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Recycled Glass Polypropylene Composites from Transportation Manufacturing Waste

Uday Vaidya [1,2,3,*], Sanjita Wasti [1], Halil Tekinalp [2], Ahmed Arabi Hassen [2] and Soydan Ozcan [2]

1 Tickle College of Engineering, University of Tennessee, 1512 Middle Drive, Knoxville, TN 37996, USA
2 Manufacturing Sciences Division (MSD), Oak Ridge National Laboratory (ORNL), 2350 Cherahala Blvd, Knoxville, TN 37932, USA
3 The Institute for Advanced Composites Manufacturing Innovation, 2370 Cherahala Blvd, Knoxville, TN 37932, USA
* Correspondence: uvaidya@utk.edu

Abstract: In recent years there has been growing interest in developing recycling technologies for composites manufacturing scrap, process waste and end-of-life parts. The focus of this work was to establish processing routes and mechanical property bounds for glass-polypropylene (PP-GF) scrap from the production of parts for truck trailers, automobiles, and rail cars. This study considered PP-GF scrap and demonstrated extrusion-compression molding (ECM) as a viable route for the closed-loop manufacture of composite parts. The results were promising in terms of the strength and modulus retention of the PP-GF recyclate. The tensile strength and modulus was the highest for 50% and 66% recycled content, compared with 100% and 83% recycle content. The flexural strength and modulus of the 100% and 83% recycled compositions was higher than the 66% and 50% recycled content, respectively. The impact energy absorption of the PP-GF recyclate at at all fiber loadings was superior in absorbing energy compared with the incumbent (benchmark) plywood. This work is useful to designers seeking to incorporate recycled materials in their products.

Keywords: recycled; glass fibers; composite; extrusion-compression molding; thermoplastics

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1. Introduction

In recent years there has been growing emphasis on a circular economy and the recycling of composites with a goal of minimum landfill use [1,2]. The sources for composites waste include, but are not limited to (a) end of life (EoL) wind turbine blades, boats, trailers, ships, and sporting goods; and (b) the manufacturing waste during production [1]. To this end, thermoplastic composites offer higher potential for recycling compared with thermoset composites [3]. Thermoplastics have superior strength, stiffness, impact energy absorption, superior vibration and noise dampening, and lower cost [3–6]. Examples of thermoplastics used in transportation include truck trailer splash guards, body interiors such as instrument panels (IP), structural duct assemblies, floor panel, and access doors. Vaidya et al. have demonstrated weight savings of 40–60% for mass transit bus components such as seats, floor segments, body panels, and access doors featuring thermoplastic composite materials [3–8].

Traditional materials such as steel, timber (or wood), or low-cost thermoset composites are used in transportation applications. However, steel has shortcomings in terms of being heavy and susceptible to corrosion. Wood is prone to termite attack, mold build up, and swelling due to moisture, while continuous fabric thermoset composites can be expensive and undergo microcracking at low load levels and environmental exposure.

Transportation trailer bodies are adopting thermoplastic composites in their construction [9–11]. However large amounts of scrap generated from edge trims and the machining of bulk parts in trailer manufacturing are presently landfilled. In this study, the feasibility of reprocessing glass-polypropylene (PP-GF) scrap (referred to as 'recyclate' from truck trailers was investigated. An innovative extrusion-compression molding (ECM) process was used to manufacture test panels. The lower-upper bound tensile, flexure, and impact properties were established for different percentages of PP-GF recyclate. The fiber-matrix interface influenced by the fiber weight fraction and wet-out was found to strongly influence the resulting properties.

2. Literature Review

Several studies have focused on recycling thermoplastic resins from its virgin constituent stages. These are typical of injection and extrusion molded plastics. Studies on the recycling of long glass fiber thermoplastics (LFT) are very limited. Several approaches adopted for composites recycling include pyrolysis [12], solvolysis [12], thermolysis [13], and mechanical shredding [14]. Since E-glass fiber is a low-cost fiber, the economics of recycling glass fiber composites poses limitations on expensive processing methods, although technically feasible. Typically, mechanical shredding and thermal processes are adopted for recycling glass fiber composites.

The American Composites Manufacturer's Association (ACMA), along with industry partners, conducted an extensive study on glass fiber recycling via thermolysis [13]. The study showed that thermolysis of glass fiber thermoset composites is a viable approach to recovering glass fiber in the 1–3 mm range, but the process is highly energy intensive [13].

Imbert et al. [15] developed mechanical laminae separation to enable the recovery of reusable laminae from laminated composite parts and offcuts. This method consists of three steps—the generation of a notch as a crack initiation area, the controlled initiation of an interlaminar crack using impact loading, and the propagation of the crack using a dynamic peel-like loading. Cheng et al. [16] investigated shredding energy consumption of glass fiber reinforced plastic (GFRP) composite waste. This work investigated the effect of glass fabric structures, the feedstock feed rate, and screen size on the specific shredding energy of unsaturated polyester resin to manufacture GFRP plates. Their study focused on optimizing feed rates and screen size to minimize energy.

Vincent et al. [17] investigated shredding and sieving thermoplastic composite scrap with a focus on fiber length distribution (FLD). The relation between flake size and FLD showed that offcut layup barely influences the FLD in comparison with flake size. Hummel et al. [18] analyzed the mechanical properties related to fiber lengths of closed-loop-recycled offcuts of organo sheet thermoplastic fiber composites. These were processed via injection molding and thermally cycled recyclate to produce hybrid components, such as car door modules.

Goncalves [19] conducted a review of the status and future perspectives for reinforced glass fiber waste. They reported that while mechanical shredding is currently the most used process, there is a potential for thermal processes to be more competitive than others due to the fiber quality after the recycling process.

Studies by the present authors have also illustrated that mechanical shredding is a viable option with lower energy consumption that avoids the need to separate the fiber from the resin constituent [1]. To our knowledge there are no published studies on ECM long thermoplastic-based post-processing of recycled PP-GF. ECM offers distinct advantages in terms of the retention of higher fiber lengths in the part. Hence, a recycling strategy that utilizes ECM can benefit from higher performing part and scale able processes.

This study focuses on PP-GF feedstock, subjected to the mechanical shredding and post-processing of the recyclate via ECM which lends itself to scale able manufacturing.

3. Materials and Methods

PP-GF scrap generated from edge and bulk trim from the manufacture of truck trailers was the source of the recyclate used in this study. The production of PP-GP splash guard(s) that run the entire length of a 17 m (53 ft) trailer results in thousands of pounds of long ribbon-like edge trims. Furthermore, structural PP-GF composite panels are used in the wall and floor areas. The source of scrap is also from trim that results from machining such rigid PP-GF panels. The source of recyclate in this work included (a) the ribbon-like PP-GF trims, and (b) the scrap composite PP-GF plates.

Scrap edge trim PP-GF material in ribbon form or consolidated laminates were shredded to pellet lengths of 38 mm (0.75″) using sieve screens in an industrial counter rotating blades shredder at Jordan Reduction Solutions, Birmingham, AL, USA [14], see Figure 1. The PP-GF scrap was processed in four weight percentages, namely 100%, 83%, 66%, and 50% recyclate by simple blending with neat PP to correspond to 60%, 50%, 40%, and 30% fiber weight fraction composite, respectively.

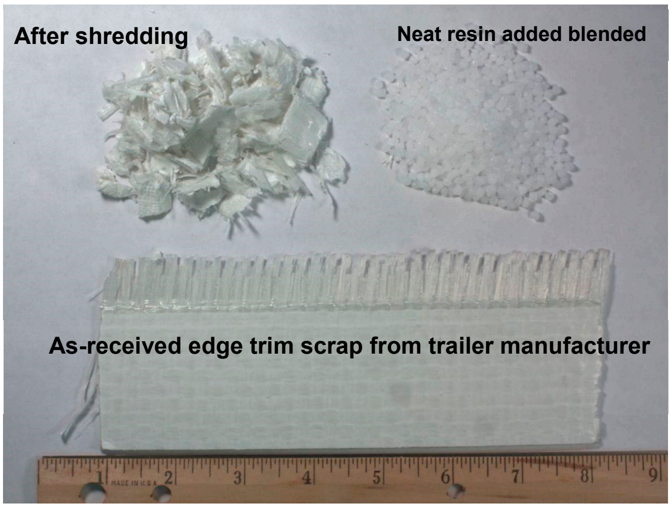


Figure 1. As-received edge trim scrap from trailer manufacture and material after shredding. Neat virgin resin is blended in limited quantities to assist in flow molding.

Table 1 provides the evidence of these fiber weight fractions in the processed panels, a minimum of five specimens for each. For comparison, plywood-backed sheet metal facings are used in trailers today (Figure 2), and 30% fiber weight ECM molded long fiber thermoplastic (LFT) PP-GF composite, a commercial material used in automotive applications were also considered. Since these materials witness severe impacts from cargo handling and forklift abuse, low velocity impact (LVI) tests [20] were conducted using a 6 kg mass dropped at 10, 15, and 20 cm impact heights.

Table 1. Summary of scrap PP-GF material in combination with virgin PP.

50% regrind with 50% virgin PP
66% regrind with 34% virgin PP
83% regrind with 17% virgin PP
100% regrind
Corresponding final fiber content: 30%, 40%, 50%, and 60%

The PP-GF scrap was reduced in an industrial shredder to two-dimensional (2D) flakes form of average length 38 mm (0.75″) in a twin-shaft shredder [14], see Figure 1. The shredding knives were made of high-strength heat treated steel alloy. The as-received material had >70% fiber weight fraction (W_f) measured via burn-off. It can be seen from Figure 3 the scanning electron microscopy (SEM) images of the as-received material indicates large presence of dry fibers, i.e., very low resin content. Hence, studies were conducted by simple blending virgin PP with the PP-GP recyclate in varying percentages. The PP-GF scrap material was processed in several weight percentages of recycled contents namely 50%, 66%, 83%, and 100% by weight. These variants are summarized in Table 1, while Table 2 provides evidence of the weight fraction of recyclate in the respective variants.

Figure 2. Sheet metal facia with plywood backing used in trailer inner liner wall panels.

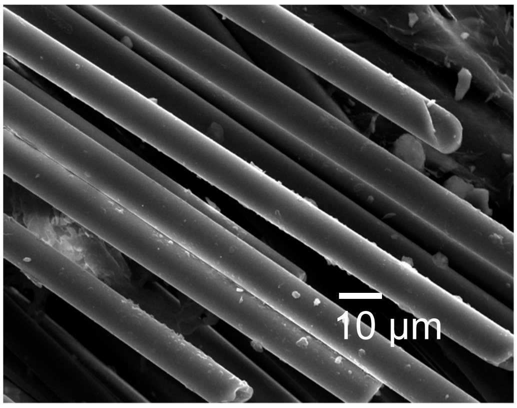


Figure 3. SEM of 'as received' manufacturing scrap material showing limited resin wet-out on glass fibers. This indicates the as-received material had very high fiber content, >70 wt%.

Table 2. Verification of fiber weight fraction in recyclate.

Sample ID	Weight of Empty Pan (grams)	Sample + Pan (grams)	Sample + Pan (grams)	Weight of the Sample (grams)	Weight of the Fiber (grams)	Fiber Weight Fraction
30-1	2.20	9.76	4.51	7.56	2.31	30.56
30-2	2.22	9.42	4.41	7.20	2.19	30.42
30-3	2.26	9.50	4.48	7.24	2.22	30.66
35-1	2.18	9.37	4.92	7.19	2.74	38.11
35-2	2.18	9.27	4.88	7.09	2.70	38.08
35-3	1.40	8.35	4.06	6.95	2.66	38.27
40-1	2.21	9.69	5.52	7.48	3.31	44.25
40-2	2.23	9.39	5.56	7.16	3.33	46.51
40-3	2.24	9.45	5.36	7.21	3.12	43.27
45-1	2.22	9.24	5.29	7.02	3.07	43.73
45-2	2.20	9.13	5.18	6.93	2.98	43.00
45-3	2.18	9.37	5.34	7.19	3.16	43.95

For comparison, 25 mm (1″) starting fiber length, 30 wt% PP-GP, LFT Celstran® (Ticona/Celanese, Winona, MN, USA), and commercial grade plywood used in interior walls of trucks were considered. Panels of 300 mm × 300 mm × 5 mm (12″ × 12″ × 0.2″) size were produced. Thermomechanical and chemical characterization was conducted via thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR), respectively.

Processing of PP-GF Recyclate Shreds

The shredded PP-GF scrap was processed using ECM process [3]. In ECM, a low shear plasticator is used to homogenize discontinuous (shreds) PP-GF into a hot-molten 'charge' as illustrated in Figure 4. Details of the ECM process is described elsewhere [3]. The 'charge' is compression molded in a two-cavity mold (tool) mounted in a fast-acting press at 2.54 m/min (100 inches/minute). The 'charge' placement in the mold (tool) results in preferential fiber orientation, also as illustrated in Figure 4. Two orientations are expected to develop, i.e., fibers flow 'along' or 'across' a reference direction in the mold based on placement of the 'charge' and filling of the mold. This is also referred to 'Longitudinal' and 'Transverse' fiber orientation throughout this manuscript.

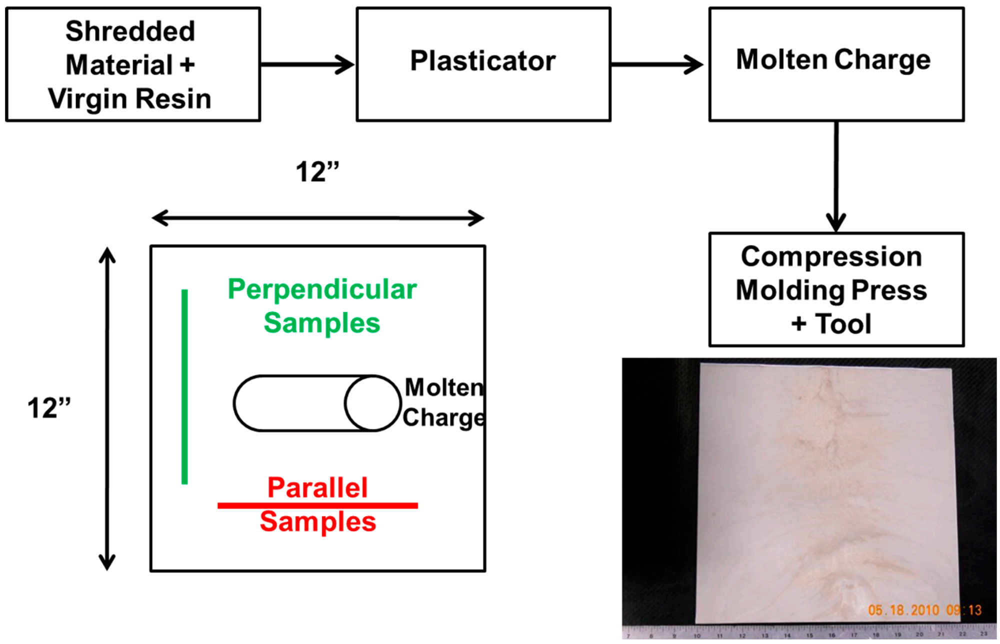


Figure 4. Processing of recyclate, as-received and simple blended recyclate with virgin PP via ECM. Specimens were cut in two directions—*Longitudinal* and *Transverse*, respectively, to capture the influence of flow induced fiber orientation. Fibers are preferentially oriented in the *Longitudinal* direction and cross-oriented in the *Transverse* direction. The plate is 300 mm × 300 mm (12″ × 12″).

Test specimens for ASTM standard tension, flexure, and low velocity impact tests were cut from the ECM processed plates. The specimens were cut along the two directions—'Longitudinal' and 'Transverse', to evaluate the influence of flow-induced fiber orientation on mechanical properties. Tensile strength and modulus were determined via dog bone coupons per ASTM D638. Flexural strength and modulus were measured with ASTM D790. Low velocity impact testing was conducted on an instrumented drop tower Instron Dynatup 8250.

4. Results

4.1. Thermal and Surface Characterization

This study investigated whether the recycled material exhibited any chemical degradation during processing. This was investigated by evaluating thermogravimetric analysis (TGA), Fourier Transform Infrared Spectroscopy (FTIR), and Differential Scanning Calorimetry (DSC). Figure 5 is a representative TGA of the as-received material. The onset of weight loss occurs at approximately 240 °C providing helpful guidelines on processing the recyclate in the ECM process. Figure 6 provides FTIR traces of the shredded material, compared with neat PP polymer and 'after processing' into a composite plate.

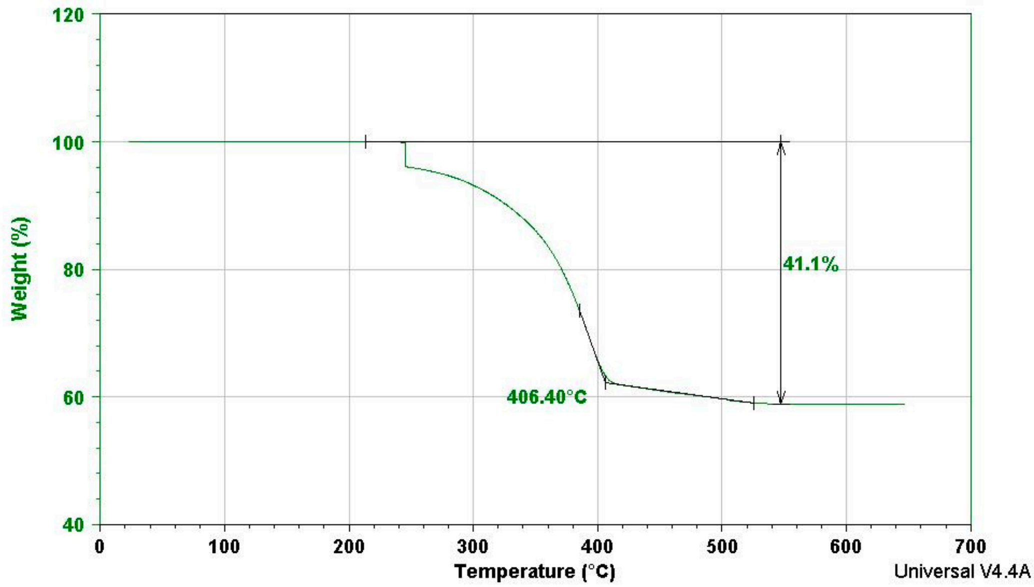


Figure 5. TGA curve of as-received PP-GF recyclate. The actual data begins at 98 wt% since there was some loss of data in the 100–98 wt% region.

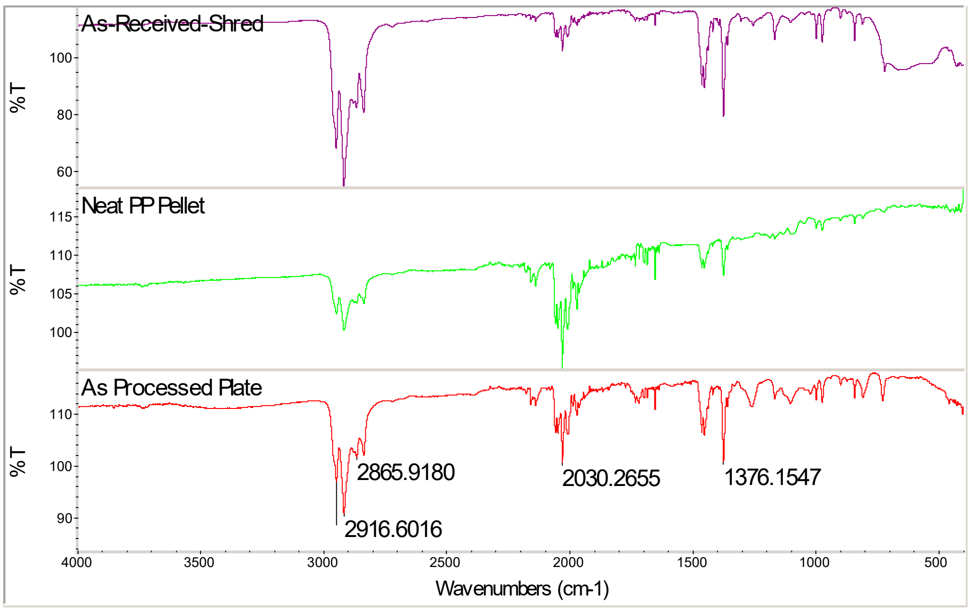


Figure 6. FTIR traces of the PP-GF shred, neat PP pellet and as-processed plate. There is no material degradation as evidenced by these tests.

It can be seen that the material had a very similar FTIR response through these different processing stages indicating there was no degradation of the material during the ECM processing. Figure 7 illustrates the heating and cooling DSC comparing the as-received shred and the plates after processing. The crystallinity values were marginally higher for the ECM processed material in comparison with the as-received material. The nominally higher crystallinity can be attributed to the blended virgin PP to the PP-GF scrap. The data also confirms that the material does not degrade through the processing steps.

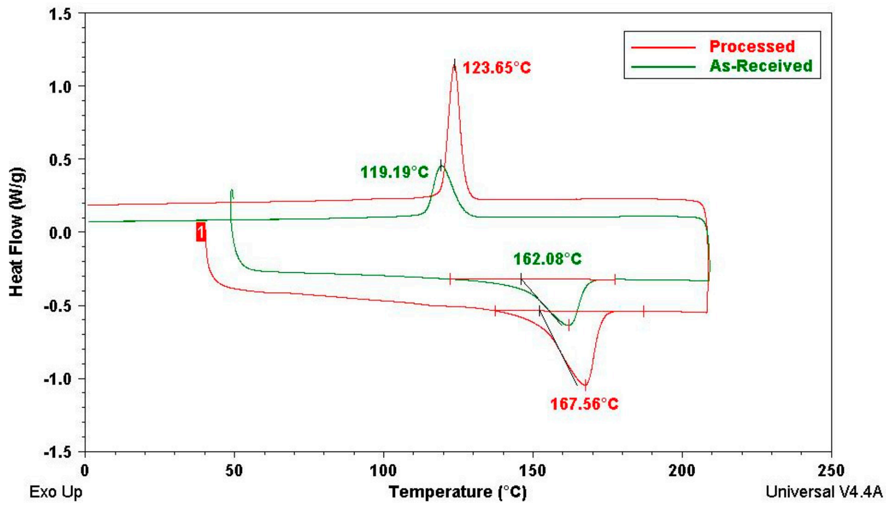


Figure 7. Heating and cooling DSC curves for the as-received shred and processed plates.

4.2. Tensile Response

Figure 8a,b summarize the tensile strength and modulus of the various recycled materials. It is seen that the strength and modulus are higher for the 66% recycled content (40% W_f) specimens, compared with the lower and higher percentages of recycled content. This indicates optimal wet-out of the fiber interface at this percent. Table 3 summarizes the tensile test data.

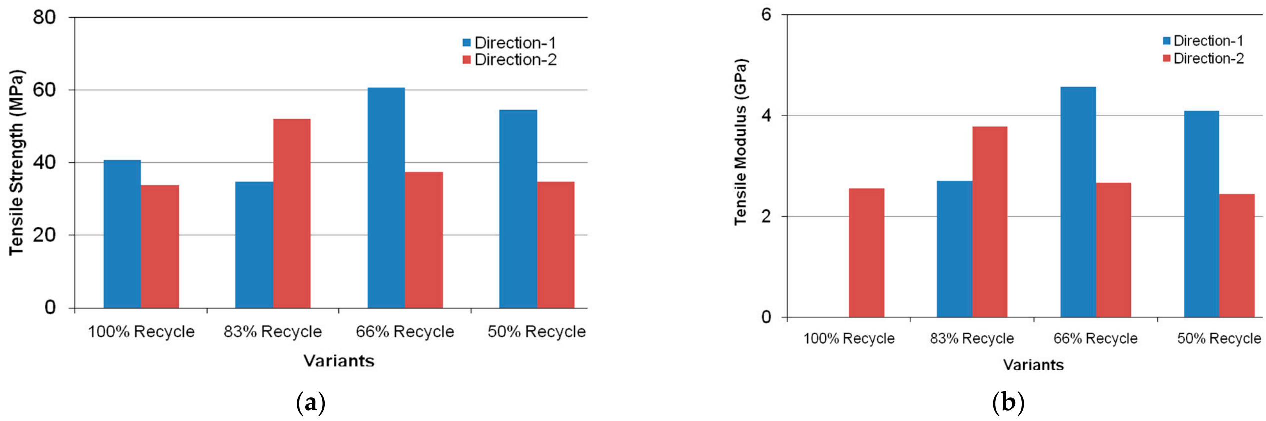


Figure 8. (**a**) Tensile strength (MPa) response from different recycle constituents for *Longitudinal* and *Transverse*, respectively; (**b**) Corresponding Tensile Modulus (GPa) for the same variants. The dashed lines represent virgin 30 wt% PP-GF LFT for the corresponding directions and 100% recyclate is the as-received PP-GF scrap.

The fiber distribution in the part has a definite influence on the resulting mechanical properties. The specimens measured in 'Longitudinal' exhibited higher value compared with 'Transverse' specimens. The 'Longitudinal' specimens had fibers oriented primarily in the direction of the loading; and the 'Transverse' samples had fibers 'Transverse' to the loading direction. The dashed line in Figure 8a,b points to the lower and upper bound of comparable 30 wt% virgin LFT specimens. It was seen that the strength is comparable for the 50% and 66% recycled content specimens. Figure 9 illustrates a typical tensile failure of the 66% recycled PP-GF compared with a PP-GF LFT specimen. The failure was through a localized fracture in tension and a similar failure was exhibited for both the recycled PP-GF and the LFT PP-GF of similar weight fractions.

Table 3. Tensile strength and modulus for 'Longitudinal' and 'Transverse', respectively.

'Longitudinal'					
Specimen	**Final Fiber Weight Percentage**	**Tensile Strength (MPa)**	**Tensile Strength Std Dev**	**Tensile Modulus (GPa)**	**Tensile Modulus Std Dev**
100% Recycle	60%	40.7	8.91	N/A	N/A
83% Recycle	50%	34.79	3.80	2.71	0.2
66% Recycle	40%	60.6	9.14	4.57	0.78
50% Recycle	30%	54.6	7.04	4.1	0.54
'Transverse'					
Specimen	**Final Fiber Weight Percentage**	**Tensile Strength (MPa)**	**Tensile Strength Std Dev**	**Tensile Modulus (GPa)**	**Tensile Modulus Std Dev**
100% Recycle	60%	33.82	3.94	2.56	0.2
83% Recycle	50%	51.96	11.80	3.79	1.02
66% Recycle	40%	37.35	5.51	2.67	0.48
50% Recycle	30%	34.67	2.52	2.44	0.19

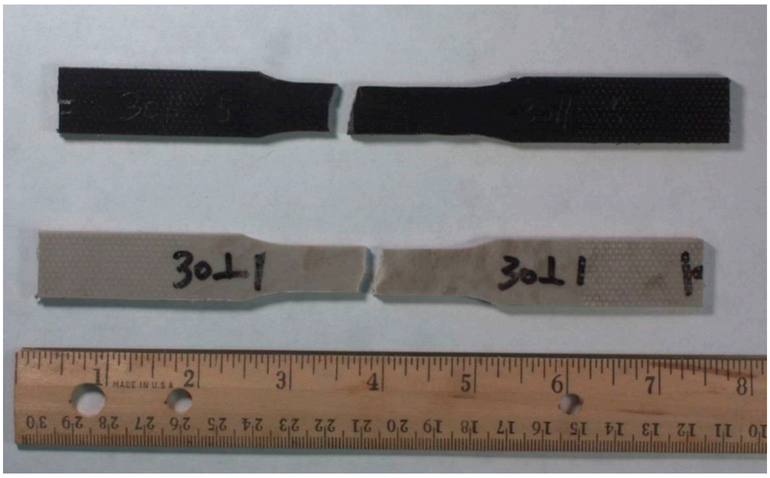


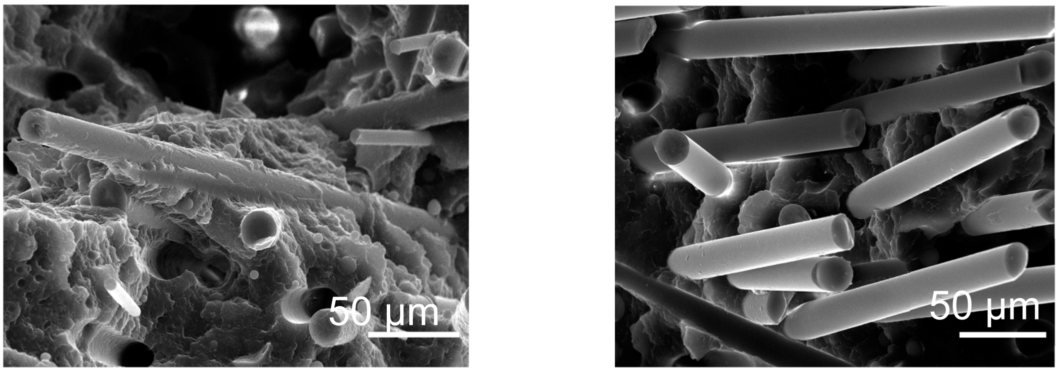
Figure 9. Tensile failure of (**top**) 30 wt% recyclate GF-PP and (**bottom**) 30 wt% LFT GP-PP failure modes.

Figure 10a,b illustrates the wet out of the tensile specimens. The higher recycled content material (Figure 10b) was seen to have lesser fiber-matrix wet-out as compared with the specimens where some amount of virgin polymer was blended (Figure 10a). The fiber-matrix interface for the 66% specimens in Figure 10a illustrates the tortuosity of crack propagation due to the excellent fiber-matrix wet-out. This suggests that for tensile performance, a small amount of virgin polymer blended with recycled PP-GF improves the material response, comparable to 100% PP-GF recyclate.

The 100 wt% recycle content has more dry fibers and hence lower strength and modulus compared with a higher wet-out and fiber-matrix interface interaction in the 66 wt% material.

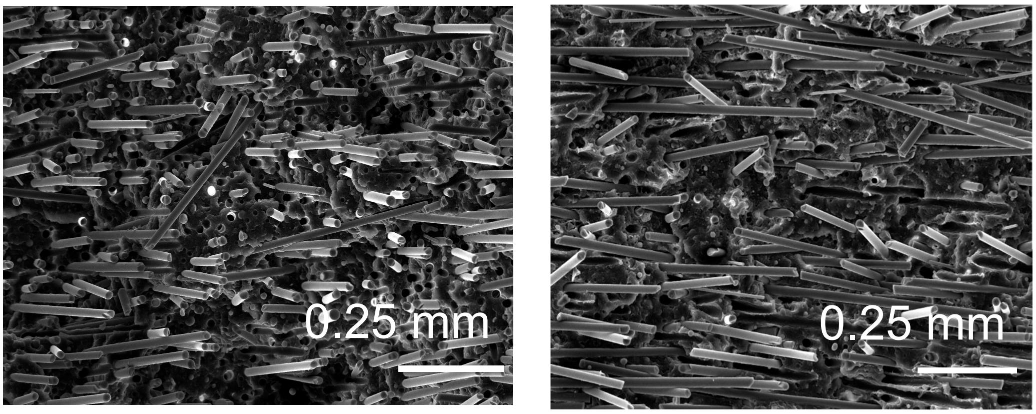
Figure 11 illustrates the effect of fiber orientation for 30 W_f%, i.e., here 30% W_f corresponds to 50% recyclate. The microstructure illustrates that 30% 'Longitudinal' recyclate sample has more fiber aligned in the loading direction and fibers aligned out of plane from the screen and the 30% 'Transverse' samples have fibers aligned in-plane to the screen. This provides evidence of higher properties for the 'Longitudinal' specimens.

Figure 12 compares LFT (commercial) with recycled ECM-molded specimens. The main difference is that less fiber attrition in the 30% LFT and longer fibers at the tensile breakage surface can be seen, compared with the recycled material. Hence the LFT exhibits higher tensile strength than 30% recyclate (recyclate) sample.



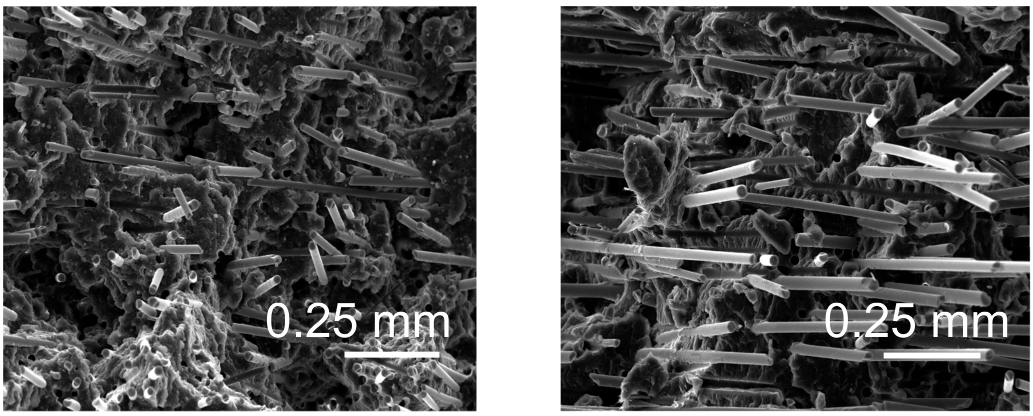
(**a**) (**b**)

Figure 10. Comparison of wet-out with (**a**) 66% recycled and (**b**) 100% recycled content material.



30% Longitudinal Regrind at 126X *30% Parallel Regrind at 126X*

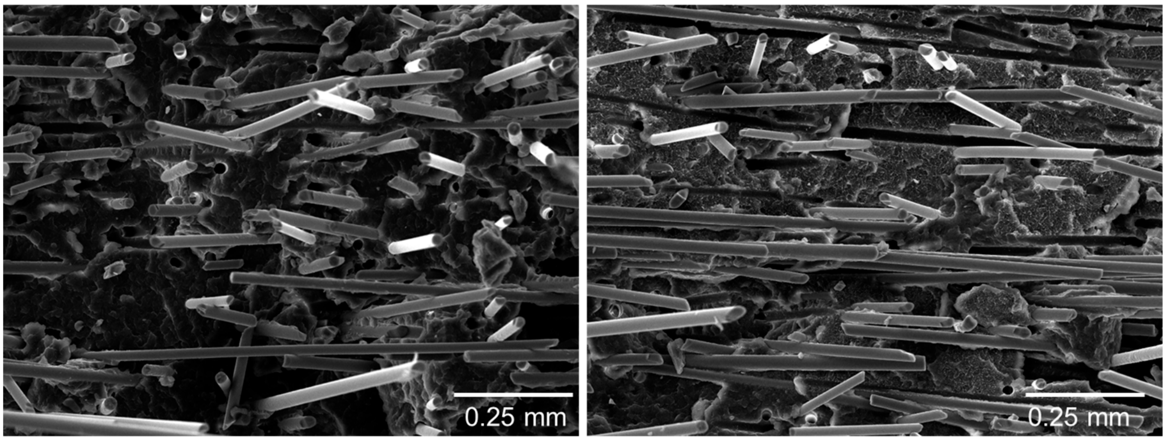
Figure 11. Effect of fiber orientation for 30 W_f%, i.e., Perpendicular vs. Parallel fibers to the loading direction. In total, 30% W_f is 50% recyclate and 30% perpendicular regrind sample has more fiber aligned in the loading direction and fibers aligned out of plane from the screen and 30% Parallel samples have fibers aligned in-plane to the screen.



30% Perpendicular Regrind at 126X *30% Perpendicular LFT at 126X*

Figure 12. The 30% LFT sample has longer fibers at the tensile breakage surface (higher tensile strength) than 30% regrind sample.

Figure 13 illustrates 30% 'Longitudinal' LFT sample indicating more fibers aligned in the loading direction compared with 30% parallel LFT sample.



30%Perpendicular LFT at 126X *30% Parallel LFT at 126X*

Figure 13. The 30% perpendicular LFT sample has more fibers aligned in the loading direction compared with the 30% parallel LFT sample.

4.3. Flexure Response

Flexural tests were conducted per ASTM D790 in a three-point bend mode. Table 4 summarizes the flexural test results. Figure 14 (Left) illustrates the load-displacement curves for various recycled contents. For higher recycled contents, i.e., the 83% and 100% recycled content, the specimens are stiffer in flexure; for example, in the 50% and 60% recycled content, the curves are gradually softening, i.e., they possess higher ductility. There was no catastrophic failure in any of the specimens evaluated. The specimens deformed gradually as seen in Figure 14 (Right).

Table 4. Summary of flexure tests for various recycled fiber contents for 'Longitudinal' and 'Transverse', respectively.

'Longitudinal'					
Specimen	**Final Fiber Weight Percentage**	**Flexural Strength (Mpa)**	**Flexural Strength Std dev**	**Flexural Modulus (Gpa)**	**Flexural Modulus Std dev**
100% Recycle	60%	93.01	4.98	8.42	0.66
83% Recycle	50%	81.69	13.69	5.55	0.58
66% Recycle	40%	79.70	6.35	5.05	0.25
50% Recycle	30%	73.77	3.62	3.75	0.21
'Transverse'					
Specimen	**Final Fiber Weight Percentage**	**Flexural Strength (Mpa)**	**Flexural Strength Std dev**	**Flexural Modulus (Gpa)**	**Flexural Modulus Std dev**
100% Recycle	60%	65.26	15.99	5.06	0.65
83% Recycle	50%	96.53	8.50	6.20	0.26
66% Recycle	40%	58.21	7.26	3.35	0.30
50% Recycle	30%	56.91	8.21	2.76	0.31

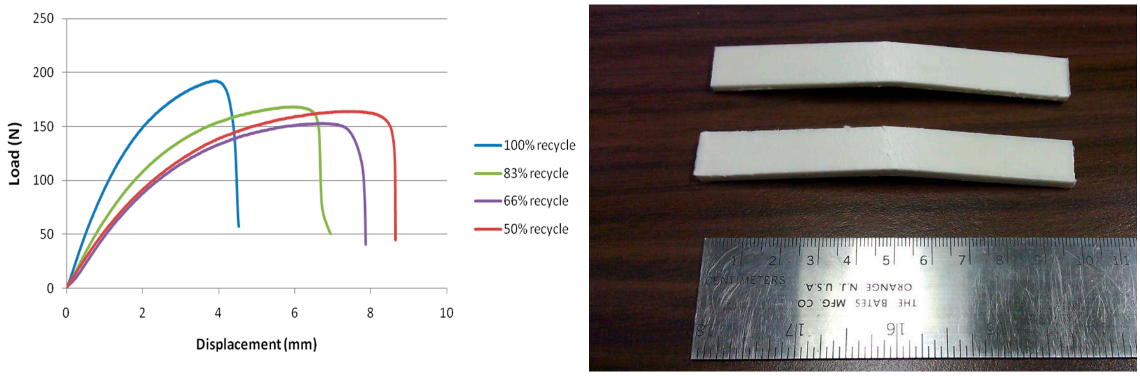


Figure 14. (**Left**)—Load-displacement curves for PP-GF with different percentages of recycled content; (**Right**)—Typical flexural failure mode for these specimens.

Unlike the tensile tests, the flexural strength and modulus of the 100% and 83% recycled compositions were higher than the 66% and 50% recycled compositions, respectively, see Figure 15 (Left, Right). The flexural modulus of the 100% recycled material was ~8.5 GPa which is comparable to that of the 30 wt% virgin LFT.

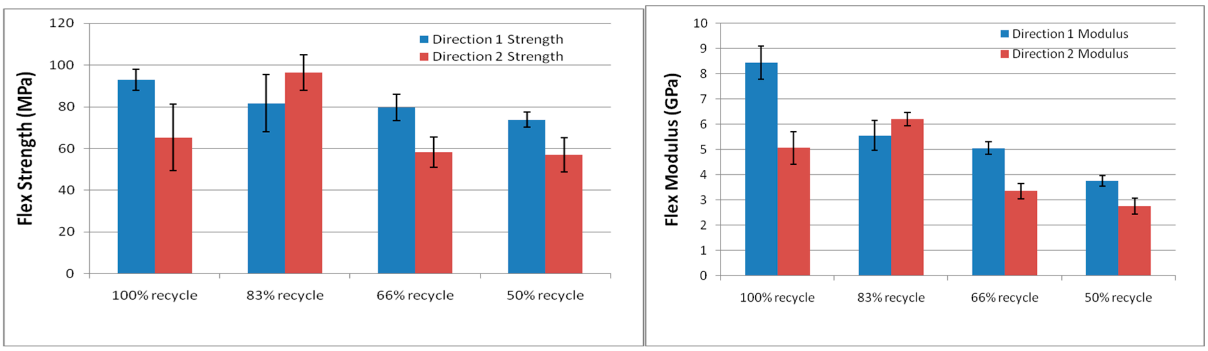


Figure 15. Flexural response of PP-GF with different percentage of recycled content; (**Left**)—Flexural strength (Mpa); (**Right**)—Flexural modulus (Gpa). In total, 100% recyclate is the as-received PP-GF scrap.

Although there is some variation in 'Longitudinal' and 'Transverse' properties, the fiber directionality resulting from ECM is less influenced for the flexural results compared with the tensile results. The flexural results suggest that in 'Transverse' loading those higher fiber fractions resist flexure effectively for through the thickness loading, provided there is adequate interfacial strength to prevent fiber/matrix separation. Since even the 100% recycled composition specimen failed by deformation (i.e., no catastrophic cracking), the fiber-matrix interface resisted deformation by strain deformation of the PP matrix effectively.

4.4. Impact Performance of PP-GF Scrap Compared with Plywood and LFT

The impact response of these panels was evaluated by subjecting them to a drop weight low velocity impact (LVI) with an impactor of 6 kg mass to impart 6 J and 24 J impact energies, respectively, under different drop heights. A typical load-time and energy-time curve is shown in Figure 16 (left). Samples with dimensions of 100 × 100 mm (4″ × 4″) were prepared for impact testing. The setup shown in Figure 16 (right) was used to conduct the LVI tests. A 19 mm (3/4″) hemispherical-shaped impactor was used. Specimens (plates) were clamped between two metal plates in a fixture with 75 mm (3″) diameter opening at its center. The impact took place in the exposed circular area. The load versus time and energy versus time were recorded.

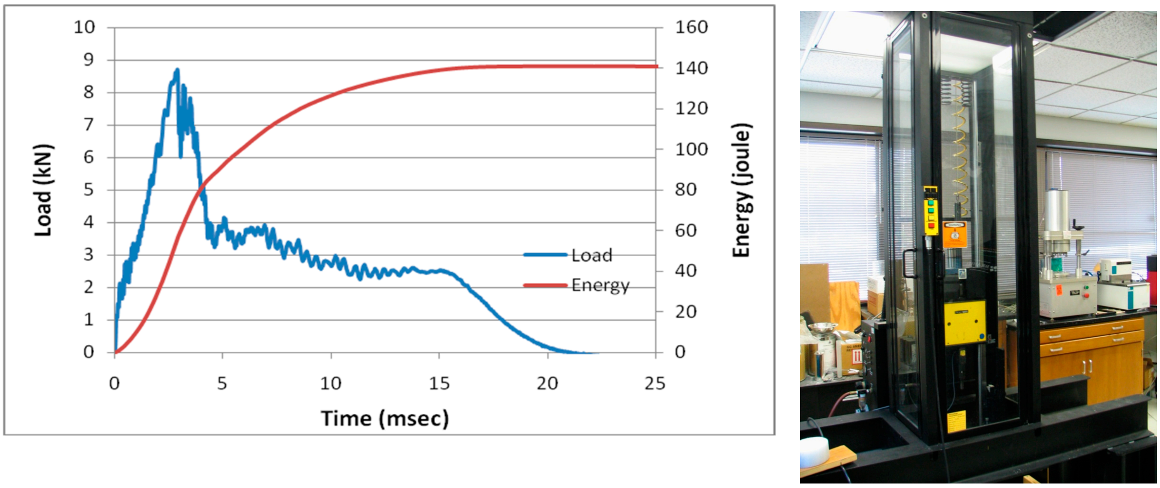


Figure 16. Low velocity impact to composite plates; (**left**) Representative load and energy versus time and (**right**) instrumented drop weight impact setup.

Two parameters, namely—Normalized Maximum Load and Normalized Energy to Maximum Load—were recorded for each specimen, a typical load-time and energy-time curve as shown in Figure 16 (right). The maximum load is the load the sample can bear before failure occurs. The energy to maximum load is the energy that the sample can absorb before failure.

Table 5 compares the density and thickness of plywood to reprocessed PP-GF scrap and standard LFT.

Table 5. Comparison of materials for use for trailer applications. Compares density and thickness of plywood to reprocessed PP-GF scrap and standard LFT.

	Plywood [1]	**60 wt% Regrind** [2]	**30 wt% Regrind** [3]	**30 wt% LFT** [4]
Areal density (g/cm^2)	0.38	0.54	0.41	0.40
Thickness (mm)	6	3.8	3.4	3.6

[1] Plywood—standard material used in trailers today (see Figure 2). [2,3] Panels made with 30 wt% and 60 wt% PP-GF trailer scrap. [4] 30 wt% PP-GF commercial LFT used in automotive and transportation.

In these tests, a 6 mm thick plywood board was used for the comparison of impact properties. The areal density of the plywood and the composite specimens was maintained as close to ~0.40 g/cm^2 as possible. The impact data was normalized with respect to thickness to eliminate the effect of thickness and areal density differences between the samples.

Figure 17 shows the representative results of the normalized energy and normalized load of 6 kg impact mass dropped from 15 cm height for plywood, 30 wt% and 60 wt% PP-GF recyclate composite, and commercial LFT [3]. The results show that the PP-GF recyclate composite plates at 30 wt% and 60 wt% fiber loading are more effective in absorbing energy and have a signficiantly higher damage tolerance than plywood. Plywood (which is the baseline) exhibits the poorest performance when subjected to impact. Fully virgin LFT performs marginally higher but is also the most expensive.

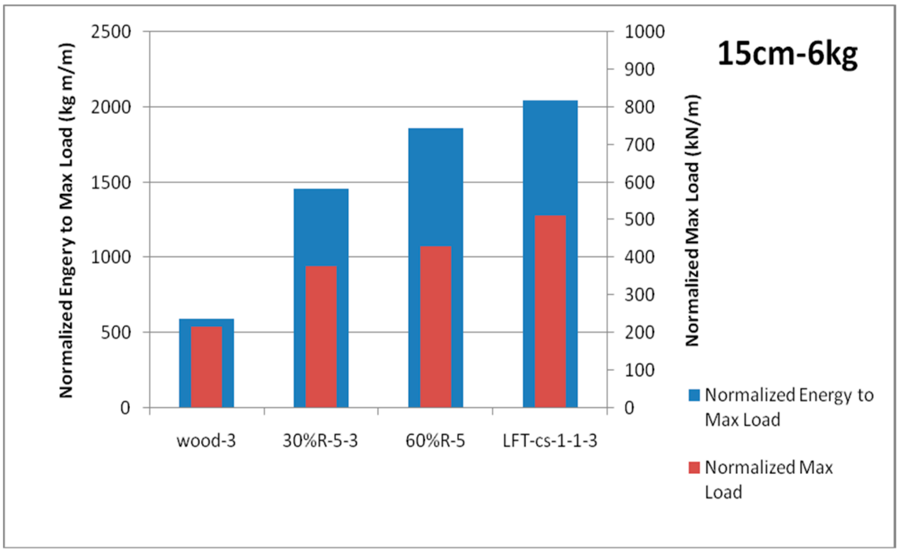


Figure 17. Normalized impact energy and normalized load of 6 kg impact mass at 15 cm height—for plywood, 30 wt% scrap, 60 wt% GF-PP recyclate composite, and conventional LFT. The results show that 60 wt% scrap material is closer in energy absorption to LFT. Wood behaves poorly.

Figure 18 summarizes the normalized energy and normalized load of a 6 kg impact mass at 6 J (Figure 18 (left)) and 24 J (Figure 18 (right)) impact energies, respectively. *At 6J impact energy*—the composite plates absorbed three times more impact energy, as compared with the plywood of comparable areal density. The peak loads and energies for the various composite recycled compositions is similar since the these are primarily elastic rebounds—there is no damage visible in the composites at the 6 J energy level. For the *24 J impact energy*—there is catastrophic damage in the plywood as seen from the front and back face damage illustrated in Figure 19. For similar energy levels, the composite specimens show minimal yet discerning damage among various recycled compositions. The 50% recycle composition (highest matrix content) is seen to absorb the highest energy due to deformation of the PP matrix. The response of the 66%, 83%, and 100% specimens was comparable in terms of peak load and energy levels. As seen from Figure 19, the failure on the composite specimen is minimal on the strike face.

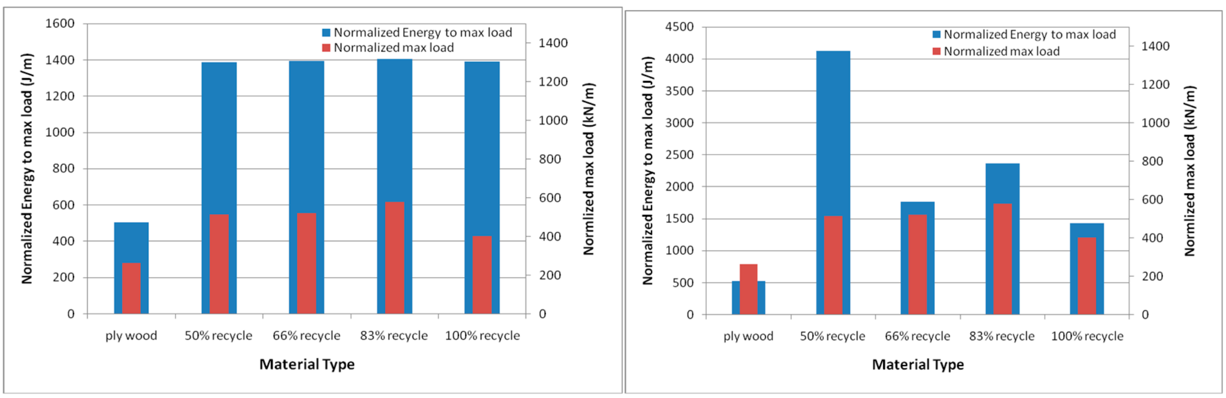


Figure 18. Low Velocity Impact (LVI) response of PP-GF with different percentages of recycled content; (**left**)—6 J impact; (**right**)—24 J impact. In total, 100% recyclate is the as-received PP-GF scrap.

Figure 19. LVI response of plywood (**left**) compared with an 83% recycled content PP-GF (**right**) impacted at 24 J impact. The top row is the strike face; the bottom row is the back face.

The sample size is 150 mm × 100 mm (6″ × 4″).

Figure 20 provides a comparison of load–time curves for the LVI response of recycled PP-GF, plywood, and 30 wt% LFT PP-GF. It can be noted that the PP-GF recycled plate was almost equivalent to the response of LFT virgin, the highest performing. Plywood absorbed the least amount of energy.

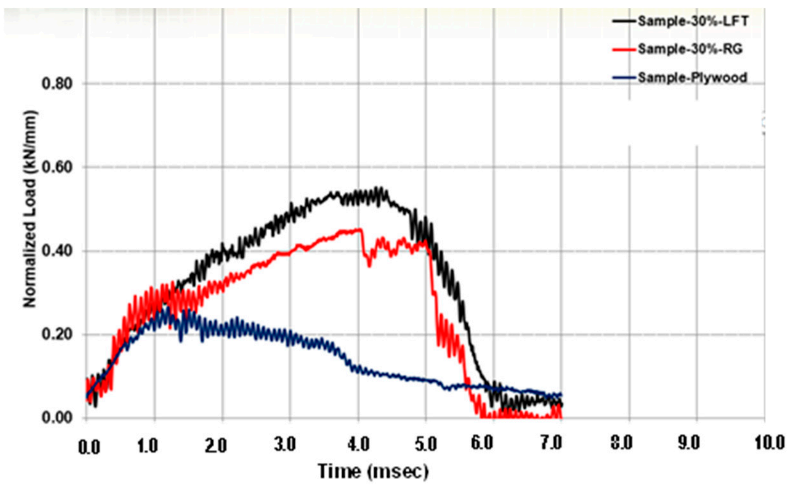


Figure 20. Comparison of LVI of recycled PP-GF, plywood and 30 wt% LFT PP-GF.

Figure 21 represents the burn-off fibers in consolidated recyclate panels and indicates an average length of 5 mm.

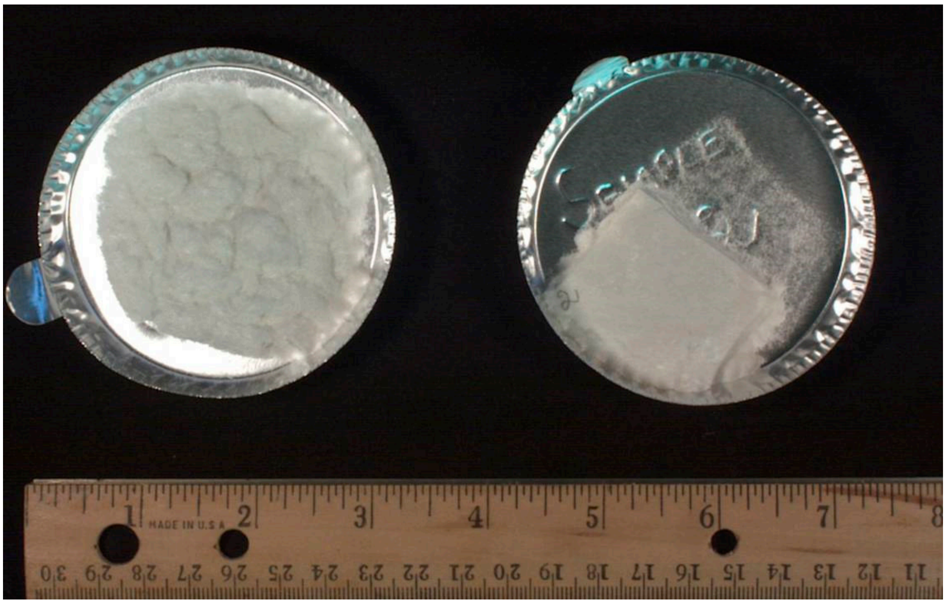


Figure 21. Fibers in consolidated regrind panel have average length of 5 mm.

5. Discussion

The tensile results were found to be most sensitive to fiber orientation and recycled content. The tensile properties were lower for higher percentages (83% and 100%) of recycled content, and very low percentages of recycled content (50%), suggesting that a threshold of 60–70% recycled content leads to optimal materials. The direction of fiber orientation was most sentitive in resulting in higher values for fibers oriented along the loading axis versus lower values for 'Transversely' oriented fibers.

The flexural and impact response was less influenced by the recycled content. The results suggest that higher percentages of recycled content can be used in applications involving 'Transverse' loading such as under flexure and impact.

The results also show that plywood, which is the baseline used in the present generation of trailers for floors, walls, and other interior components, exhibits the poorest mechanical response amongst them all. The recycled PP-GF scrap was effective in absorbing the impact energy and exhibited much superior damage tolerance than the presently used plywood, which shows poor performance at the various impact conditions. Standard long fiber thermoplastic performs the best, but a comparable performance was obtained using 100% PP-GF recycled scrap.

Scale Up

Figure 22 illustrates that we have been able to scale-up the 300 mm × 300 mm (12″ × 12″) PP-GF panels made from 100% recyclate shred, to sizes of 0.6 m × 0.6 m (24″ × 24″) with similar performance and quality. We have further developed 1.2 m × 1.2 m (4′ × 4′) and 1.2 m × 2.4 m (4′ × 8′) sizes relevant to the panelized applications for truck flooring and building wall panels.

We have also been able to demonstrate the ability to form shaped parts such as shown in Figure 22 as well. The body parts of trucks increasingly require aerodynamic surfaces that have shapes around corners and bends. The use of recycled materials for creating such rounded/shaped features will have high value in future products.

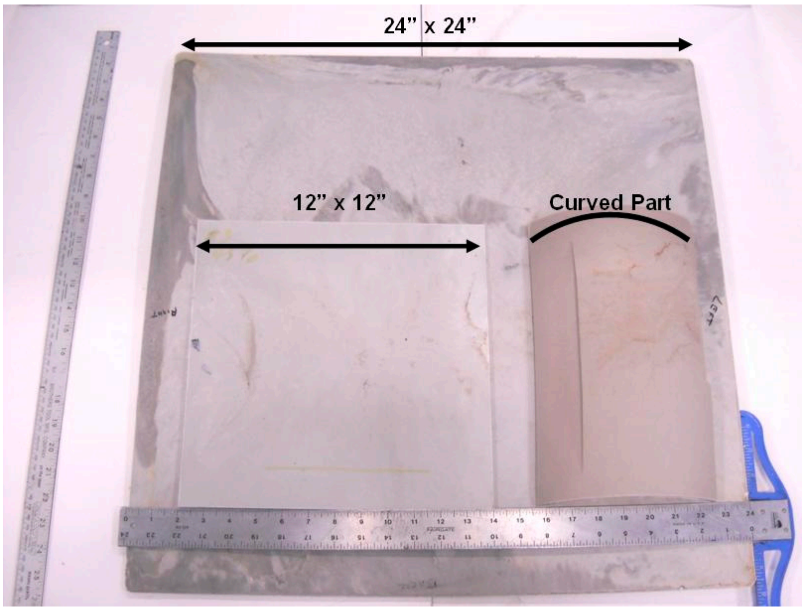


Figure 22. Scale up and shape illustration. PP-GF panels of various sizes and shapes produced from scrap/recycled materials. Demonstration of ability to scale-up the process into panels and curved shapes for parts The large plate is 600 mm × 600 mm (24″ × 24″) and the small plate is 300 mm × 300 mm (12″ × 12″) in dimension.

6. Conclusions

Extrusion-compression molding (ECM) was shown to be an effective way of processing and scaling up recycled glass fiber thermoplastics in a flake-like form. The results were sensitive to various percentages of recyclates. In general, (a) the tensile strength was comparable for 50% and 66% of recycled content specimens. The failure was through localized fractures in tension and similar failures were exhibited for both the recycled PP-GF and the LFT PP-GF of similar weight fractions; (b) the flexural strength and modulus of the 100% and 83% recycled compositions was higher than the 66% and 50% recycled compositions, respectively, indicating a gradual softening with lesser recycled fiber content, i.e., possessing higher ductility. The influence of fiber orientation was more prominent in tensile failure. The fiber directionality resulting from ECM is less influenced for the flexural results compared with the tensile results; (c) in terms of energy absorption, the PP-GF recyclate at 30 wt% and 60 wt% fiber loading was effective in absorbing energy and had a signficiantly higher damage tolerance than plywood. The composite plates absorbed three times more impact energy, as compared with the plywood of a comparable areal density. For similar energy levels, the composite specimens showed minimal yet discerning damage among various recycled compositions. The practical utility of this work is that process methodology and shapes are scaleable for larger structures.

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