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Material Properties of Recycled Polypropylene/Polyethylene Terephthalate for Rooftop Applications

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Graphical Abstract

Highlights

- Recycled PP/PET composites were developed using a circular economy approach with added compatibilizer
- Density, tensile strength, hardness, and impact resistance were systematically evaluated
- A 3% compatibilizer showed optimal performance for thicker sections
- A 13% compatibilizer provided better properties for thinner sections
- The recycled materials demonstrated competitive performance compared with PVC roofing products

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ABSTRACT

Plastic waste management remains a major challenge, particularly for multi-material plastics such as polypropylene/polyethylene terephthalate (PP/PET) composites commonly used in packaging. This study applies a circular economy approach by recycling a PP/PET blend (95% PP, 5% PET) with maleic anhydride compatibilizer contents of 3%, 7%, 10%, and 13%. Recycled samples were produced via extrusion, granulation, and injection molding, then evaluated for density, tensile properties (7 mm and 2 mm thicknesses), hardness (Shore D), and Izod impact strength. The results were compared with two commercial PVC roofing products. The 13% compatibilizer sample showed the highest density and impact resistance, while the 3% sample exhibited the best tensile strength at 7 mm thickness and the highest hardness. Overall, increasing compatibilizer content did not lead to significant property improvements. The 3% compatibilizer formulation was identified as the most effective for rooftop applications, offering competitive performance with minimal additive use. Compared to PVC roofing, recycled PP/PET achieved comparable density, tensile strength, and impact resistance, although PVC remained stiffer.

1. Introduction

The proliferation of plastic usage in modern life has led to a parallel increase in plastic waste generation. For instance, Indonesia produces approximately 7.8 million tons of plastic waste annually, accounting for about 15% of total solid waste [1,2]. A significant portion of this waste is mismanaged, with an estimated 15–30% entering marine environments [3,4]. Many common plastics like polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are non-biodegradable and persist in the environment for decades [5]. Recycling and circular economy strategies are therefore critical to mitigate this problem. However, one of the toughest challenges is recycling multi-material plastics – composites of different polymers that are difficult to separate and reprocess. Such materials (e.g., laminated PP/PET packaging) complicate conventional recycling processes and often yield recycled products with reduced quality compared to virgin polymers [6,7].

Despite these difficulties, approaches exist to enhance the recyclability of mixed plastics. One effective method is to add compatibilizers (coupling agents) to improve interfacial bonding between immiscible polymers. For PP/PET blends, various compatibilizers such as polypropylene grafted with maleic anhydride (PP-g-MA) or acrylic acid (PP-g-AA), and other grafted copolymers, have been used to enhance blend homogeneity and mechanical performance [8,9,10,11]. Prior studies report that adding compatibilizers significantly improves the tensile properties and morphology of recycled PP/PET blends [9, 10]. In this study, Maleic anhydride-grafted PP utilize as a compatibilizer to enhance the bonding between recycled PP and PET phases. Recycled plastics have already been explored in the manufacture of roofing products, which require materials that are lightweight, durable, and weather-resistant. Various plastic types have been incorporated in roofing materials. Some studies have used 100% recycled HDPE for roof panels, high PP content (90–95%), mixed plastic waste (e.g., HDPE) up to 50%, PET up to 100%, and LDPE up to 15% in composite roof tiles [12,13]. Notably, a recycled PP/PET blend has not yet been reported as a roofing material, indicating a gap in the literature. This study addresses that gap by developing and testing recycled PP/PET blends for rooftop application. We investigate a post-consumer PP/PET composite (from multi-layer drink cups) combined with a PP-g-MA compatibilizer at 3%, 7%, 10%, and 13% by weight. The mechanical properties of the recycled materials—specifically density, tensile strength, hardness, and impact toughness—were evaluated and compared against two commercial roofing products (referred to as Rooftop A and Rooftop B) as well as the baseline properties of rigid PVC roofing. The primary objective of this study is to identify the optimal recycled PP/PET formulation that meets or surpasses the performance requirements for rooftop applications.

2. Materials and Methods

2.1 Materials

Post-consumer multi-layer PP/PET plastic waste was used, sourced from discarded Ale-Ale beverage cups consisting of approximately 95% PP and 5% PET by weight. This PP/PET composite was shredded into flakes. A maleic anhydride grafted polypropylene (PP-g-MA) compatibilizer was added to the mix at four levels: 3%, 7%, 10%, and 13% (by weight). These compatibilizer levels produce four recycled PP/PET formulations. Two commercially available roofing sheets (designated Rooftop A and Rooftop B) made of PVC were used as benchmarks.

2.2 Recycling Process

The shredded PP/PET flakes were dry-mixed with the compatibilizer granules using a laboratory mixer for 5–10 minutes to ensure homogeneous blending. The blend was then processed in a single-screw extruder at ~340 °C to melt and compound the materials. The extrudate emerged as continuous cylindrical strands which were immediately quenched in water to solidify. Next, the solidified extrudate was cut into pellets using a granulator. These recycled pellets were subsequently fed into a custom injection moulding machine (hand-operated) to produce test specimens. The injection moulding barrel was heated to 340 °C. For each formulation, specimens of two different thicknesses (approximately 7 mm and 2 mm) were moulded by adjusting a removable spacer in the mold. Key parameters for the injection moulding process (melting temperature, melt time, cooling/rest time before mold release, and pouring/injection speed) are shown in figure 1 and summarized in table 1.

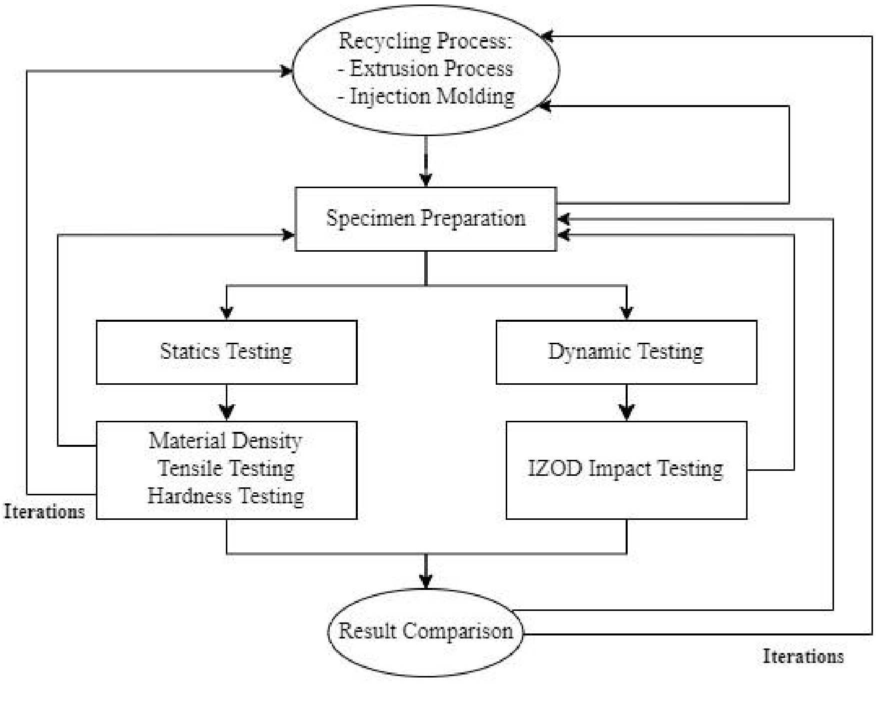


Figure 1. Recycling Stages

Table 1. Injection Moulding Parameters for Producing Recycled PP/PET And PVC Specimens

Specimen	Melting Temp (°C)	Melting Time (min) (2 mm/7 mm)	Resting Time (2 mm/7 mm)	Pouring Speed (2 mm/7 mm)
r-PP/PET + 3% comp.	340	8-Oct	0 min/0 min	Fast/Slow
r-PP/PET + 7% comp.	340	8-Oct	0 min/5 min	Fast/Slow
r-PP/PET + 10% comp.	340	8-Oct	0 min/5 min	Fast/Slow
r-PP/PET + 13% comp.	340	8-Oct	0 min/5 min	Fast/Slow
Rooftop A (PVC)	340	8-Aug	0 min/0 min	Fast/Slow
Rooftop B (PVC)	340	8-Aug	0 min/0 min	Fast/Slow

After moulding, the raw specimen shapes (rough rectangles) were machined to testing dimensions. Excess flash and the injection gate portion were removed using a saw. Each specimen was then traced against a standard template and cut to final shape with a scroll saw, ensuring dimensions met ASTM standards. Tensile test specimens were prepared according to ASTM D638 Type I geometry (dog bone shape) with gauge lengths of 50 mm; two thicknesses (7 mm and 2 mm) were prepared in table 2 and figure 2 for testing [14]. Additionally, for the IZOD impact test, notched beam specimens of 7 mm thickness were prepared following ASTM D256 requirements (Table 3) [15].

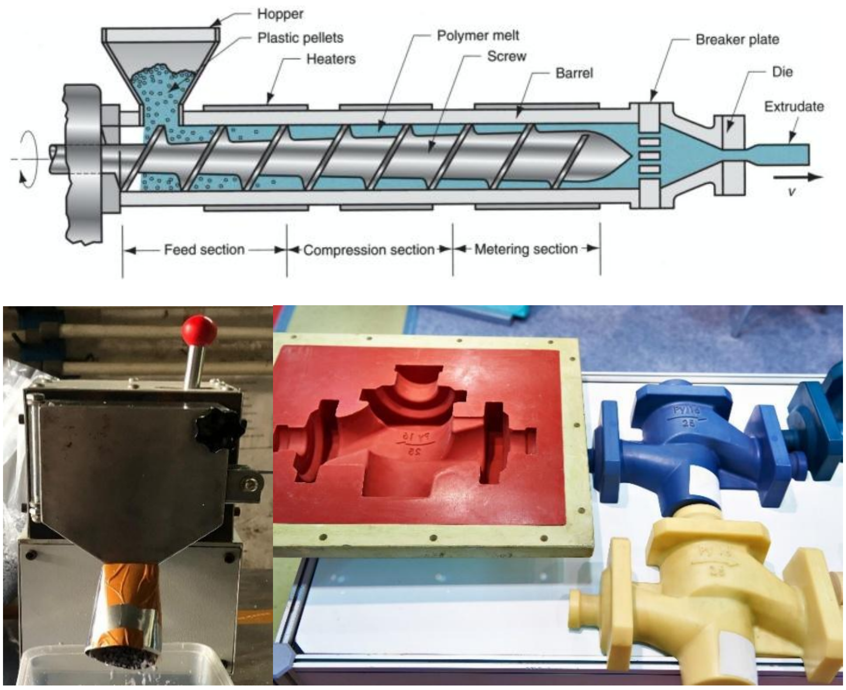


Figure 2. Injection Moulding

Table 2. Tensile test specimen dimensions (ASTM D638 Type I)

Parameter	Symbol	Dimension (mm)
Width (narrow section)	W	13
Width (overall)	W0	19
Gauge length	G	50
Length of narrow section	L	57
Overall length	L0	165
Distance between grips	D	115
Fillet radius	R	76
Thickness (tested)	T	2 or 7

Table 3. IZOD impact test specimen dimensions (ASTM D256)

Parameter	Dimension (mm)
Length (overall)	63.5
Height	12.7
Thickness	10.16
Notch depth	2.54 (with 0.25 mm notch radius)

2.3 Testing Methods

Density of each material was determined by measuring the mass and volume of moulded 7 mm thick samples. Tensile tests were conducted on a universal testing machine according to ASTM D638 at room temperature [14]. For each formulation and thickness, five replicate specimens were tested in tension (crosshead speed 5 mm/min). From the stress–strain data, the Young's modulus (E), yield strength, and ultimate tensile strength (UTS) were recorded. Hardness was measured using a Shore D durometer (following ASTM D2240) on 7 mm thick coupon samples [16]. Multiple indents (at least 5) were made on each sample at different locations and the average Shore D hardness was taken. Impact toughness was evaluated by Izod impact testing on notched specimens (7 mm thickness) according to ASTM D256 [15]. A pendulum impact tester with a 2.75 J hammer was used to break five replicate specimens of each material, and the energy absorbed was recorded. The impact strength (resilience) was calculated as the absorbed energy per unit cross-sectional area of the specimen. A digital microscope (50×–100× magnification) was used to examine the fracture surfaces of the impact specimens to qualitatively assess internal features (e.g., void inclusions) among the different materials. The tensile, hardness and izod machine testing shown in figures 3-5.

Figure 3. Universal test machine

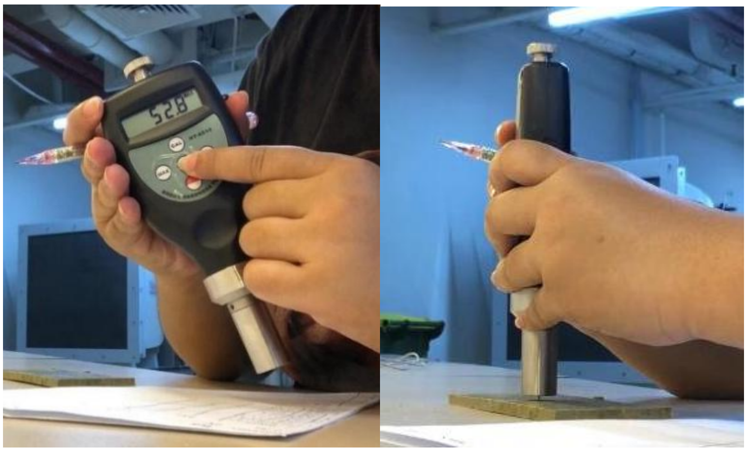


Figure 4. Hardness test machine

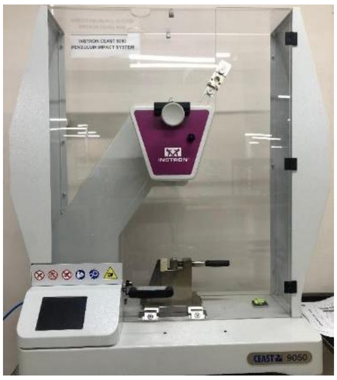


Figure 5. Izod impact test machine

3. Results and Discussion

3. 1 Density

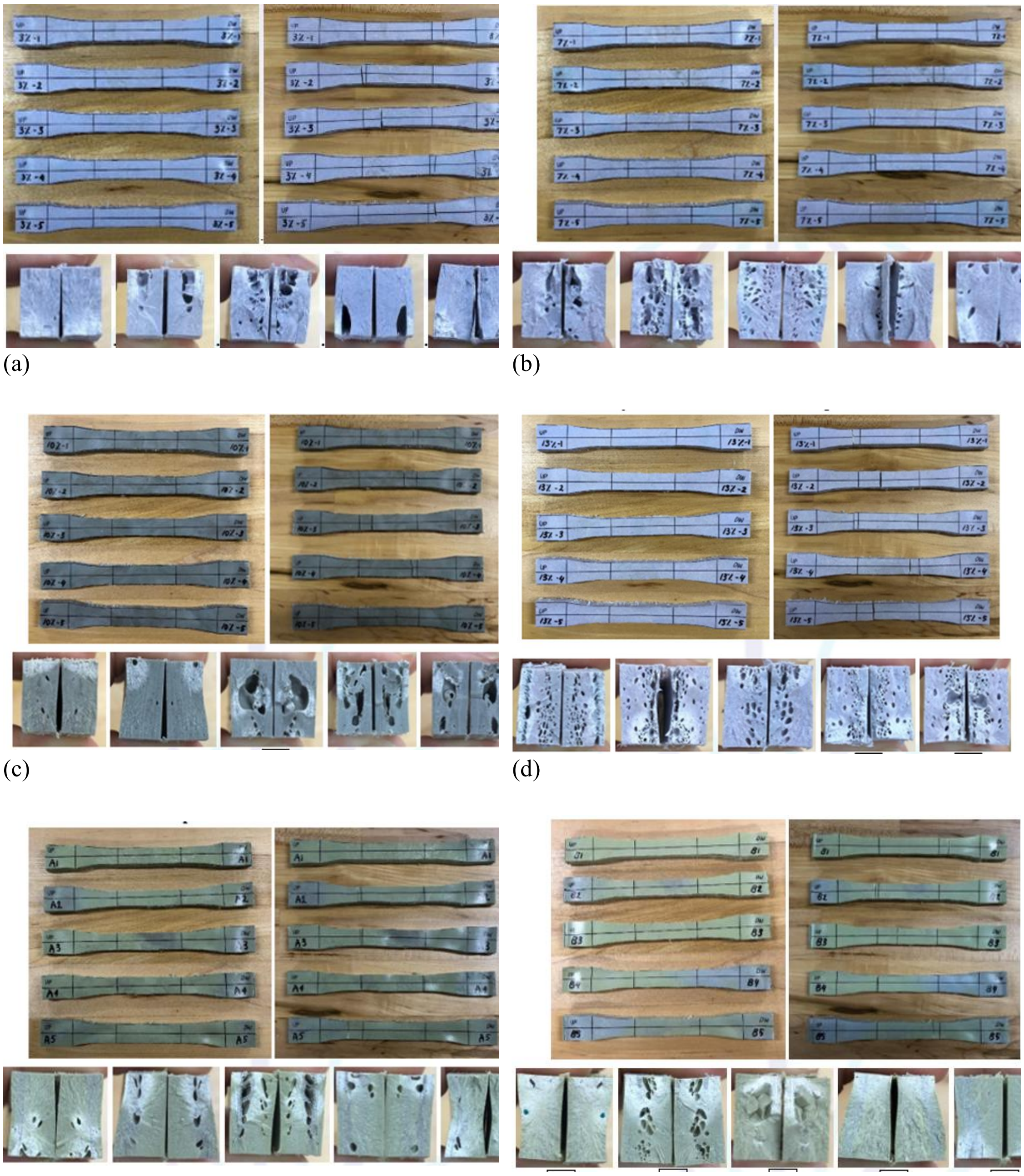
All recycled PP/PET specimens had densities on the order of 1.06–1.11 g/cm^3 (table 4). Increasing the compatibilizer slightly raised the density (from 1.066 g/cm^3 at 3% to 1.113 g/cm^3 at 13%). These values are somewhat lower than the densities of the commercial PVC roof samples: Rooftop A = 1.189 g/cm^3 and Rooftop B = 1.344 g/cm^3. The 13% compatibilizer sample was closest to the commercial products, with density only about 6.8% lower than Rooftop A and 20.2% lower than Rooftop B. In contrast, the 3% sample was about 11% and 24% lower than Rooftop A and B, respectively.

Table 4. Density of recycled PP/PET samples vs. commercial roofs

Material	Density (g/cm^3)
r-PP/PET + 3% compatibilizer	1.066
r-PP/PET + 7% compatibilizer	1.092
r-PP/PET + 10% compatibilizer	1.11
r-PP/PET + 13% compatibilizer	1.113
Rooftop A (PVC)	1.189
Rooftop B (PVC)	1.344

3. 2 Tensile Properties

The tensile test outcomes differed between the thick (7 mm) and thin (2 mm) specimens. For the 7 mm specimens, the recycled PP/PET with 3% compatibilizer exhibited the highest stiffness and strength among the blends. It achieved a Young's modulus of ~579 MPa, yield strength ~13.2 MPa, and UTS ~26.5 MPa (table 5), which were higher than those of the other recycled samples. In fact, the 3% compatibilizer sample's modulus and yield strength slightly exceeded those of Rooftop A (the weaker of the two commercial roofs). For example, its Young's modulus was ~14% above Rooftop A and ~1% above Rooftop B, and its yield strength was ~12.6% above Rooftop A. In contrast, the 7 mm samples with 10% compatibilizer had the lowest tensile properties among the recycled blends (E ~402 MPa, Y ~11.4 MPa). The PVC roofs still showed higher ultimate strength (UTS ~21–24 MPa) than all recycled blends at 7 mm thickness. For the 2 mm specimens, all materials showed higher strength and stiffness compared to their 7 mm counterparts (due to reduced internal defects in thinner sections). Among the recycled blends, the 13% compatibilizer sample had the best tensile performance at 2 mm thickness (E ~676 MPa, Y ~16.4 MPa, UTS ~36.2 MPa). However, none of the recycled 2 mm samples reached the strength or stiffness of the commercial PVC roofs. The 13% sample's Young's modulus was ~15% lower than Rooftop A (774 MPa) and ~25% lower than Rooftop B (884 MPa), and its UTS was ~14.9% below Rooftop A (41.5 MPa). Other recycled samples were further behind. Overall, the 2 mm tests confirmed that adding compatibilizer beyond 3% did not linearly improve tensile properties – notably, the 10% blend had the lowest performance in both thicknesses. The detailed results of specimens' dimensions and masses are provided for recycled PP/PET with 3%, 7%, 10%, 13% compatibilizer, rooftop: A and rooftop: B which is shown in figure 6.



(a) (b) (c) (d) (e) (f)

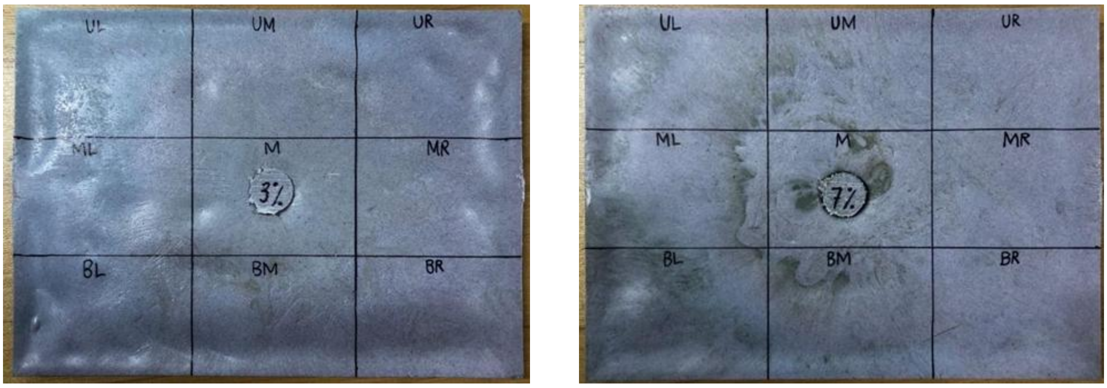
Figure 6. Tensile Test of Recycled PP/PET (a) with 3% Compatibilizer; (b) with 7% Compatibilizer; (c) with 10% Compatibilizer; (d) with 13% Compatibilizer; (e) Real Rooftop: A; and (f) Real Rooftop: B

Table 5. Tensile properties (young's modulus e, yield strength y, ultimate tensile strength uts, and elongation at break) for recycled pp/pet blends and commercial roofs (average values)

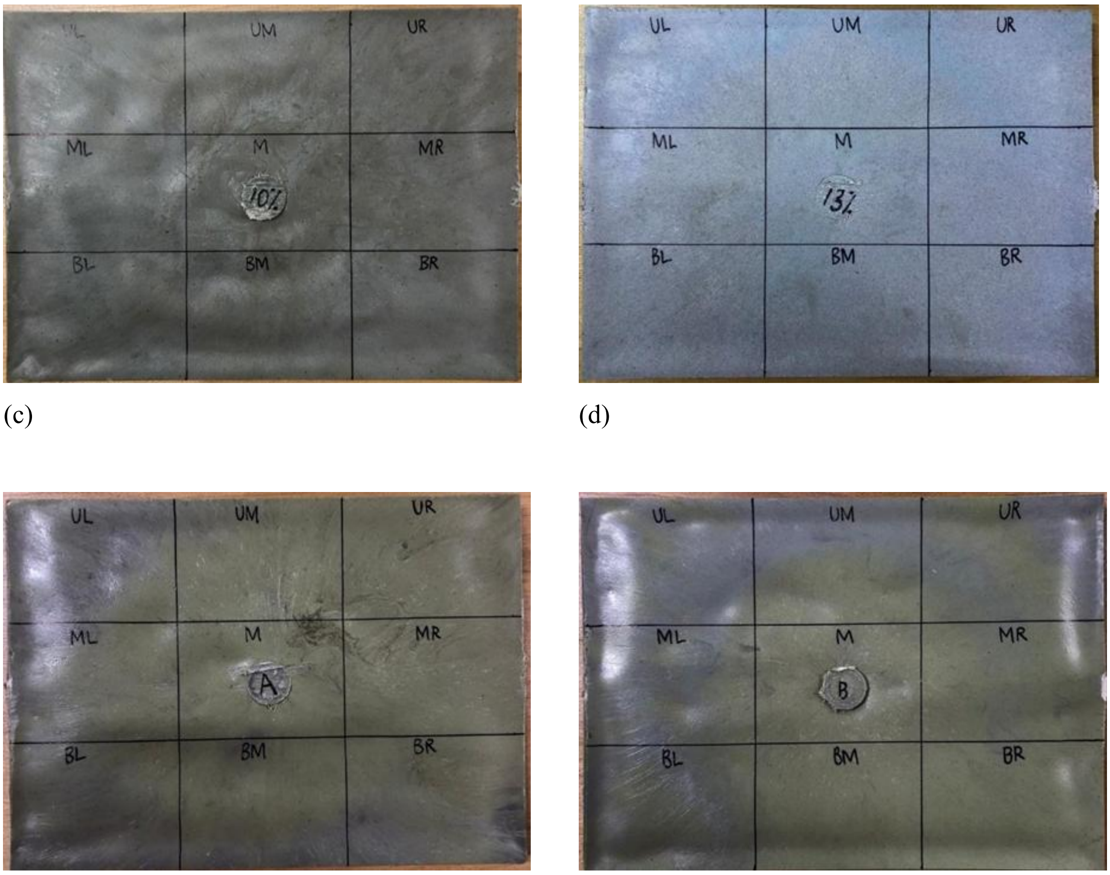
Material	Thickness	E (MPa)	Y (MPa)	UTS (MPa)	Elongation (%)
r-PP/PET + 3% comp.	7 mm	579.1	13.2	26.5	12.6
	2 mm	651.6	16.2	35.1	48.8
r-PP/PET + 7% comp.	7 mm	483.5	12.5	24.3	12.6
	2 mm	614.5	15.6	34.7	54.8
r-PP/PET + 10% comp.	7 mm	402.1	11.4	18.3	8
	2 mm	567.8	15	31.3	20.8
r-PP/PET + 13% comp.	7 mm	419.7	11.1	24.3	14.8
	2 mm	675.9	16.4	36.2	35.1
Rooftop A (PVC)	7 mm	512.6	11.7	21.5	9.5
	2 mm	773.4	19.5	41.5	28
Rooftop B (PVC)	7 mm	572.9	12.5	24.5	12.8
	2 mm	883.9	22.7	47.7	53.8

3. 3 Hardness

All recycled samples showed Shore D hardness in a narrow range (~71–73 on the Shore D scale). The 3% compatibilizer blend had the highest hardness (approximately 73.0 Shore D), followed closely by the 13% blend (~72.8). These values were only marginally lower (within 1%) than the commercial rooftops (which measured ~73.2–73.9 Shore D). In fact, the difference between the 3% sample and Rooftop A was only 0.31%, indicating comparable hardness. There was no clear trend of hardness improvement with higher compatibilizer content – the variations observed were very small and likely within experimental scatter. Hardness tests using a shore D durometer is shown in figure 7 and table 6.



(a) (b)



(c) (d)

(e) (f)

Figure 7. Hardness test of recycled pp/pet (a) with 3% compatibilizer; (b) with 7% compatibilizer; (c) with 10% compatibilizer; (d) with 13% compatibilizer; (e) real rooftop: a; and (f) real roo ftop: b

Table 6 Hardness Value Comparison Between r-PP/PET and Rooftops

	Compared to A	Compared to B
3%	-0.31%	-0.67%
7%	-0.98%	-1.34%
10%	-2.91%	-3.27%
13%	-0.75%	-1.11%

3. 4 Impact Resistance

In Izod impact tests, the energy absorbed by the recycled specimens ranged from 0.14 J to 0.19 J. The 10% compatibilizer sample absorbed the least energy (0.14 J), indicating the lowest impact toughness, whereas the 7% and 13% samples absorbed the most (0.19 J each). Rooftop A absorbed 0.18 J and Rooftop B 0.23 J under the same test conditions. The corresponding notched impact strength (resilience) values are given in table 7. Recycled samples with 7% and 13% compatibilizer achieved impact strengths (approximately 2.71 kJ/m²) that exceeded Rooftop A (2.52 kJ/m²) and were within ~15% of Rooftop B (3.20 kJ/m²). The 3% sample's impact strength (2.35 kJ/m²) was slightly below Rooftop A, while the 10% samples was substantially lower (table 7).

Table 7. Izod impact test results (notched specimens, 7 mm thick) for recycled blends and PVC roofs. (Energy absorbed is the average per specimen; resilience is normalized by cross-sectional area.)

Material	Energy Absorbed (J)	Resilience (kJ/m²)
r-PP/PET + 3% comp.	0.17	2.35
r-PP/PET + 7% comp.	0.19	2.71
r-PP/PET + 10% comp.	0.14	1.95
r-PP/PET + 13% comp.	0.19	2.71
Rooftop A (PVC)	0.18	2.52
Rooftop B (PVC)	0.23	3.2

3. 5 Fracture Observations

Fractographic analysis using a digital microscope revealed similar features in all materials. The fracture surfaces of the 7 mm specimens showed evidence of internal voids and a brittle failure mode (clean break without significant plastic deformation). In contrast, the 2 mm specimens sometimes exhibited localized necking at the break, indicating slightly more ductile behaviour due to the thinner section. All recycled PP/PET samples, as well as the PVC roofs, showed the presence of some micro-voids and inclusions (coloured specks from contaminants) on the fracture surfaces. No significant differences in microstructural defects were observed between the different compatibilizer formulations – all had comparable levels of porosity and heterogeneity. This suggests that the compatibilizer did not markedly affect the internal defect structure of the recycled material at the scales observed.

The mechanical testing results did not show a simple linear improvement with increasing compatibilizer content. Instead, the recycled PP/PET blends exhibited a non-monotonic, somewhat pattern less behaviour across the 3–13% compatibilizer range. In the 7 mm specimens, the lowest compatibilizer level (3%) provided the highest tensile properties, whereas mid-level additions (7% and 10%) performed worse. In the 2 mm specimens, the highest compatibilizer level (13%) gave the best results, but the differences among 3%, 7%, and 13% were small. This suggests that adding more compatibilizer beyond a certain point does not substantially enhance (and in some cases slightly reduces) the mechanical properties of the recycled PP/PET. Excessive compatibilizer could create an overly rubbery interface or promote agglomeration, counteracting the benefits of improved interfacial bonding [16, 17]. Thus, a moderate compatibilizer content (around 3% for thick sections or 13% for thin sections in this study) appears sufficient to achieve most of the attainable property improvements. A major factor influencing the recycled material performance is the presence of internal voids and other inhomogeneities introduced during processing. The 7 mm injection-moulded samples contained visible cavities (as observed in microscope images) that act as stress concentrators and likely led to the lower strength and stiffness compared to thinner samples. These voids, caused by gas entrapment and shrinkage during moulding, effectively reduce the load-bearing cross-section and initiate premature failure. The thinner (2 mm) samples had far fewer and smaller voids, which explains their higher measured strength and ductility (e.g., noticeable necking prior to fracture). The similar hardness values across all samples further indicate that the bulk material properties (governed by the PP/PET matrix) were comparable; it was the defect population and distribution that caused the variability in tensile and impact performance. Improving the moulding process (for instance, by incorporating a vacuum degassing system or optimized mold design) could reduce these defects and likely yield more consistent, higher mechanical properties for the recycled material [18, 19]. When benchmarked against a conventional roofing material (PVC), the recycled PP/PET composites showed competitive performance in several aspects. The densities of the recycled blends (1.06–1.11 g/cm^3) are only slightly lower than PVC (1.18–1.34 g/cm^3), indicating a similar weight per area, which is beneficial for roofing. The tensile strength of the best recycled formulation (13% comp., ~36 MPa) approached that of rigid PVC (around 42–48 MPa for the samples tested), and impact strengths of the top blends actually matched or exceeded the lower-bound performance of PVC roofing (the 7% and 13% blends outperformed one of the commercial samples in the notched impact test). However, one area where the recycled PP/PET falls short is stiffness: even the best recycled sample's Young's modulus (~676 MPa at 2 mm) was only about one-quarter of that of typical PVC (~2900 MPa) [20]. This is expected, as PET and PP are semi-crystalline polymers with lower rigidity than PVC. For roofing applications, this implies that while the recycled PP/PET material may have adequate strength and impact resistance, it may flex more under load compared to PVC. Depending on roof design, this could be addressed by profile geometry or internal reinforcement if needed.

Table 8. Digital Microscope Results of r-PP/PET from Impact Specimen

	3%	7%	10%	13%
Surface				
Cut Surface				

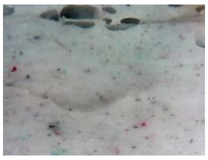
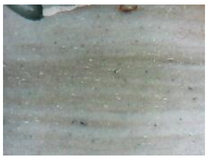
	3%	7%	10%	13%
Fracture Surface				

Table 9. Digital Microscope Results of Rooftops from Impact Specimen

	Roof A	Roof B
Surface		
Cut Surface		
Fracture Surface		

4. Conclusion

A recycled PP/PET blend with a small amount of compatibilizer can attain mechanical properties in the range of existing roofing products. The optimal formulation appears to be the lowest compatibilizer content tested (3%) for thick sections or the highest (13%) for thin sections; in practice, using the lower compatibilizer content is more cost-effective and yielded acceptable properties. The addition of compatibilizer improved compatibility between PP and PET phases, but beyond a certain point the returns diminished. Future work should focus on process improvements to minimize internal defects and possibly incorporate fillers or fibers to boost stiffness. By addressing these factors, recycled PP/PET roofing materials could become a viable sustainable alternative to conventional roof

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Credit Authorship Contribution Statement

The manuscript was written through the contribution of Fatima Tasya Kamila.

Conflicts of Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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