

Characterization of Composites Manufactured Through Reshaping of EoL Thermoplastic Polymers Reinforced with Recycled Carbon Fibers

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Abstract: This article investigates if and at what extent a recycling process based on grinding, melting and reshaping of recycled carbon fibers reinforced thermoplastic polymers (rCFRPs) can affect their physical, mechanical and thermal properties. The aim is to establish if they can be taken into consideration in the manufacturing of new composite materials in different sectors: automotive, marine, sporting goods, etc. Composites materials were submitted to the measurement of the fibers length they are composed of, and then analyzed by means of tensile and impact tests and a dynamic mechanical analysis (DMA). All the characterizations were performed to both initial and recycled composites and, in some cases, they were replied also after the intermediate accelerated aging. Characterization performed confirmed that, as expected, the recycling process affects the properties of the composites, but in different manners and to a different extent when different polymers are involved. Tensile and impact tests pointed out that the polypropylene based composites showed a less stiff and a more brittle behaviour after the recycling process and the DMA confirmed this evidence, highlighting in addition a more viscous behavior of the polymer after the recycling. Conversely, the polyamide 6 based composites increased their stiffness and ductility after the recycling. For all the composites the tensile strength dropped, confirming the weakening of the materials.

Keywords: Composites; Mechanical recycling; Reshaping; Thermoplastics; Characterization.

1. Introduction

Carbon fibers reinforced plastics (CFRPs) were introduced in the 1960's and rapidly widespread in different market segments like automotive, wind farm, construction, sporting goods and consumer goods, thanks to their ability to combine high mechanical performance with very low weight compared to metallic counterparts [1-5].

Since 1970's to the present, the production and the use of CFRPs and carbon fibers in general is increasing. Indeed, despite the coronavirus (covid-19) experienced since 2020 was severe globally and the carbon fiber industry was not exempt, experts say that potential growth can be assured for many market segments. For examples, in wind energy the carbon fibers is expected to grow from 16 ktonnes in 2015 to more than 40 ktonnes in 2026 and an explosive growth in demand for carbon fibers is expected also in the automotive industry with the manufacture of battery housings for electric vehicles, but above all with the production of lightweight high-pressure vessels for the storage of hydrogen in fuel-cell vehicles [6].

Lifespan of CFRPs is estimated to be approximately 50 years [7] and therefore in the last decade the management of the EoL composites is becoming very crucial. This is why great efforts have been spent in the study of CFRPs waste management, allowing to move important steps in the development of recycling processes. In the last years a lot of recycling processes have been tested for CFs based composite materials (mechanical grinding, conventional pyrolysis, microwave pyrolysis, high voltage fragmentation, solvolysis, combustion and incineration) [8-12]. Among this, the pyrolysis is up to now considered the more mature and technologically consolidated recycling route, allowing to recover the carbon fibers that retain mechanical properties very close to the virgin ones [13]. On another hand, the mechanical recycling process has been in depth analysed from several researchers [8, 14-19] and has achieved an average score of 6.3 in the TRL scale, indicating that prototypes demonstration in a relevant environment is reached as technology readiness [20].

Once the carbon fibers are reclaimed from EoL composites, they are reintroduced in the market through the manufacturing of new products. Several works investigated the technical feasibility, mechanical performances and potential applications of composite reinforced with reclaimed carbon fibers. Commonly, injection moulding (IM) and bulk moulding compound (BMC) are two techniques used to remold rCFs into new composites [13]. Injection moulding was used to manufacture and compare CFRPs [21]. The author claims that the recyclate was 25% less

stiff than the virgin control and with a tensile strength reduction of 12%, likely thanks to an improved adhesion between the matrix and the fibers. Turner et al. [22] produced some rCFRPs through BMC using recycled carbon fibers and noticed that they had mechanical performances superior to that of commercial BMCs manufactured with glass fibers. Another wide use of rCFs was the re-impregnation of 2D and 3D non-woven dry products. Several researchers dealt with this technique [22-26] and showed that the rCFRPs compared favorably with different virgin materials (like aluminum and GFRP) [22-24], or that the mechanical performance of three-dimensional engineered performing can be increased by using constant fiber-lengths [24, 25]. Thanks to mechanical performance similar to those of virgin carbon fibers (vCFs), rCFs were already used in the manufacturing of few structural components. In particular, rCFRPs are nowadays employed in the manufacturing on non-critical structural components [27] in different areas. One of this is the Automotive Industry, where the manufacturing of rCFRPs is strongly encouraged also by sustainable and green reasons. Also the aeronautics industry is looking with increasing interest on rCFRPs, in particular for the manufacturing of the interiors of the aircrafts [28].

Among the few structural components made with rCFRPs they are included a Corvette wheelhouse and an aircraft seat arm rest [24], a wing mirror cover and a car door panel [29], a driver's seat of a Student Formula SAE car [30].

Other markets in which the rCFRPs are introduced include sporting goods, household goods and construction industry. Pimenta et al. [13] provided a comprehensive overview of the potential applications of different types of rCFRPs (Table 1) where they are indicated with E_T and X_T the Young's modulus and the tensile strength, respectively

Table 1. Potential structural application for rCFRPs (source: Pimenta et al. [13])

Type of rCFRP	Possible processes		Foreseen markets for rCFRP	Examples of current solutions with virgin materials				
	Recycling	Manufacturing		Component	Materials	E_T [GPa]	X_T [MPa]	
Reinforced TP	Pyrolysis	• Injection moulding	• Automotive semi-structural parts	• Car dashboard	GF+PP	5.3	100	
	Fluidised bed			• Car underbody shielding	GF+PP	4.5	60	
	Chemical	• Compression moulding of non-woven mats	• Construction materials	• Plywood replacement	GF+PP			
Low-reinforced TS	Pyrolysis	• BMC compression	• Automotive semi-structural parts	• Car door panel	GF+UP	14	36	
				Fluidised bed	• Carburator housing	GF+UP	13	37
	Chemical	• Compression moulding of non woven mats	• Equipment housing	• Car headlamp reflectors	GF+UP	12	48	
				• Fridge handler	GF+UP	12	44	
Medium-reinforced TS	Pyrolysis	• Compression moulding of non woven mats	• Automotive non-critical structures	• Car rear wing	CF+VE	27	152	
	Fluidised bed			• Aircraft interiors	• Car decklid	GF+un.	12	120
	Chemical			• Aircraft interiors	• Aircraft seat structure	Al 2024	73	469
Aligned TS	Pyrolysis	• Compression moulding of aligned mats	• Automotive non-critical structures	• Aircraft seat structure	GF+PF	20	167	
				Chemical	• Lay-up of aligned pre-pregs	• Wind-turbine structures	• Car roof shell	CF+EP
					• Wind turbine non.critical layers	GF+EP	22	367
Woven TS	Pyrolysis (pre-preg rolls)	• Resin infusion	• Automotive structures	• Car body panels	CF+EP	53	450	
				• RTM	• Wind-turbine structures	• Wind turbine non.critical layers	GF+EP	38

* Key for type of rCFRP: TP, thermoplastic matrix; TS, thermosetting matrix

* Key for materials: GF, glass fiber; PP, polypropylene; CF, carbon fiber; PA, polyamide; UP, unsaturated polyester; VE, vinyl ester resin; un., unknown; Al, aluminium; PF, phenolic resin; EP, epoxy resin.

In this frame, and in particular with the aim to provide additional novel elements toward the study of mechanical recycling process when applied to EoL composites, we developed a new approach in recycling of carbon fibers reinforced composites thermoplastic polymers (CFRTPs). In particular, in a previous work [31] we successfully

investigated the possibility to re-shape EoL components by combining mechanical recycling with moulding technologies, and the process was studied also from both the mass and energy balances points of view; we invite the readers to refer to this work to deepen the subject. Anyway, further studies were necessary in order to establish at what extent the mechanical properties of the recycled materials were retained and with the aim to address the materials toward potential applications, in view of possible market exploitation. The present work deals with this subject: different types of composite materials made with virgin and recycled polypropylene (PP) and polyamide6 (PA6) reinforced with recycled carbon fibers were submitted to the aforementioned recycling process and then submitted to morphological, mechanical and thermal characterization. Measurement of the fibers length, tensile test, impact test and dynamic mechanical analysis are the techniques used to characterize the recycled materials, in order to provide useful and clear information of their properties and therefore envisioning potential routes of reuse. All the activities here reported have been performed within the REVALUE Project (REcycled carbon fibers for high VALUE composites funded by the European Institute of Innovation and Technology (EIT) Raw Materials.

2. Materials

Materials submitted to the recycling process were composites made with both virgin and recycled polypropylene (PP) and polyamide 6 (PA6) reinforced with recycled carbon fibers, in the form of glove compartments (Figure 1a).

RADILON S27 100 NT provided by RADICI Group was used as virgin polyamide 6.

PP 595A specifically developed for use in automotive compounding and provided by SABIC was used as virgin polypropylene.

Recycled PP and recycled PA6 were both provided by SUEZ Group, a leading French multinational corporation operating also in waste management, and partner of REVALUE Project.

ELG Carbon Fiber Ltd. provided recycled carbon fibers reclaimed by pyrolysis of EoL composite materials, having an average length and diameter of about 0.1 mm and 5.4 μm , respectively.

More in detail four types of composite materials were investigated:

- 1) virgin polypropylene reinforced with 10 wt.% of recycled carbon fibers (vPP/rCF);
- 2) virgin polyamide 6 reinforced with 10 wt.% of recycled carbon fibers (vPA6/rCF);
- 3) recycled polypropylene reinforced with 10 wt.% of recycled carbon fibers (rPP/rCF);
- 4) recycled polyamide 6 reinforced with 10 wt.% of recycled carbon fibers (rPA6/rCF).

In all the aforementioned cases, the recycled carbon fibers are previously submitted to a sizing treatment in order to improve the adhesion with thermoplastics.

All of them were manufactured by FCA Group using the injection moulding technology, within the REVALUE Project and therefore specifically made for this study.

All the glove compartments were submitted to a recycling process deeply described in a previous work [31] and based on a multi-step process: accelerated aging in order to simulate the natural aging they undergo to during the lifespan, followed by shredding & grinding, extrusion and at last compression moulding. The outcomes of the recycling process were composite plates (Figure 1b). Some samples for the characterization procedure were cut from both the glove compartments and the recycled composites.

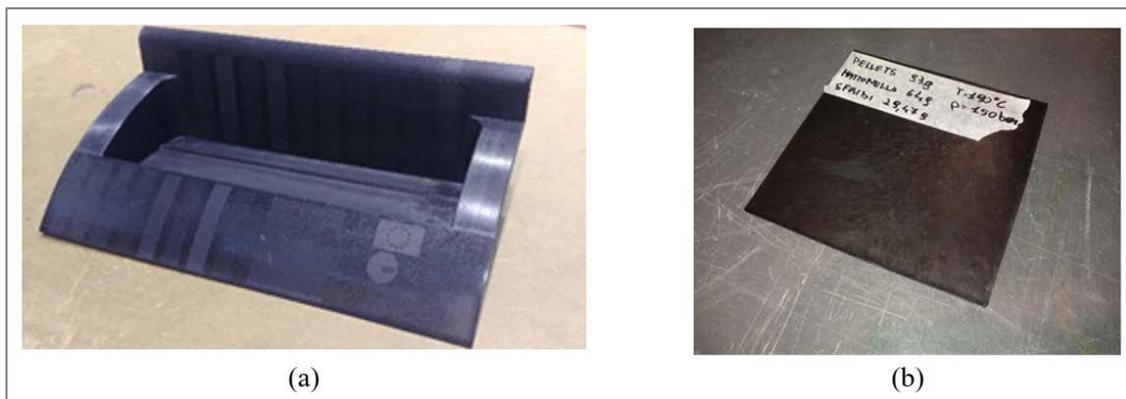


Figure 1. Composite materials in the form of glove compartments before the recycling process (a) and in the form of plates after the recycling process (b).

3. Methods

The recycled composites have been submitted to morphological, mechanical and thermal characterizations, in order to understand to what extent the recycling process would change their main physical and mechanical properties. The investigation involved the measurements of the average fiber length, tensile tests, impact tests and a dynamic mechanical analysis (DMA). In the following paragraphs, the methodology for each of them is described.

3.1 Fiber length measurement

The measurement of fiber length occurs in two steps:

- 1) Calcination in order to bring the composites to the complete thermal decomposition of the resin;
- 2) Drying and measurement of fibers length by optical microscope.

More in detail, samples weighing average 500 mg were heated in an Economy Chamber Furnace Lenton, model EF11/8B up to 450 °C and for 50 min. The temperature was chosen based on thermal decomposition points of both polypropylene (425°C) and Polyamide6 (450 °C), as reported on data sheets. As a result of the thermal treatment, the resin was completely decomposed and the dispersed fibers were removed from the resulting ashes.

The fibers dispersion was then dried and some images with a resolution of 1.82µm were captured using a DVM6 digital optical microscope. At last, the fibers length was determined by using ImageJ software. Measurements were performed on about a hundred fibres for each type of sample.

3.2 Tensile test

Tensile testing is the measurement of the ability of a material to overcome forces pulling the sample apart and of the extent it stretches before breaking [32].

The test on the manufactured composites was performed in accordance to standard *ISO 527:2:2012 - Plastics - Determination of tensile properties -- Part 2: Test conditions for moulding and extrusion plastics* on a MTS Alliance RT/50 testing machine.

According to the standard, some bone shaped specimen type 1A (thickness=4 mm, gauge length=50 mm, grip distance=110 mm) were obtained from both the glove compartments and the recycled composites. Testing was performed at room temperature (T=20°C, RH=50%) and at a speed of 1 mm/min. Load and elongation of the sample were controlled via a monitor until the specimen was fractured. All the mechanical data are compiled in a stress-strain diagram, from which some basic mechanical properties are evaluated (tensile strength, Young's modulus, yield stress, strain at break). For each type of materials, the tensile test was repeated on five specimens and average values were considered, together with standard deviation.

3.3 Impact test

Impact testing is the method allowing to evaluate the brittleness of a material under high strain rates. It is performed by submitting the material to a sudden, intense blow, in which the strain rate is extremely rapid hence the material may behave in a much more brittle manner than is observed in tensile stress. The energy required to break the samples per original cross section area is the impact strength. The impact tests on the manufactured composites were carried out according to standard *ISO 179:1:2010 Plastics -- Determination of Charpy impact properties -- Part 1: Non-instrumented impact test* and on a CEAST 9050 impact pendulum.

According to the standard, some rectangular specimen (thickness=4 mm, length= 100 mm, width= 10 mm) were placed horizontally on the instrument and were hit by a pendulum which gives readings after the specimen fractures. Both notched and un-notched specimen were used and in the case of notched specimen the notch was V-shaped, with 2.54 mm in depth, an angle of 45° and a tip curvature radius of 0.25 mm. The results of the readings are the amount of energy that can be absorbed in the test specimen. Thus, from the readings it can be seen how strong the specimen is able to absorb energy that is transferred from the pendulum to the specimen. For each type of materials, the Charpy impact test was repeated on five specimen and average value were considered, together with standard deviation

3.4 Dynamic mechanical analysis

The dynamic mechanical behaviour of both rCF reinforced vPP and vPA6 composites was determined using the dynamic mechanical analyser Q800 TA Instruments. DMA measures the stiffness and damping properties of materials as a function of time, temperature, and frequency by applying a sinusoidal load to a specimen and measuring the resultant deformation, whilst the sample is subjected to a controlled temperature programme. The magnitude of the applied stress and the resultant strain are used to calculate the stiffness (modulus) of the material under stress. The phase lag δ between stress and strain is used to determine $\tan \delta$, the damping factor that represents the dissipation of energy in a material under cyclic load. Therefore, the damping factor tells us how good a material will be at absorbing energy.

Specimens with dimensions of 36 mm × 13 mm × 3 mm were cut from compression-moulded plates produced with the recycling process, and tested in single cantilever mode at a frequency of 1 Hz with a heating rate of 3°C min⁻¹. The temperature was ranged from 25°C to 130°C for PA6 composites and under cryogenic environment from -30°C to 110°C for PP composites, to detect the phenomenon of the glass transition, which in PP material is known to be below the room temperature. Two to five test specimens were tested for each type of material.

4. Result and discussion

It is known that the mechanical properties of fiber reinforced composite materials strongly depends from the fibers length [33]. Due to comminution of the shredding and grinding steps, the recycling process could have involved a fragmentation of carbon fibers. Based on this considerations, several measurements of fiber length were performed on each kind of sample produced, with the aim to estimate the influence of recycling process on the variation of the average carbon fibers length (if any) and, therefore, on mechanical properties of recycled composites.

The measurement of the average fiber length in both initial prototypes and composites materials obtained with the recycling process was performed, according to the methodology described in Section 3.1.

Samples taken from initial composites were in the form of small pieces cut from prototypes and having average size of 2 cm², meanwhile the samples taken from recycled composites were in the form of extruded materials.

In the case of rPA6/rCF composites it was noticed that after the calcination both the samples taken from initial and recycled prototypes appeared to be contaminated by traces of thermoplastic material not completely removed; as a consequence, the residuals of calcination where composed by areas of aggregated fibers and areas where fibers were more clearly separated. Only the latter were used for image processing and measurements of fibers length.

In Figure 2 an example of an optical microscopic image is reported.



Figure 2. Image acquired from optical microscope with resolution 1.82 μm

Figure 3 summarizes the results of the fiber length measurements of all the composite materials investigated. From both the Figures 2 and 3 it appears evident that the range comprising the lengths of all the fibers is very wide, with large differences between the longer and shorter fibers, resulting in large values of standard deviations.

Considering this evidence and the similar values of the average length of the fibers before and after the recycling, it can be stated that the recycling process does not significantly affect the geometry of fibers, preserving their initial length. Evidently, a quite different situation would have been expected if the initial composites were composed of longer fibers: in this case the recycling process would have reduced the length of the fibers, with the inevitable effect of reducing the mechanical properties, especially with regard to the tensile strength values.

In Table 2, the results of the tensile test are summarized (in the brackets, the standard deviations).

Table 2 shows that for vPP/rCF, rPP/rCF and rPA6/rCF the tensile strength and the yield stress of recycled composites are lower than those referred to initial composites, indicating that the material has weakened due to the recycling process. The reduction is more evident for composites made in vPP/rCF (-64% for the tensile strength and -57% for the yield stress), followed by those in and rPA6/rCF (-34% for the tensile strength and -56% for the yield stress) and rPP/rCF (-17% for the tensile strength and -47% for the yield stress). An exception is the composite in vPA6/rCF, for which an increase in the tensile strength (+10%) and especially in the yield stress (+29%) values are noticed.

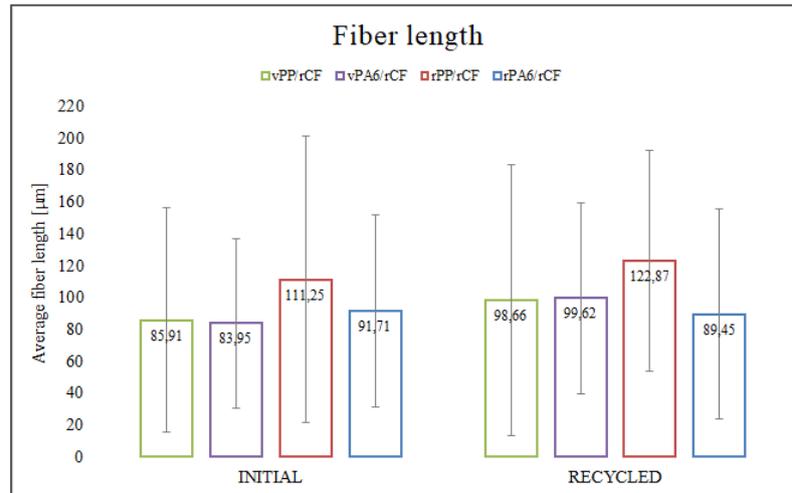


Figure 3. Comparison between length of fibers in initial and recycled composite materials.

Table 2. Results of tensile test of the investigated materials.

		Young's module (E) [GPa]	Tensile strength (σ_f) [MPa]	Yield stress (σ_y) [MPa]	Strain at break (ϵ) (%)
vPP/rCF	before recycling	5.5 (0.1)	34.7 (1.2)	31.1 (1.8)	1.5 (0.0)
	after recycling	3.1 (0.5)	12.6 (1.3)	13.4 (0.0)	0.5 (0.1)
vPA6/rCF	before recycling	7.1 (0.7)	83.4 (1.7)	48.2 (8.9)	2.6 (0.2)
	after recycling	6.8 (0.3)	92.1 (1.5)	62.2 (2.9)	6.8 (0.8)
rPP/rCF	before recycling	4.3 (0.1)	26.7 (0.7)	27.9 (0.2)	6.7 (1.0)
	after recycling	3.4 (0.5)	19.7 (1.6)	14.9 (2.3)	2.1 (0.6)
rPA6/rCF	before recycling	4.9 (0.2)	116.1 (0.9)	116.1 (0.9)	5.3 (0.3)
	after recycling	5.9 (1.3)	76.7 (8.8)	51.3 (5.6)	5.4 (1.1)

Moreover, from the tensile test results it can be stated that the Young's module decrease for vPP/rCF and rPP/rCF, it is about unchanged for vPA6/rCF, the difference staying between the standard deviation, and is slightly increased for rPA6/rCF. This evidence confirms that the recycling had a greater impact on the polypropylene based composites, making them stiffer than initial composites.

Lastly, for both the virgin and recycled polypropylene, the elongation at break is strongly reduced after the recycling, confirming again that this polymer is more sensitive to the recycling and become much less ductile. With regard to polyamide 6, the elongation at break again looks unchanged on rPA6/rCF. On the contrary, beyond expected, it is strongly increased for vPA6/rCF, detecting an increase in ductility.

Figure 4 highlights at a glance all the aforementioned considerations and shows in percentage how the tensile parameters changing from the values referred to the initial composites to those of the recycled ones. It appears evident as the composites made with both virgin and recycled polypropylene are more affected by the recycling process.

Considering this, one can state that the polypropylene seems more sensitive to the recycling process, in particular for the vPP/rCF for which all the tensile parameters are roughly halved. Controversial results were observed for composites made with polyamide6: for vPA6/rCF it seems that the recycling process does not change consistently the tensile strength and the yield stress, but affects basically the elongation at break and one can conclude that the material becomes more ductile. On the other hand, for rPA6/rCF the elongation at break looks the same before and after the recycling, while the drops of both the tensile strength and the yield stress underline that the materials is weakened.

The Charpy impact test was performed on notched specimens of initial composites and on un-notched specimens recycled composites. Moreover, the Charpy impact test was carried out also on un-notched specimens of aged composites, which are the composite submitted only to the accelerated aging, and therefore before undergoing to the recycling process. Commonly, the un-notched impact resistance of a material may be one or two

orders of magnitude higher than the notched impact resistance for the same material, as reported in several works [34-36] and the theory of work of fracture can explain these differences. As a matter of fact, in the un-notched impact strength the entire test piece receives the impact energy caused by the hammer striking, whereas in determining the notched impact strength, breakage is promoted by concentrating the impact energy on the notch.

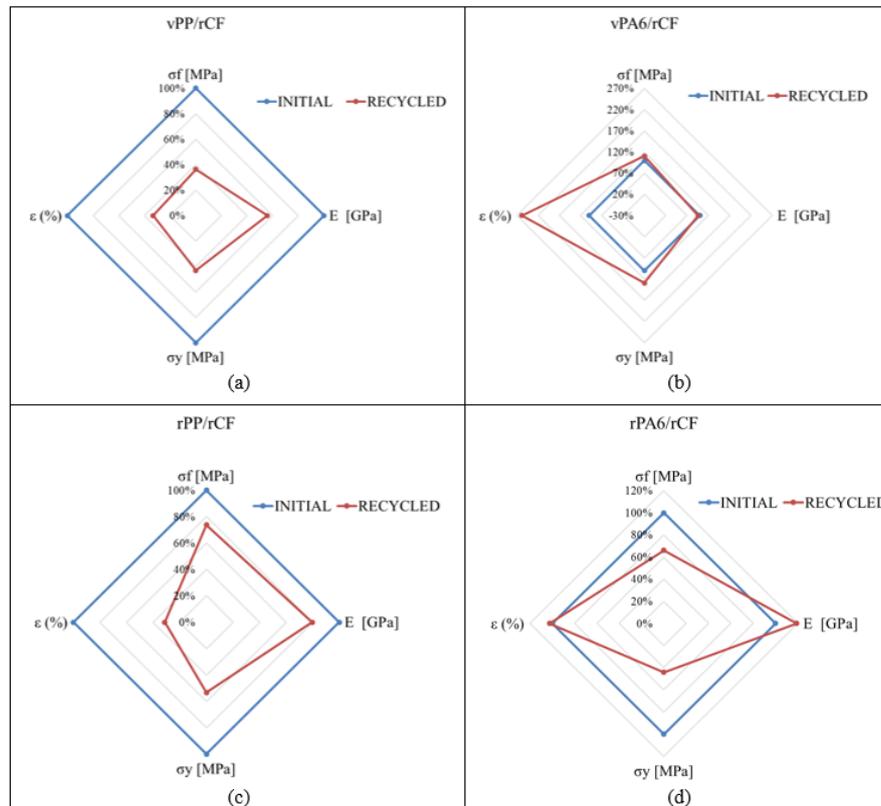


Figure 4. Effects of the recycling process on the tensile parameters of all the investigated materials.

Based on this general statement, no direct comparison is possible between initial and recycled materials. However, a direct comparison is possible between aged and recycled composites: from the Figure 5 it can be inferred that for the composites made with virgin polymers (both PP and PA6) the Charpy impact values increase after the recycling process, suggesting that the materials become more tough. This is in line with results of tensile test for vPA6/rCF for which both the tensile strength and the elongation at break increase after the recycling, therefore increasing the area subtended by the stress-strain curve, which represents the energy stored before failure. but it seems to contradict the evidence for vPP/rCF.

On the other hand, the Charpy impact values decrease after the recycling process for the composites made with recycled polymers, suggesting in these cases a reduction of the toughness of the materials. When compared with the tensile tests we can infer that for rPP/rCF both the results are congruent and evidence that the recycling process drop the toughness of this composite. With regard to rPA6/rCF, the Charpy impact again is in agreement with the tensile test results. In fact, since the elongation at break remains unchanged, the reduction of the tensile strength leads to a reduction of the energy stored during deformation, and therefore the toughness of materials.

With regard to the DMA results, complete analysis have been performed from both the vPP/rCF and vPA6/rCF, while no measurements were carried out on rPP/rCF and rPA6/rCF. For these two typologies of materials the DMA has been carried out for initial samples, aged samples and recycled samples. In this way it has been possible to investigate separately the effects induced by the aging and those induced by the recycling process. It was found that for both the materials the storage modulus (E') decrease when the temperature increases, due to the structural change occurring in polymeric materials as a result of the molecular mobility at different time scales. These motions are known as molecular relaxations. The main relaxation or relaxation α corresponding to the drastically decrease of the storage modulus and the highest peak of the $\tan \delta$; this relaxation is associated to the glass transition, and in PA6 occurs approximately at $T\alpha = 80 - 90^\circ\text{C}$ depending on frequency [37] (Figures 6 and 7). For the vPA6/rCF it was found that the recycled materials were more stiff than the others (Figure 7), but this does not happen to vPP/rCF, for which the aged materials exhibit more stiffness, while the recycled materials had a stiffness comparable with that of initial composites (Figure 6).

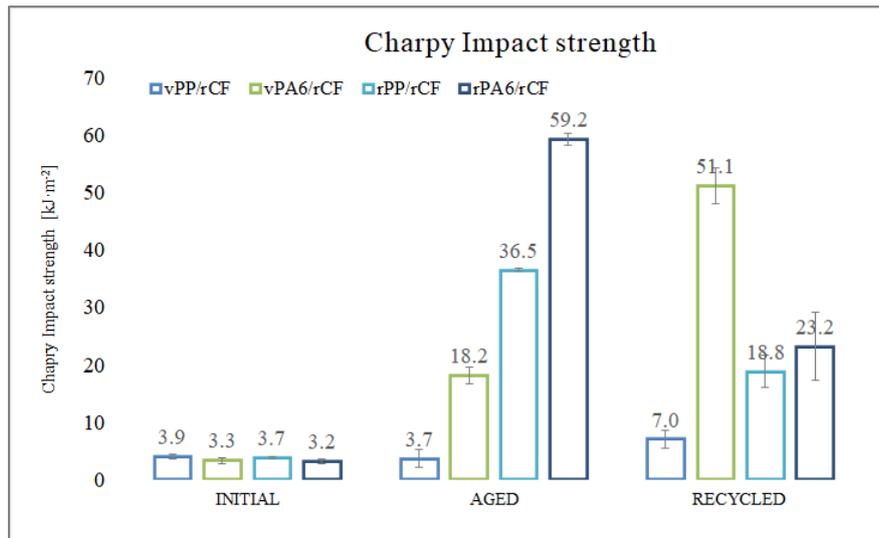


Figure 5. Comparison of Charpy test results on the investigated materials.

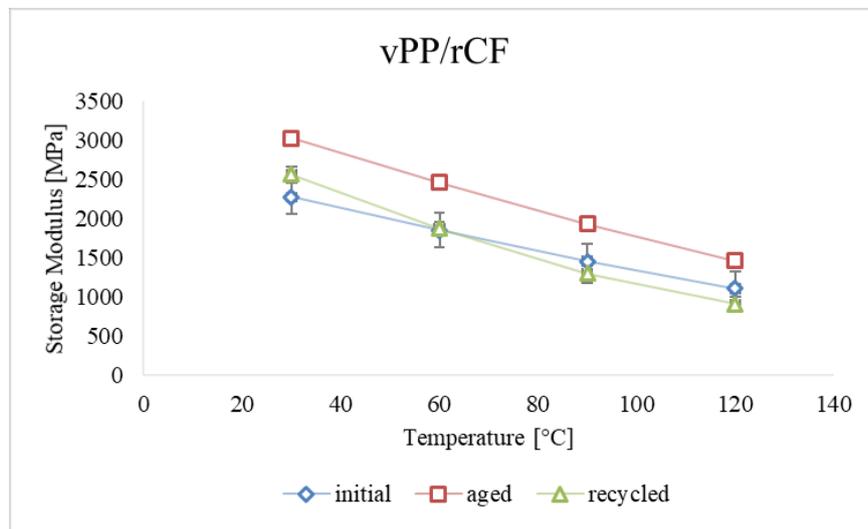


Figure 6. Comparison between the storage Modulus of vPP/rCF based materials.

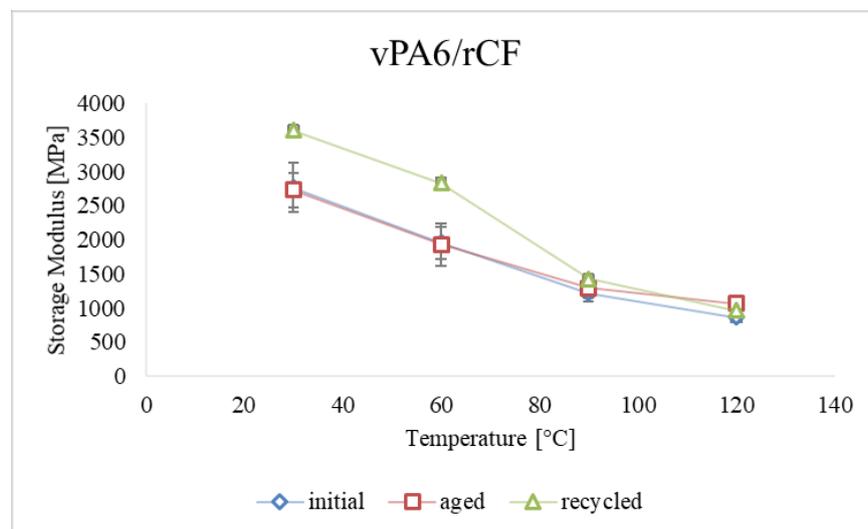


Figure 7. Comparison between the storage Modulus of vPA6/rCF based materials.

Generally, the loss modulus (E'') obtained from the DMA is proportional to the energy dissipated. It represents energy loss as heat, which cannot be recovered. It indicates the viscous nature of the polymer [38]. The E'' peak shown in Figure 8 around 60 °C represents the transition region from the glassy state to the rubbery state. We noticed that the E'' of vPA6/rCF decreases when the temperature increases, suggesting that the viscosity of vPA6/rCF composites decreases gradually with the increase of temperature (Figure 8). However, after the recycling process the vPA6/rCF exhibits higher values of loss modulus that can be explained with an increased viscosity of polymer reduced mobility with respect to initial and aged samples. Substantially the same trend was noted in a more reduced way, also in the recycled vPP/rCF samples (Figure 9).

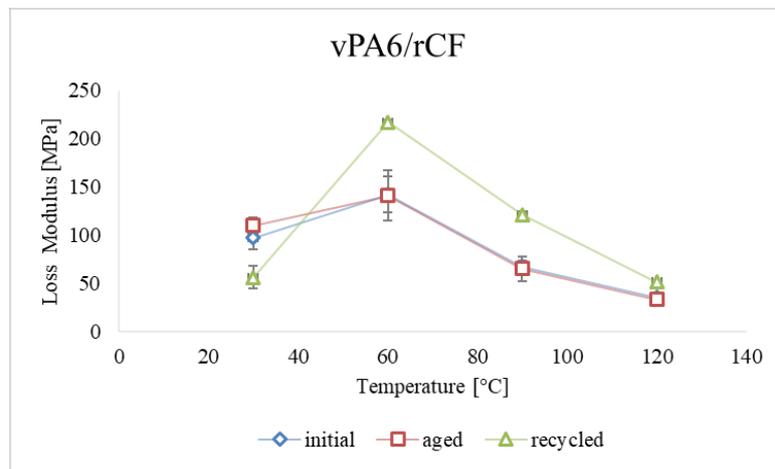


Figure 8. Comparison between the Loss Modulus of vPA6/rCF based materials

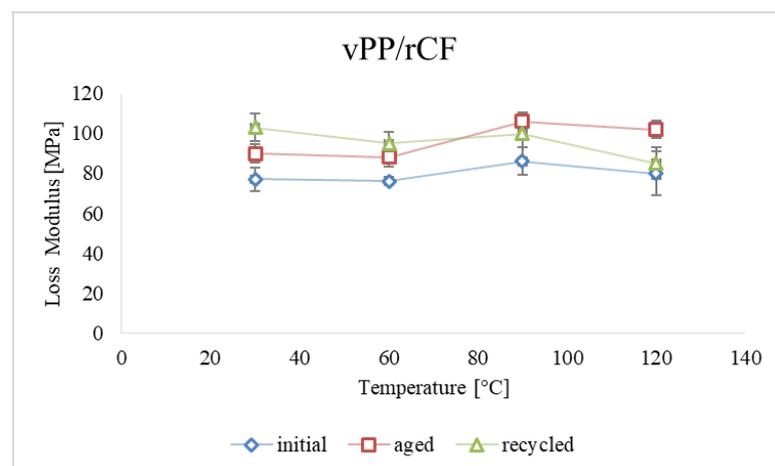


Figure 9. Comparison between the Loss Modulus of vPP/rCF based materials

Furthermore, the damping factor ($\tan \delta$) can also be obtained from DMA tests. $\tan \delta$, is a measurement of the energy loss, expressed in terms of a ratio with the recoverable energy, and represents mechanical damping or internal friction in a viscoelastic system [38]. Regard to vPP/rCF it can be inferred that the aging does not imply any variation on the $\tan \delta$ (Figure 10). Conversely, the damping factor of the recycled composites increases in the whole temperature range, suggesting that the recycled have a high, non-elastic strain component, with respect the aged that are more elastic [38]. The same, but in a reduced temperature range happens also for vPA6/rCF materials (Figure 11). This behavior seems to confirm what the results of the Charpy impact already told us.

At last, Table 3 summarizes the variations induced by the recycling process on the investigated parameters, compared to those of the starting materials, in a synthetic and all-encompassing way to better focus on main results obtained in this characterization procedure. The following statements helps the reader to understand Table 3 in an efficient manner:

- 1) high tensile strength indicates high strength;
- 2) high Young's module indicates high stiffness;
- 3) high elongation at break indicates high ductility;
- 4) toughness is a combination of tensile strength and elongation at break. Indeed, toughness is the ability to deform plastically and to absorb energy in the process before fracture. Therefore is the area of the (σ, ϵ) diagram

before the fracture. High tensile strength (strength) in combination with high elongation at break (ductility) contribute to increase the area and therefore the toughness of a material;

5) high impact strength indicates high toughness;

6) The Storage Modulus is the ability to store energy during elastic deformation;

7) The Loss Modulus is the ability to dissipate energy (energy lost as heat);

8) Damping is a measure of how well a material can get rid of energy and is reported as the tangent of the phase angle. It tells us how good a material will be at absorbing energy.

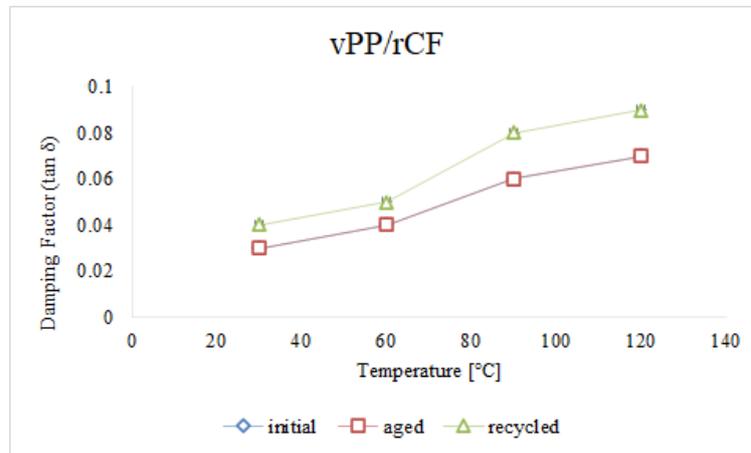


Figure 10. Comparison between the damping factors of vPP/rCF based materials

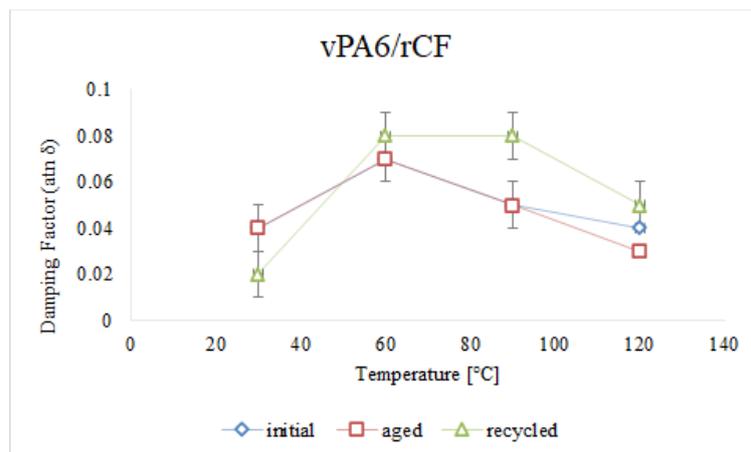


Figure 11. Comparison between the damping factors of vA6/rCF based materials

Table 3. Overview of changes in physical, mechanical and thermal parameters of composites after the recycling process

		vPP/rCF	vPA6/rCF	rPP/rCF	rPA6/rCF
	Fiber length	unchanged	unchanged	unchanged	unchanged
TENSILE TEST	Tensile strength	very less strength	slight increase in strength (almost unchanged)	less strength	less strength
	Young's module	very less stiff	unchanged	less stiff	more stiff
	elongation at break	more brittle	very more ductile	more brittle	unchanged
IMPACT TEST	impact strength energy	more though (higher toughness)	more though (higher toughness)	less though (lower toughness)	less though (lower toughness)
DMA	storage modulus	unchanged	more stiff		
	loss modulus	more viscous	more viscous		
	damping factor	more stiff	more stiff		

5. Conclusions

The present work aimed to investigate if and at what extent both virgin and recycled polypropylene and polyamide 6 reinforced with recycled carbon fibers could retain their mechanical properties after a recycling process based on grinding and reshaping of composites.

The investigation pointed out that composites made with both virgin and recycled polypropylene showed a greater reduction in tensile strength and in the Young's module, as well as in the elongation of break, highlighting less stiff and more brittle behaviours. DMA analysis confirmed this evidence, and pointed out a more viscous behaviour of the polymer after the recycling. On the other hand, the composites made with virgin and recycled polyamide6 showed controversial results. Indeed the effect of the recycling on vPA6/rCF composites is an increasing in both ductility and toughness, while higher stiffness and lower toughness were observed for rPA6/rCF. Also for polyamide6 based composites the DMA highlighted an increase in the viscosity of the polymer as effect of the recycling.

Even if, as expected, the recycling process affects the overall performance of the composites, some positive conclusions can be drawn from our investigation. In fact the mechanical properties retained in particular by PA6/rCF based composites allow the potential use of recycled materials in applications as automotive semi-structural or non-structural parts of equipment housing (like car door panel, car headlamp reflectors, etc).

It is worth notice that the initial composites were already manufactured with recycled carbon fibers having a very short average length that was not further reduced during the shredding and grinding of materials. This contributed to reduce to a lower extent the mechanical properties of the composites after the overall recycling process.

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