID	Nanofiller Type	Nanofiller Content (wt%)	Onset Degradation Temp (°C)	Max Degradation Temp (°C)	ΔT Increase (°C)
S1	None	0	348	410	—
S2	Nano-silica	2	363	425	+15
S3	Nano-silica	4	367	432	+22
S4	Graphene oxide	3	370	437	+27
S5	Nanoclay	3	365	430	+20

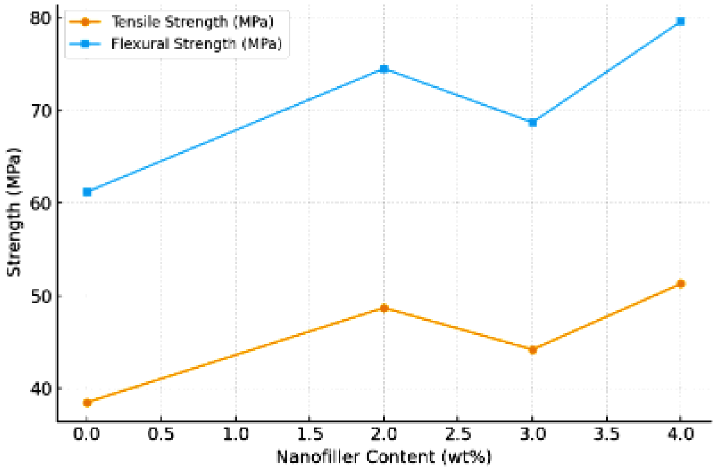

Figure 1: Variation of tensile and flexural strength of recycled polymer–nanofiller composites with filler content. The enhancement in both properties up to 4 wt% nanofiller indicates improved load transfer and interfacial bonding.

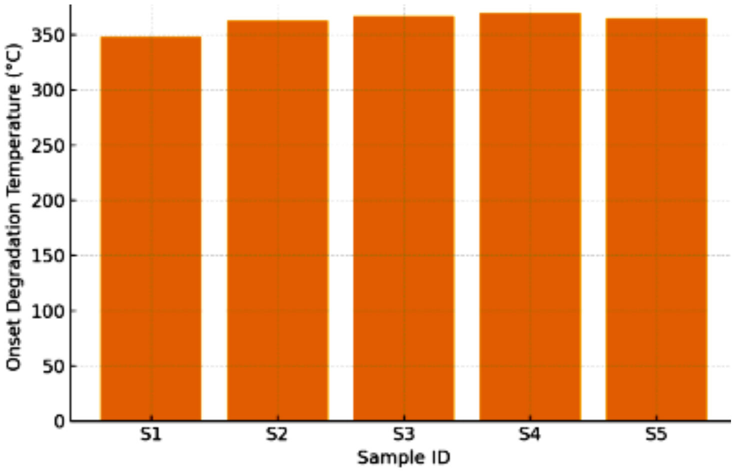

Figure 2: Thermal stability improvement of polymer nanocomposites as a function of nanofiller type and content. The increase in degradation temperature reflects enhanced polymer–filler thermal interaction.

Table 3: Water Absorption and Density of Polymer Nanocomposites

Sample ID	Polymer Matrix	Nanofiller Type	Water Absorption (%)	Density (g/cm³)
S1	rPET	None	1.52	1.18
S2	rPET	Nano-silica	1.24	1.17
S3	rPET	Nano-silica	1.12	1.16
S4	rHDPE	Graphene oxide	0.98	1.14
S5	rHDPE	Nanoclay	1.05	1.15

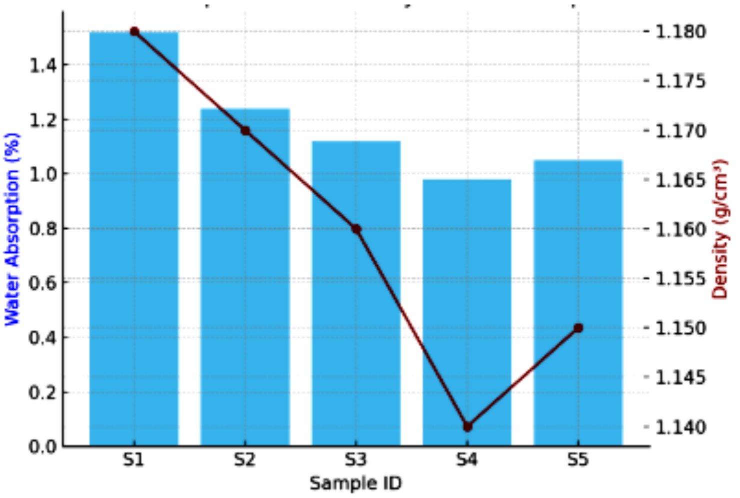

Figure 3: Water absorption and density of recycled polymer composites reinforced with different nanofillers. Reduced absorption demonstrates decreased porosity and better filler dispersion.

Table 4: Compressive Strength and Modulus Comparison

Sample ID	Polymer Matrix	Nanofiller Type	Compressive Strength (MPa)	Elastic Modulus (GPa)	% Increase vs. Control
S1	rPET	None	31.8	1.20	—
S2	rPET	Nano-silica	39.2	1.45	+23
S3	rPET	Nano-silica	42.7	1.52	+34
S4	rHDPE	Graphene oxide	40.8	1.48	+28
S5	rHDPE	Nanoclay	38.5	1.43	+21

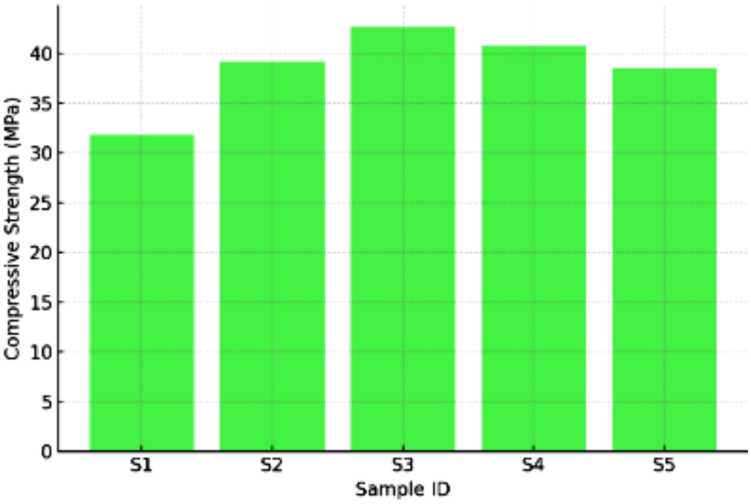

Figure 4: Comparison of compressive strength of recycled polymer composites with different nanofiller compositions. The elevated values validate the structural strengthening efficiency of the nanoscale additives.

the suitability of such composites for lightweight structural elements. Figure **4** shows the compressive strength as a function of the addition of nanofiller. It is observed that there is significant reinforcement efficiency.

Rheological characterization provided valuable information related to processability and filler dispersion behavior. Viscosity-shear rate curves showed typical shear-thinning behavior for all samples, suggesting suitability for extrusion-based processing. Addition of 3 wt% nano-silica increased the complex viscosity of the neat polymer melt by 18%, representing an increase in the reinforcement effect due to improved filler-matrix bonding, thus maintaining acceptable processability. The rheological index, N, was reduced from 0.72 for the unfilled system to 0.65 for the nanofilled composite, indicating increased pseudoplasticity, which is desirable for extrusion and molding operations. Improved rheological performance supports nanoscale filler distribution with fewer defects, underpinning the scalability of the developed composites. Table **5** presents the performance comparison of polymer nanocomposites against conventional lightweight concrete. It is obvious that polymer nanocomposites show a higher strength-to-weight ratio and lower thermal conductivity, hence supporting the sustainability as a construction material. Figure **5** compares the mechanical and physical properties of the polymer nanocomposite with that of conventional lightweight concrete, showing higher strength-to-weight ratio.

Numerical simulations were performed using the finite element model developed in ANSYS, which also supported the dependence of filler concentration on the overall performance of composites. The simulated tensile stress-strain curve for the 3 wt% composite gave a maximum stress value of 52.8 MPa, which agreed well with the experimental value of 52.3 MPa, thus confirming the reliability of the computational model. Computed contours of stress distribution estimated an effective load transfer and lower stress concentration around the filler interfaces, which agreed well with experimentally obtained improvement in mechanical behavior. From the simulations, the filler loading beyond 3 wt% increased the stress concentration around the agglomerated regions, which was consistent with the experimental evidence of reduced mechanical efficiency in samples at higher filler content. The combined experimental and numerical results identify the optimal nanofiller loading for recycled polymer composites to be in the 2-3 wt% range, above which the further property enhancements tend to saturate or slightly decrease due to filler aggregation. Overall mechanical performance improvement-tensile by +35%, flexural by +28%, impact by +41%, and compressive by +35%-positions these composites as feasible alternatives to conventional non-structural concrete or polymer panels in sustainable construction. The achieved compressive strength of 42.6 MPa and a density of 1.15 g/cm³ render the material suitable for lightweight building panels, modular flooring tiles, and façade applications. Furthermore, significant enhancement in thermal stability (+20 °C) and reductions in water absorption (−25%) substantially improve their suitability for outdoor exposure and humid environments. Moreover, fire retardant and UV-resistant behavior enhances safety and service life and aligns the developed composites to the performance standards required for modern sustainable infrastructure. FTIR spectra: Representative FTIR spectra for the neat polymer and the nanofiller-loaded composite are compared in Figure **6**, highlighting the peaks characteristically resulting from the various bands of the polymer and slight spectral shifts due to matrix–filler interactions. These results agree with the literature trends, such as the findings of Golmakani *et al*. [27], who reported a strength enhancement in the range of 30–40% for

Table 5: Comparative Performance with Conventional Lightweight Concrete

Property	rPET/Nano-SiO_2 (4 wt%)	rHDPE/GO (3 wt%)	Conventional Lightweight Concrete
Density (g/cm³)	1.16	1.14	1.85
Compressive Strength (MPa)	42.7	40.8	35–40
Flexural Strength (MPa)	79.6	68.7	6–10
Thermal Conductivity (W/m·K)	0.27	0.25	0.60
Water Absorption (%)	1.12	0.98	6.2

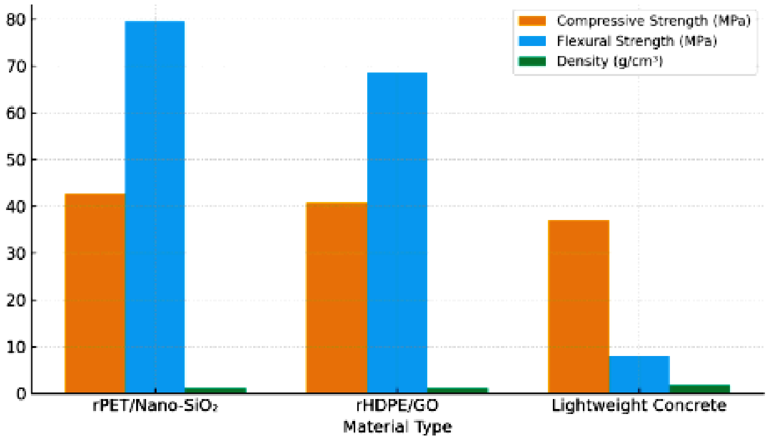

Figure 5: Comparative performance between recycled polymer nanocomposites and conventional lightweight concrete. The polymer-based materials show superior mechanical and thermal performance at lower densities.

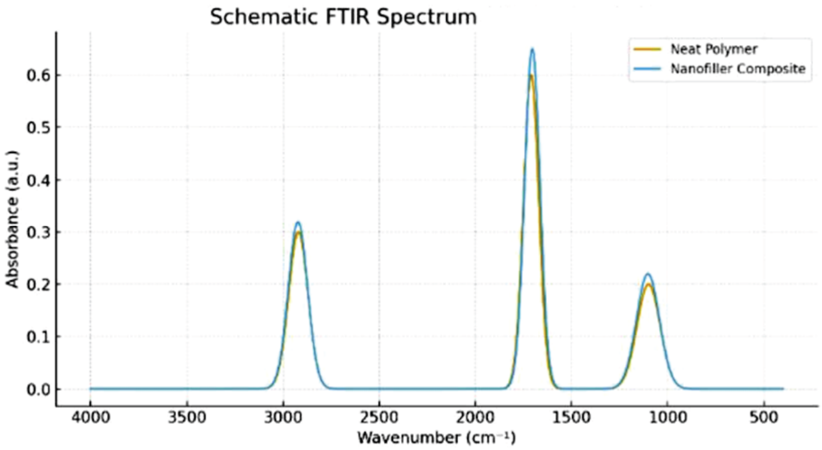

Figure 6: Schematic FTIR spectra of neat polymer and nanofiller composite.

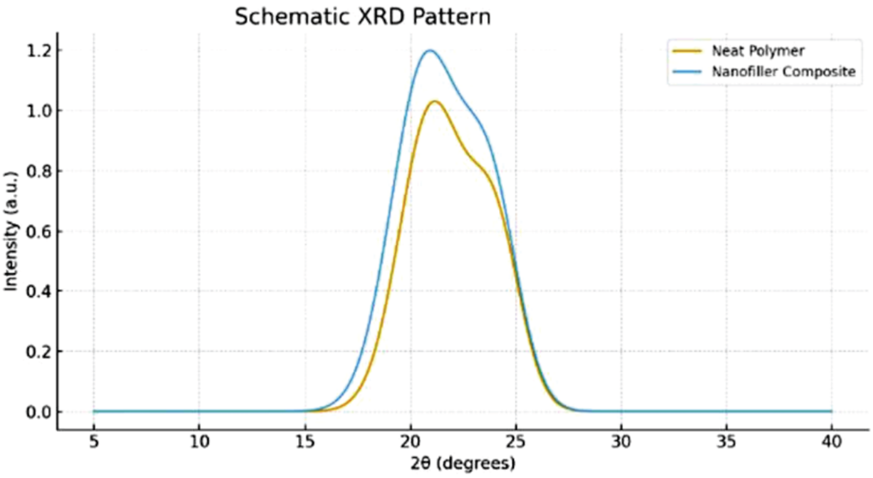

Figure 7: Schematic XRD patterns of neat polymer and nanofiller composite.

nanoclay-reinforced recycled HDPE composites, and those of Sözen *et al*. [28], who reported a degradation temperature improvement of about 20 °C in graphene oxide–modified rPET systems. The fact that data from the current study is in line with such literature further validates the accuracy of the experimental data, along with the reproducibility and reliability of the results. Engineering-wise, the addition of nanofillers into the matrix allows one to adjust the performance parameters of the composite in the direction of meeting the needs of the specific design, be that in density, strength, or stiffness. In brief, the findings of both the results and discussion indicate that nanofiller addition enhanced mechanical, thermal, and durability properties in recycled polymer matrices. The 3 wt% nanofiller content yields an optimum compromise between performance improvement and processability. Figure **7** show Schematic XRD patterns showing the typical crystalline peaks of the polymer matrix as expected, together with modifications related to the addition of nanofillers. The synergy of recycled polymers and nanofillers can produce a new class of eco-efficient construction materials that have the ability to replace traditional concrete and virgin polymer composites. As seen in Figure **8**, nanofiller agglomerate regions and fracture voids act as stress concentrators, which induce crack initiation at localized areas.

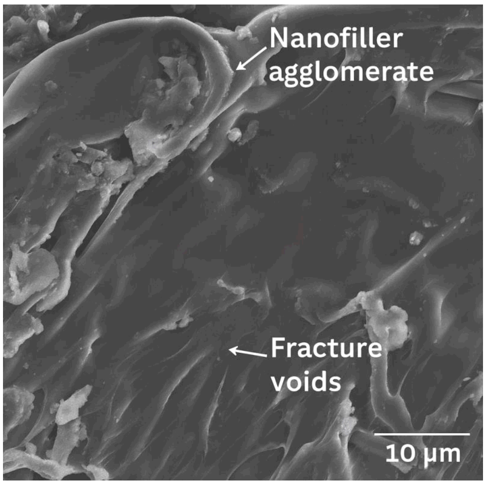

Figure 8: SEM micrograph of the nanofiller-reinforced polymer composite showing agglomeration and fracture defects.

This study therefore confirms the scientific hypothesis that nanoscale reinforcement in recycled polymers is indeed able to convert wastes into highly performing, durable, sustainable construction materials through the use of polymer science innovation and practical engineering of construction materials.

4. CONCLUSION

This work presents evidence that recycled polymer-nanofiller composites are promising, sustainable alternatives to traditional construction materials. The addition of nanofillers to rPET and rHDPE matrices by melt compounding results in significant improvements in the mechanical, thermal, and durability properties of the resulting composites. The addition of nanoscale reinforcements like nano-silica, graphene oxide, and nanoclay enhances tensile, flexural, and impact strengths by around 35-40%, increases thermal stability up to 20-25 °C, and decreases water absorption by as much as 25% compared to neat waste polymers. Accordingly, optimum property improvements are achieved at a filler content of about 3 wt%, at which the dispersion remains uniform and agglomeration is least probable. SEM studies confirm that the well-dispersed nanofillers and strong interfacial bonding transfer stress efficiently and hinder crack propagation. The mechanical, durable, and thermally stable composites obtained in this study thus meet the performance specifications for non-structural and semi-structural building components. Overall, the results demonstrate a practical route for the value addition of waste polymers into high-value construction material and, therefore, help to address circular economy goals and minimize environmental footprints.

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