

Article

Dynamic Mechanical Response of PA12-GTR Composites Utilized with Selective Laser Sintering Additive Manufacturing

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Abstract

Waste material valorization as a feedstock for net-zero waste manufacturing processes has emerged as a key sustainability strategy. Process technologies such as Additive Manufacturing (AM) have helped to limit material waste and allowed the production of complex designs with lower required costs and less time than other conventional manufacturing methods. In this study, an investigation of the addition of end-of-life Ground Tire Rubber (GTR) waste to a Polyamide 12 (PA12, nylon 12) matrix was conducted. Three different PA12-based powders were produced in a lab-scale environment with different weight fractions (wt.%) of reused GTR and specimens for static tensile, cyclic tensile, compression testing, Dynamic Mechanical Analysis (DMA), and vibrational analysis were designed assessing both the static and dynamic mechanical response. The specimens were 3D printed using Selective Laser Sintering (SLS) AM, a technique that promotes thermal coalescence between adjacent powder particles and successive layers, resulting in a more interconnected material structure and potentially reduced directional anisotropy compared to Fused Filament Fabrication (FFF) AM, although process-induced anisotropy may still be present, while the material used has a low powder refresh requirement of 22%. The results showed that the introduction of reused GTR helped improve the damping properties of the material. Combining the strength of PA12 even at high thermal stresses with the increasing damping properties of the GTR can be vital for vibration isolators in industrial, structural, and automotive applications while simultaneously reducing the material footprint.

Keywords: selective laser sintering; dynamic mechanical analysis; modal testing; micromechanical modeling; finite element analysis; ground tire rubber

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1. Introduction

Additive Manufacturing (AM) has emerged as a swift, accurate, low-cost, and reliable technique for rapid prototyping, small-scale functional products, and low- to medium-volume mass manufacturing. The ability to produce complex designs without the need for a conventional mold, the ability for rapid customization, and the limited material waste that it produces make AM a good candidate for the development of efficient net-zero waste manufacturing and production systems. AM also provides the ability for easy material customization, allowing the insertion of eco-friendly reinforcement materials for the development of advanced, high-performance, sustainable composite materials. The development of sustainable composites can help achieve the general goal of addressing the existing environmental issues that have been caused by the conventional manufacturing processes and achieving the environmental goals that have been set by the European Union (EU) and the United Nations (UN) [1,2]. Powder Bed Fusion (PBF) AM, such as Selective Laser Sintering (SLS) for polymeric materials or Selective Laser Melting (SLM) for metals, is rapidly growing due to its greater dimensional and printing accuracy and its better surface finish compared to the most common Material Extrusion (MEX) AM. Most powders utilized by SLS can be recollected and reused for a significant number of cycles or even adapted for use in other techniques such as Fused Filament Fabrication (FFF) AM. Although powder reuse may reduce raw-material consumption and waste-disposal costs, the overall economic viability also depends on preprocessing, quality control, energy consumption, and production scale. Polyamide 12 (PA-12, nylon 12) is one of those polymers that can retain its material properties for a significant number of use cycles and is the most well-known material for SLS AM along with Thermoplastic Polyurethane (TPU) and Polyether-Ether-Ketone (PEEK) [3–8].

Polyamide 12 (PA12) is a relatively strong polymer and is also easily processable and compatible with PBF AM techniques. Many studies have focused on the customization of PA-12 matrices with several composites, with various forms of Copper (Cu) [9,10] helping to enhance the electroconductivity properties and glass fibers or microspheres [11–13] affecting the energy absorption properties to expand the range of possible applications. Carbon fibers and nanotubes applied to PA-12 helped improve the overall strength while simultaneously improving the electrical conductivity of the final structure. SLS AM is adequate for creating structures with thermal and electrical conductivity that are adequate for the rapid manufacturing of sensors with anti-static and conductive range in industrial, automotive and aerospace applications [14,15], while Boron-Nitride (BN) also helped enhance the thermal conductivity, which is vital for the development of novel heat transfer devices adequate for biomedical applications in the field of biomimetics [16,17]. Previous research has demonstrated the potential of PA12 for producing high-strength, durable parts, making it an ideal candidate for applications requiring energy absorption and vibration damping in large structures. Vibration isolation plays a crucial role in enhancing the performance and longevity of mechanical systems by minimizing the transmission of vibrations to surrounding structures. Materials used for vibration isolation must exhibit a balance of mechanical strength and damping characteristics to effectively absorb and dissipate energy. In this context, fiber-reinforced composites have been manufactured by AM processes, but the results vary due to the printing orientation, the fiber orientation, and the composition interface region of the structure, with a focus being given to natural or reusable reinforcements [18]. Switching to sustainable alternatives can help with the production of materials with high energy-dissipating characteristics while simultaneously reducing the material footprint. Ground Tire Rubber (GTR) in powder form could work as a reinforcing material for polymer-based materials extracted out of SLS AM. Composites made out of SLS could result in fewer anisotropies and better dimensional accuracy and surface finish, resulting in better overall properties closer to the maximum potential bib-

liographical specifications of the materials compared to other standard AM processes like FFF [19]. In this study, reused Ground Tire Rubber (GTR) was inserted into Polyamide-12 (PA-12, nylon-12) polymeric matrix in different weight fractions up to 20% wt., and the final powder mix was utilized with the aid of Selective Laser Sintering (SLS) Additive Manufacturing (AM). The objective of this paper is to assess the effect of the reused GTR, which is a material that can be acquired in large quantities from end-of-life tires, and the use of AM for the efficient expansion of its life expectancy by increasing the number of used cycles for such end-of-life materials. The pretreated GTR was inserted into PA-12 SLS powder, a material that can be recycled and reused at high rates for a significant number of cycles. Tensile, compression, and modal analysis specimens were printed with the final mixed powder, and an evaluation of the final structure's main mechanical properties was done with the exploitation of static tensile testing and static compression testing. Also, a calculation of the structure's dynamic properties, such as the energy absorption properties that can be extracted via the compression testing, along with the damping of the material that can be extracted by the loading/unloading tests was performed. Finally, specimens used to identify the composites' vibrational properties through modal testing and the materials' viscoelasticity through Dynamic Mechanical Analysis (DMA) were printed. The insertion of dynamic testing, such as Modal Analysis and DMA, allows a more complete identification of the dynamic response of PA-12-GTR composites, which is vital for upscaling and inserting this material in real-life applications such as the construction of effective mounts for automotive or industrial engineering applications. In Figure 1, a brief graphical illustration of this study is presented. Initially, the blending process of the matrix powder (PA-12) and the reinforcement material was conducted through repeated blending and heating cycles. In Section 2, the final blend was used as the feedstock material for the development of coupon-level specimens with the aid of SLS AM. Section 3 consists of the experimental process divided into mechanical testing (static and dynamic), the computational investigation of the projected unit cell's static behavior and the identification of the interfacial properties with the aid of scanning electron microscopy. Finally, in the evaluation stage, the reinforcement's effect on the composite's absolute strength, impact strength and viscoelasticity was assessed, providing a complete overview of the composites' behavior and the probability of possible upcycling for industrial applications.

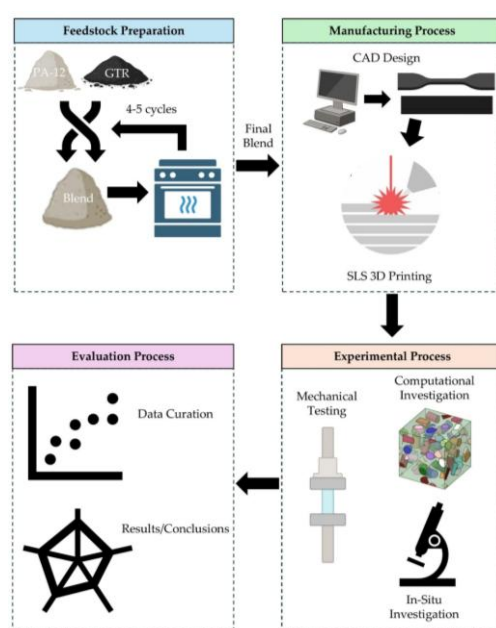


Figure 1. Schematic workflow of powder preparation, SLS fabrication, experimental and numerical characterization, and evaluation of the PA-12/GTR composites.

2. Materials and Methods

2.1. 3D Design

With the aid of SolidWorks™ Version PDM 2024 (Dassault Systèmes SE, Vélizy-Villacoublay, France), specimens for the assessment of both the static and the dynamic mechanical response were designed. The static analysis consisted of uniaxial tensile testing and uniaxial compression testing while the dynamic mechanical testing consisted of DMA, loading–unloading and modal-vibrational analysis. The dog bone specimens were designed according to the Standards of ISO 37 for the determination of the tensile response of rubber thermoplastic and vulcanized materials [20]. The ISO 7743 standard [21] for the determination of the compressive stress–strain properties of rubber thermoplastic and vulcanized materials was utilized for the design of the compression specimens. For the DMA, the 3-point bending test was utilized in alignment with the ISO 6721-1 regulations for the determination of the dynamic mechanical properties [22] and the ISO 7626 was utilized for the determination of the mechanical vibration and machine vibrations (modal analysis) [23]. For each material composition and testing methodology, three replicate specimens were tested, and the results are reported as mean values with the corresponding standard deviations.

2.2. Additive Manufacturing

PA12 smooth powder (Sinterit™, Krakow, Poland) was used to create the composite specimens, and it was progressively combined with obtained waste Ground Tire Rubber (GTR) powder [24]. The end-of-life tires were shredded into tiny pieces, the steel wire was removed using a magnet, and the rubber fragments were then ground into a fine powder to create the Ground Tire Rubber (GTR) waste (RETIRE ABEE, Drama, Greece). The next stage entailed creating three different mixtures. The developed blends were then utilized as feedstock material for Selective Laser Sintering (SLS) Additive Manufacturing (AM). The Sinterit Lisa REV C (Sinterit™, Kraków, Poland) 3D printer was utilized for the development of the aforementioned specimens [25]. The Sinterit Lisa REV C 3D printer is equipped with an IR laser-diode source, and the laser beam power was set at 5 W. The scan speed was set at 100 mm/s, and the printing temperature was around 170–190 °C. To achieve the optimal accuracy, the layer height of the structures was set at 0.075 mm, such a low layer height along with the sintering mechanism of this technique allows the development of highly accurate structures with minimal anisotropies, which is vital for possible upscaling, especially for bulk structures where the possible handled loads are not always one-dimensional. Although SLS AM presents minimal anisotropies, the orientation for each type of specimen was selected according to the standards of the aforementioned ISOs to ensure the maximum structural performance for each lab-scale experimental test [26,27].

2.3. Mechanical Testing

2.3.1. Tensile Testing

To carry out the tensile testing, the Testometric M500-50AT (Testometric Company, Rochdale, UK) was utilized. The equipped load cell was 50 kN, the motor speed was set at 10 mm/min, which was described as the optimal solution after trials with 5, 10 and 20 mm/min, and the sampling frequency was set at 50 Hz. From the extracted stress–strain curves, the effect of the GTR waste on the composite's main mechanical properties was studied along with the material's behavior at the yield point and the fracture point. The structural integrity was monitored throughout the tests, with particular emphasis on crack initiation and propagation.

2.3.2. Compression Testing

The Testometric M500-50AT (Testometric Company, Rochdale, UK), which has a 50 kN load cell in accordance with ISO 7743 standards, was used to help with the compression testing. The sampling frequency was set at 50 Hz, and the motor speed was set at 5 mm/min. The compression values were then translated to crucial energy absorption parameters such as the overall energy absorption (EA) value, the specific energy absorption (SEA_m), the specific energy absorption per volume (SEA_v), the Mean Crushing Force (MCF), the energy absorption efficiency ($\eta(\epsilon)$) and the densification strain (ϵ_d). The EA is defined by the integral of the compression load–displacement curve of an energy absorber over the effective crushing displacement and is given by the following equation:

$$EA(d) = SEA_v(d) = \int_0^{\epsilon} \sigma(\epsilon) d\epsilon \quad (1)$$

In this equation, σ represents the experimental stress at the ϵ experimental strain point, where, according to ISO 844 [28], is set to be the 50% mark of the compression stress–strain curve. SEA_m displays the energy absorbed per unit mass and can be defined by the following equation:

$$SEA_m(d) = \frac{EA(d)}{p} \quad (2)$$

where p is the density of the structure and $EA(d)$ is the total energy absorbed throughout the experiment as determined by Equation (2). The MCF, which is defined by the ratio of the total absorbed energy to the effective experimental displacement, is an important structural parameter that characterizes the average crushing force during the experiment in the overall effective compression deformation. The MCF evaluation is essential for determining the overall effect of phenomenon tolerance and for evaluating the effectiveness of real-world models. The calculation is done with the aid of Equation (3):

$$MCF = \frac{EA(d)}{d_{max}} \quad (3)$$

$\eta(\epsilon_\alpha)$ is the division of the stress function integral and the ideal absorber at the reference strain ϵ_α [25,29]. Equation (4) describes the mathematical relation that is utilized for the evaluation of the energy absorption efficiency:

$$\eta(\epsilon_\alpha) = \frac{\int_0^{\epsilon_\alpha} \sigma(\epsilon) d\epsilon}{\sigma_\alpha(\epsilon) \times \epsilon_\alpha} \quad (4)$$

For the loading–unloading testing, the experimental conditions regarding the speed and the sampling rate were kept identical while the maximum strength was set equal to the observed load at 60% of the materials yield point strain. From this test, the identification of the damping factor (specific damping capacity, SDC) was done with the aid of Equation (5):

$$SDC = \frac{\Delta W}{W} \times 100\% = \left(\frac{\oint \sigma d\epsilon}{\int_{\omega t=0}^{\frac{\pi}{2}} \sigma d\epsilon} \right) \times 100\% \quad (5)$$

where W is the highest energy generated during this one cycle, ΔW is the energy wasted after one cycle, and σ is the equivalent engineering stress at the reference point [30]. The generated and wasted energy are calculated based on the trapezoid rule. W represents the overall energy absorbed (positive gain) while ΔW also includes the hysteresis loop area. The SDC is determined using the equation and is connected to the damping factor:

$$n = \frac{\Delta W}{2\pi \times W} \times 100\% \quad (6)$$

where n is the experimental loss factor. When n has high values, the structures present good vibration mitigation capabilities and are adequate for applications that require energy isolators, such as engineering mounts.

2.3.3. Dynamic Mechanical Analysis

The DMA 242 E ARTEMIS (NETSCH Group, Selb, Bavaria, Germany) was used to conduct the Dynamic Mechanical Analysis (DMA) testing. The storage modulus (E'), loss modulus (E''), and damping coefficient (n), which evaluate the composites' vibration isolation qualities, were determined frequency-dependently using the isothermal 3-point bending DMA test. The test samples were fastened on a metal base that had an effective length of 40 mm and an effective width of 20 mm. As for the boundary conditions, the frequency was set at a discrete range from 0.1 Hz to 100 Hz with a logarithmic step, and the temperature was maintained at about 25 °C. The shell's maximum load was 8 N (± 4 N), and the preload value was set to a value close to 0 (0.1 N). Both the hysteretic and viscous damping were concluded by the exported experimental damping factor from the DMA. The static and dynamic force values for each experiment are shown in Table 1.

Table 1. Preset conditions of DMA testing.

Material	Static Force (N)	Dynamic Force (N)
PA-12	0.26	0.59
PA-12/GTR 10 wt. %	0.24	0.56
PA-12/GTR 20 wt. %	0.22	0.54

2.3.4. Modal Analysis

By employing an impact hammer fitted with a premium piezoelectric force transducer (Endevco Model 2302-10, Dainan Tech (S) Pte Ltd., Singapore), modal testing was carried out to determine the vibration characteristics of the fabricated composite specimens. One side of the tested specimen was fixed as a rigid support that resembled a cantilever beam in terms of the experiment's boundary conditions. A free-damping vibration was started when the hammer applies an initial vibration to the free area. A laser vibrometer sensor (IVS-400 Polytec, Polytec GmbH, Baden-Württemberg, Germany) was used to detect the reaction in the free space on the specimen's right tip. A multiple degree of freedom algorithm was created in order to determine the experimental parameters using MATLAB™ Version 24.2 (R2024b) (Mathworks, Natick, MA, USA). A two-channel acquisition procedure that included both an acquisition and a real-time analysis that provided digital filtering was used for impact excitation. An analog-to-digital converter was used to acquire the experimental force and velocity data, and a computer recorded the final related results. The sampling rate was set at 4096 samples per second, and the velocity signal's frequency was set at a range of up to 1600 Hz. The hammer calibration was done with proper adjustments to the level of the triggering force signal. Each type of specimen underwent several tests, and the data was cured by applying the necessary linear averaging to convert the experimental results into the final related vibration isolation qualities. The final modal properties were related to the experimental response signals with the Fourier transform equation. The ratio of response to excitation functions is calculated in order to obtain an equation from the pertinent transfer function. The response can be calculated in terms of displacement, velocity, or acceleration, and as a result, different terms have been used for the ratios of response to force. The displacement response and references to the transfer function (TF) expressed for the system's dynamic compliance were the main focus of this investigation. A single integration procedure was used to gather and analyze experimental data from the laser vibrometer sensor in order to estimate the displacement. High-pass filters have been used to remove the direct current components and avoid integration mistakes. Thus, by calculating the ratio of the resultant displacement to the applied force, the experimental transfer function may be found [30–32]. In

Figure 2, a schematic presentation of the signal processing and conversion process is presented along with the basic analytical equations for each stage of the process.

The relationship between the input excitation at point i and the output response at point j of the system is described by the transfer function G_{ij} shown in Figure 2. To fit experimental transfer function data for analytical mode characterization, a set of superposed, single-mode response functions has been fitted using a genetic algorithm (GA) optimization technique. Consequently, these analytical-experimental transfer functions can be used to calculate an equivalent Young's modulus. When $\omega_i = 0$, the constant value $G(\omega_i)$ defines the static response factor $G(0)$. The inverse value of the vibratory system's single-degree-of-freedom spring, compliance $1/K$, is identical to the true parameter, which represents the system's proportionate gain. The system's stiffness under fixed-free boundary conditions is $K = 3EI/L^3$, where $I = bh^3/12$ is the moment of inertia for a rectangular beam, L is the cantilever beam's free length, b is its width, and h is its thickness in the direction of vibration. The equivalent elastic modulus can be determined from the first mode of the transfer function by the following equation:

$$E = KL^3/3I \quad (7)$$

The viscoelastic response of materials under test can be expressed by the following equation:

$$n = \frac{E''}{E'} \quad (8)$$

where the quantity E' is the storage modulus, because it defines the energy stored in the specimen due to the applied strain, and it is conceptually identical to E , elastic modulus. The quantity E'' defines the dissipation of energy and is called the loss modulus. The experimental values regarding the storage modulus, the loss modulus and the loss factor are directly comparable to the DMA values mentioned above.

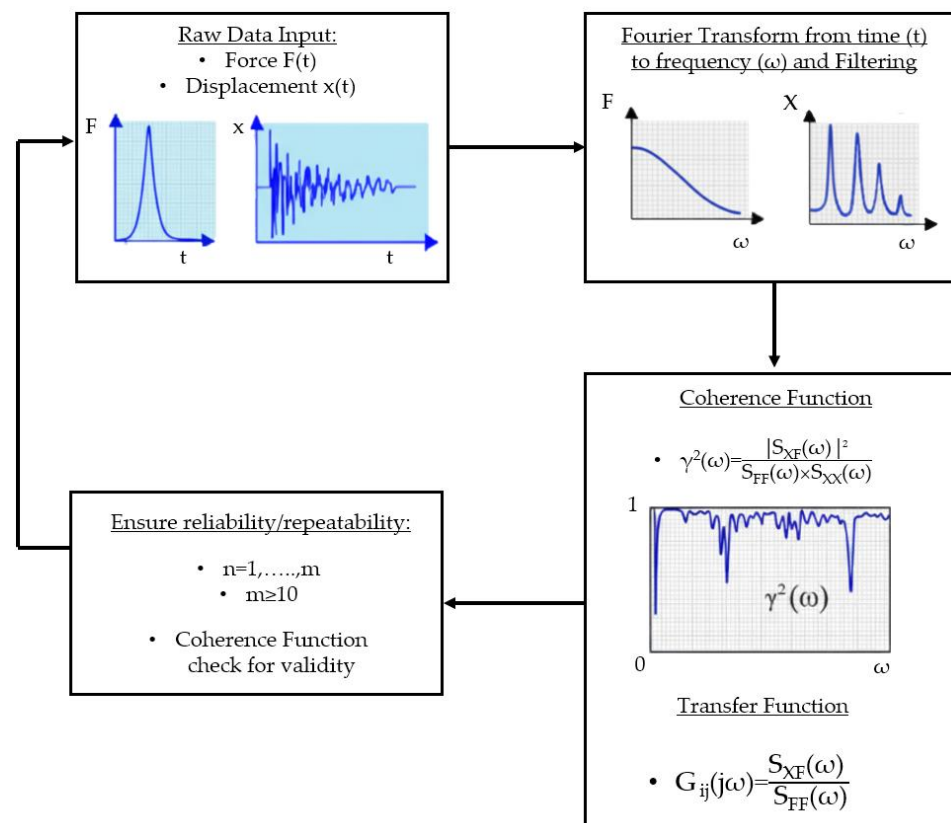


Figure 2. Modal testing signal processing and conversion process for the determination of the transfer function.

2.4. Finite Element Analysis and Micromechanical Modeling

To evaluate the efficiency of the mixing process and the degree of unification on the final blend, a comparative model was constructed that simulated the tensile behavior of the ideal composite. This model was developed with the aid of Representative Volume Elements that replicated the ideal unit cell of the final composite. The matrix material was PA-12, and the filler material was the reacquired waste GTR. The orientation was set as random, and the shape of the particles was similar to that of chopped fibers. Using the Finite Element Analysis (FEA) approach and the ANSYS software Version 2026 R1 (ANSYS, Inc., Canonsburg, PA, USA), the mechanical behavior on unit cell scale was examined. The Monte-Carlo model was used to determine the particle orientation [33], while the dimensions of the particles were portrayed accurately in the form of chopped fibers with length in the range of 130–200 μm , as was observed in previous research where the same reinforcement was utilized. The Monte-Carlo model provides a stochastic approach on the homogenization and the particle orientation for unknown and randomized distributions. The general relation expressing the distribution is described in Equation (9):

$$\sigma = C\varepsilon \quad (9)$$

where the σ and the ε values are stress and strain tensors that are expressed in Voigt notation converting the 3×3 element matrix into a 6-element vector (e.g., $\sigma = [\sigma_{11}, \sigma_{22}, \sigma_{33}, \sqrt{2}\sigma_{23}, \sqrt{2}\sigma_{13}, \sqrt{2}\sigma_{12}]$). The off-diagonal elements (e.g., $\sigma_{12} = \sigma_{21}$) are taken into consideration as symmetrical in this model. A computational application of linearly independent macroscopic strain states allows the identification of the corresponding average stresses (both tensile and shear) and the determination of the full tensor C parameter [34]. In Table 2, the weight and volume fractions are presented for each RVE unit cell.

Table 2. Material compositions of the developed composites.

RVE Model	PA-12 Density (g/cm ³)	GTR Density (g/cm ³)	Weight Fraction of GTR (%)	Volume Fraction of GTR (%)
Neat PA-12	0.96	1.16	0	0
PA-12/GTR 10 wt. %	0.96	1.16	10	8.5
PA-12/GTR 20 wt. %	0.96	1.16	20	17

After generating a representative and statistically meaningful reinforcement dispersion, the Ji model was employed [35], which is a three-phase micromechanical homogenization framework that explicitly accounts for the polymer matrix, a finite-thickness interfacial (interphase) region, and the filler phase. The Ji formulation is particularly suitable for particulate composites where the interphase surrounding each particle affects the load transfer and the effective stiffness. The model is applicable to randomly distributed inclusions and accommodates different idealized particle morphologies (spherical, cylindrical or platelet-type) by introducing a geometrically controlled contribution of the interphase to the overall homogenized response. The effective (equivalent) Young's modulus of the composite, E_c , is expressed through a compliance-type mixture relation (Equation (10)), where the inverse modulus ($1/E_c$) is decomposed into contributions associated with the matrix, the interphase, and the filler-containing region:

$$\frac{1}{E_c} = \frac{1-a}{E_m} + \frac{a-\beta}{(1-a)E_m + \frac{a(k-1)E_m}{\ln(k)}} + \frac{\beta}{(1-a)E_m + (a-\beta)(k \mp 1)\frac{E_m}{2} + \beta E_f} \quad (10)$$

where E_m and E_f denote the Young's modulus of the matrix and filler, respectively, while α , β and k are non-dimensional parameters that quantify the extent of the interphase and its relative stiffness compared to the matrix. Equation (10) averages moduli and compliances (inverse moduli) and highlights the influence of the softer constituents on the over-

all deformation. Therefore, it is evident that the existence of low-stiffness interphase has a significant influence on the final value of E_c . The geometric weighting parameters α and β are defined by Equations (11) and (12) as follows:

$$\alpha = \sqrt{\left(\frac{r + \tau}{r}\right)^2 V_f} \quad (11)$$

$$\beta = \sqrt{V_f} \quad (12)$$

where V_f is the filler volume fraction (Table 2), r is the effective characteristic GTR particle size, and τ is the interfacial thickness. Since the recycled GTR particles exhibit an irregular morphology, r was not considered a strict geometrical radius. Instead, it was estimated from manual measurements of representative particles in the SEM micrographs. The interphase contribution is relevant to the volume fraction (V_f), and the ratio between the interphase and the particle (τ/r). The mechanical contrast between the interphase and the matrix is introduced through the dimensionless parameter k (Equation (13)):

$$k = \frac{E_i}{E_m} \quad (13)$$

where E_i is the projected interfacial Young's modulus. The parameter k controls the efficiency of load transfer across the transition zone. When $k \approx 1$, the interphase behaves similarly to the matrix and the composite response approaches that of a conventional two-phase system. Conversely, $k \ll 1$ corresponds to a highly compliant interphase, which increases the composite compliance and thus reduces E_c . The $\ln(k)$ term in Equation (10) highlights the effect of the interfacial stiffness contact parameter. Decrease in k hints at the increase in the relation between the overall stiffness and the k factor, in alignment with the model's scenario in which deformation localizes within a soft transition layer surrounding the inclusions.

For the mechanical evaluation of the proposed unit cells, the explicit dynamic model was utilized, and the simulation of the uniaxial tensile behavior was analyzed on the microstructural scale. For the convergence, 80,000–85,000 steps were applied for each case with no preset loads or velocity. The moving force was the momentum transition from the steady kinematic velocity. During the experimental phase, isotropic properties were observed due to the feedstock morphology and the printing technique. In the plastic region, the model appears nonlinear and approaches curvature behavior; therefore, the multilinear hardening was selected. In this model, some distinctive experimental engineering stress/strain data points on the observed inflection points are converted to true stress and engineering strain. Then the plastic strain is calculated by subtracting the elastic strain from the total strain with the aid of the experimental Young's modulus. The plastic strain is utilized along with the true stress value from the material model to represent the plastic region's curvature. The degree of convergence between the RVE model and the experimental results indicates the rate of efficiency and homogeneity of the printed structure. Prior to the sintering process, the particle contacts were regarded as frictional; however, because of the mechanical interlocking and thermal bonding during the printing process, they were set as bonded in the final explicit dynamics model. Regarding the meshing conditions, an approximate number of 110,000 to 120,000 elements per unit cell showed mesh-independent results, and the element size ranged from 20 to 40 μm , with the finer mesh on the interfaces between the GTR particles and the matrix material. The RVE geometries were discretized using linear four-node tetrahedral elements (SOLID 285) generated through a patch-conforming meshing algorithm. This formulation was selected because it is well suited to the irregular particle geometries and complex interfacial distributions represented in the composite microstructure.

3. Results

3.1. Micromechanical Characterization

Uniaxial tensile testing was used to obtain the primary material parameters for the created composites in order to evaluate the mechanical performance. For every composite construction, the elastic, plastic, and fracture initiation zones were determined by extracting the corresponding stress–strain curves. Because the distribution of GTR particles and the final composite’s homogeneity cannot be entirely controlled by the Additive Manufacturing method alone, a Representative Volume Element (RVE) model was constructed for each type of unknown composite representing the ideal homogenous structure on unit cell scale and a computational execution of the uniaxial tensile testing was conducted with the aid of Finite Element Analysis (FEA) on the microstructure. The PA-12 and GTR powders were examined using scanning electron microscopy (SEM) in order to determine the size and form of the particles and to create a precise material model for the RVE model. The corresponding shape and dimensions of an indicative region of matrix material (PA-12) and reinforcement material (GTR) are illustrated in Figure 3. The GTR chemical composition characterization was conducted in a previous experimental study on polymer-GTR composite at coupon-level scale [25] and at an equivalent use case scenario with high impact absorption demands [36].

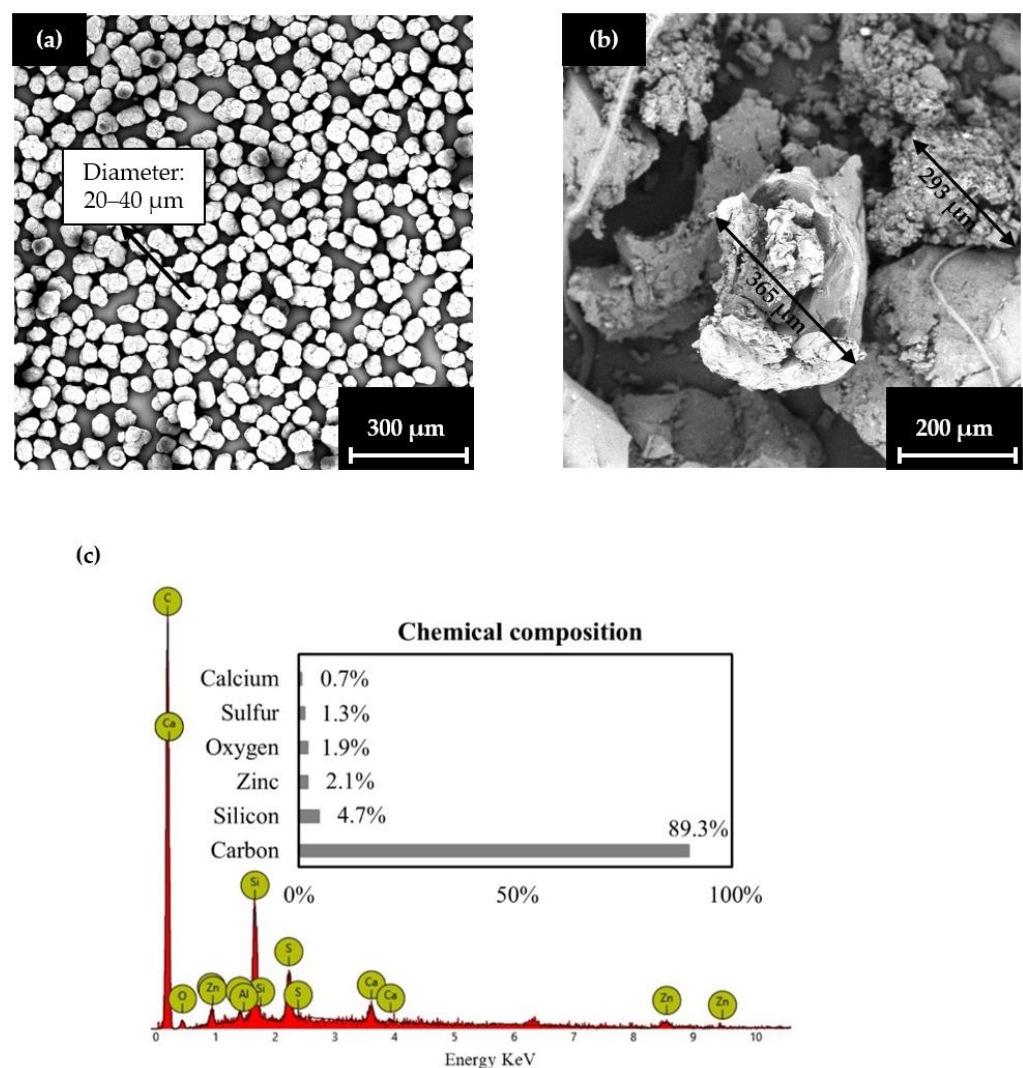


Figure 3. Shape and size characterization of the feedstock materials: (a) PA-12 powder; (b) waste GTR; (c) chemical composition of waste GTR [25].

From Figure 3, it is visible that the reinforcement material particles are bulkier than those of the matrix; therefore, it is safe to assume that after the laser sintering, a distinct solid state of the reinforcement will be present in the final structure. In Figure 4, an image of the interface and the as-printed specimen's fractural surface following tensile testing is displayed, confirming the above hypothesis.

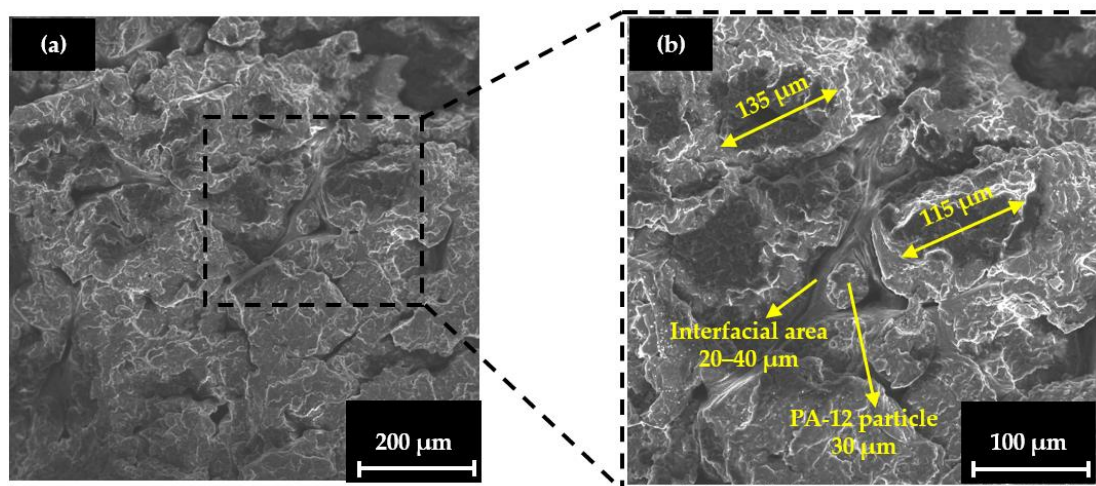


Figure 4. Analysis of the fractural surface: (a) identification of the interface area and presentation of the bonding between the reinforcement and the matrix; (b) crack initiation mechanisms.

From Figure 4, it is indicated that the GTR particle shape is irregular when sintered with 20% of the initial volume homogenized with the matrix material to create the interfacial surface. A median value of 125 µm was used with a 20% deviation for the length of the irregular shaped particles that were inserted into the RVE model with the weight and volume fractions that were presented in Table 2, meaning that the projected GTR particles presented length after the sintering process in the range of 110–145 µm. In the interfacial area, the bonding between the reinforcement and the matrix is present due to mechanical interlocking from the manufacturing process. PA-12 and GTR present low chemical compatibility due to the non-polar and cross-linked nature of the GTR, but in the present manufacturing process, compatibilizers or coupling agents were not utilized to assess the effect of the thermal bonding extracted from the SLS AM on the final structural integrity; therefore, the mechanical bonding produced by 3D printing determines the stability of the finished composite. The Fourier heat transfer law determines the interface area's vertical length. From Figure 4b, it is visible that the crack initiation did not happen in the matrix-filler interface, which indicates that a high-quality bonding was achieved due to the elevated print bed and laser temperature. This leads to unified structures without the need for chemical compatibilizers and without the need for extensive pre-treatment of the feed-stock material, making SLS AM a strong candidate for rapid transformation from waste to valuable materials and promoting sustainable manufacturing processes from an economic and environmental point of view. The bonded conditions based on the results of the microstructural characterization from the SEM were utilized to construct the final RVEs for the two unknown composites that are presented in Figure 5. In Figure 6, the comparison of the equivalent Young's modulus between the experimental results, the analytical model and the RVE model is portrayed. The experimental and the RVE model results are portrayed for the composites of interest and their equivalent volume fractions (8.5% for the 10 wt.% composite and 17% for the 20 wt.% composite) while the analytical model's results are portrayed in the continuous blue curve.

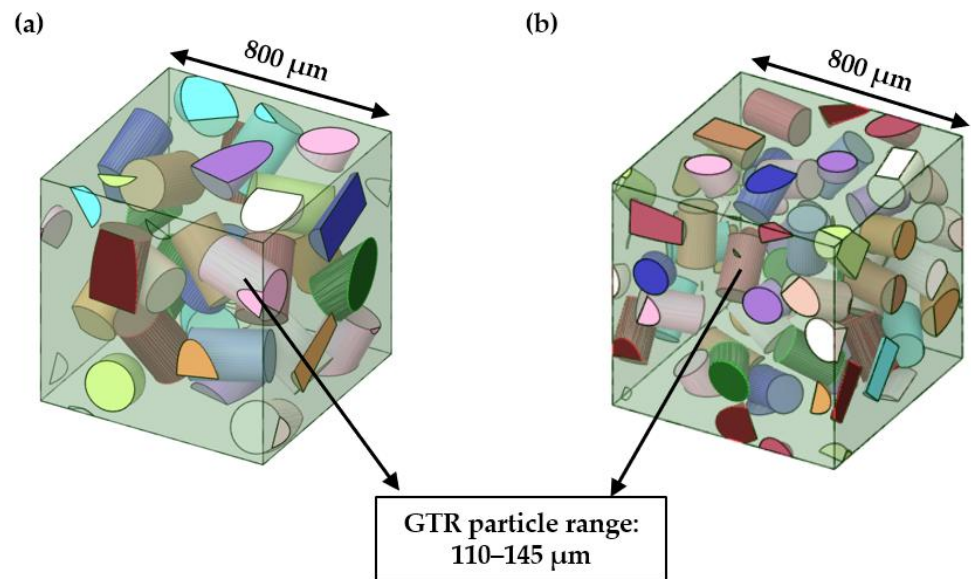


Figure 5. Representative Volume Elements (RVE) unit cells for: (a) PA-12/GTR 10 wt.%; (b) PA-12/GTR 20 wt.%).

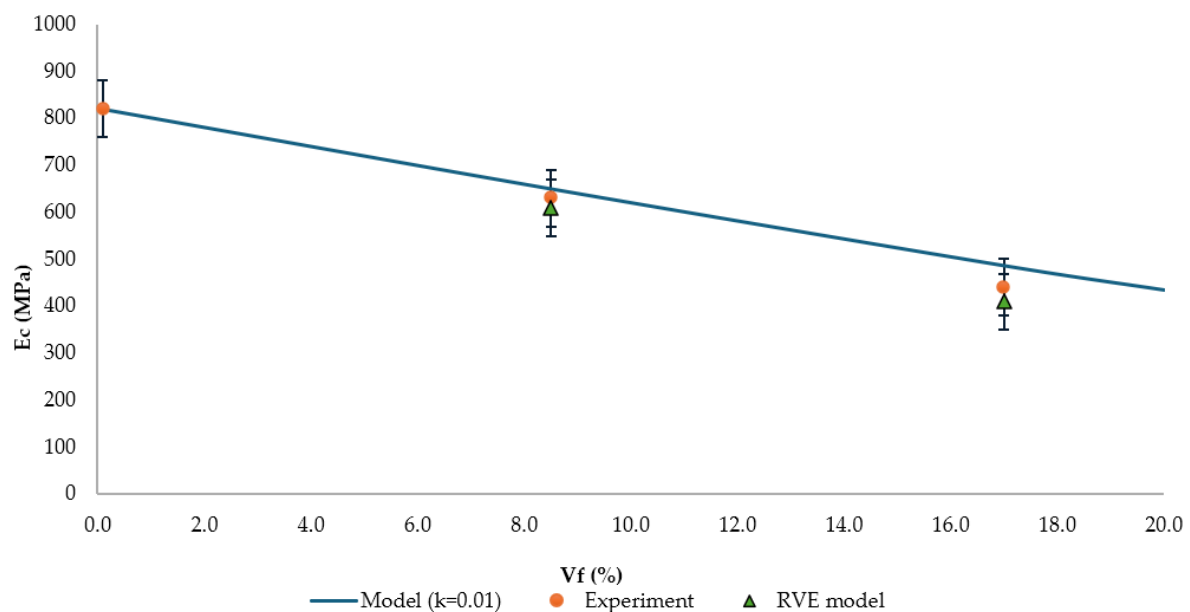


Figure 6. Dependence of Young's modulus on GTR volume fraction (V_f , %), as predicted by the micromechanical Ji model and compared with Representative Volume Element (RVE) numerical simulations and tensile experimental measurements. Experimental values are presented as mean $\pm$ standard deviation ($n = 3$), whereas the variability of the RVE results reflects simulations performed using different random particle distributions.

Figure 6 illustrates the determination of Young's modulus with increasing GTR content and provides a direct comparison between the experimental measurements, the RVE/FEA predictions, and the proposed Ji-based analytical estimate. Across the investigated compositions, all three approaches consistently capture a clear reduction in stiffness as the GTR volume fraction increases, while the close agreement between the RVE results and the experimental data supports that the adopted microstructural representation (particulate dispersion at the representative volume scale) is adequate for describing the effective elastic response. Importantly, the Ji-model curve reproduces the same monotonic

trend and magnitude of degradation, indicating that an interphase-governed description is necessary to rationalize the measured modulus drop in PA-12/GTR composites.

To interpret these comparative results, the proposed micromechanical model (Ji model) adopted in this work is formulated as a three-phase homogenization scheme (matrix–filler–interphase), which is more appropriate than classical two-phase approaches for PA-12/GTR systems where the effective stiffness is strongly influenced by the interfacial transition zone. In the model, the composite is idealized as a particulate filler of characteristic particle size r surrounded by an interphase of finite thickness τ , so that the interfacial contribution is introduced both geometrically (via the τ/r ratio, which controls the “active” interphase fraction) and mechanically (via the interphase modulus E_i). The measured characteristic particle dimensions ranged from approximately 110 to 145 μm , with a representative median value of approximately 125 μm . Therefore, $r = 62.5 \mu\text{m}$ was adopted in the Ji model. The interphase thickness τ was set to 35 μm and was determined by SEM measurement. The parameter k acts as an interfacial efficiency factor scaling the interphase stiffness relative to the matrix; selecting $k = 0.01$ implies a highly compliant interphase, i.e., $E_i \ll E_m$; this means that in the interface, a hyperelastic bond between the two phases is present where the interfacial Young’s modulus is equal to 100 times lower than the matrix material. In the present analysis, $E_i = 8.2 \text{ MPa}$, approximately two orders of magnitude lower than PA-12, indicating that load transfer from the matrix to the elastomeric filler occurs through a markedly soft transition zone. For a consistent micromechanical description, the analysis is performed in terms of the filler volume fraction V_f (rather than wt.%), with $V_f = 8.5\%$ and $V_f = 17\%$ corresponding to 10 and 20 wt.% GTR, respectively, based on the constituent densities. Under these assumptions, the predicted decrease in the effective modulus E_c with increasing V_f arises from two concurrent mechanisms: replacement of the stiffer polymer matrix by a low-modulus elastomeric phase, and growth of the effective interphase volume participating in the homogenized response, particularly when τ/r is not negligible.

3.2. Macro-Mechanical Characterization

The simulation of the tensile behavior on the RVE unit cell was conducted by utilizing the explicit dynamics analysis. The material behavior of the PA-12 composites was expressed with a linear elasticity model and multilinear hardening in the plastic region. In Figure 7a, the results of the lab-scale experimental tensile testing are presented for the three different composites. On the unknown composites (Figure 7b,c), along with the experimental stress–strain curves, a comparison of the FEA curves and the experimental ones is illustrated to assess the convergence of both studies. The interphase properties estimated through the Ji micromechanical model were incorporated into the numerical analysis to describe stress transfer between the PA-12 matrix and GTR particles. The presented stress and strain contours correspond to a post-yield loading condition close to the experimentally observed failure point and were used to identify regions of localized deformation. The relatively low necking indicates that the material presents brittle fracture mechanisms.

As indicated in Figure 7, as the weight percentage of recycled Ground Tire Rubber (GTR) increases, the composite’s Ultimate Tensile Strength (UTS) at the fracture point decreases. This drop is characterized as minimal since the difference between the UTS’s absolute value of the neat polymer, and the high weight fraction composite is lower than 15%. Also, significant differences are observed between the yield point and the fracture point. It is evident that the clean polymer exhibits nearly no plastic deformation and a more brittle characteristic. The impact of the GTR on the final structure, expressed as a percentage is evident since the difference in the maximum elongation at the fracture point between the neat material and the high weight fraction composite ranged between 250

and 300% (from 0.06 to 0.15–0.18). The same distinction in elasticity is observed both in the elastic and the plastic region. The yield strength presents minimal difference (from 16 to 20 MPa), but there is a significant deviation in the elastic modulus, indicating significant changes in the elongation at yield and therefore the whole elastic behavior of the structure. The FEA contours at the post-yield condition close to the fracture initiation further demonstrate that. Also, the similarity of both the computational and the experimental curves indicates that the level of sintering is relatively good. The fractural mechanisms for the neat polymer (Figure 8a) and the hybrid (Figure 8b) composite are also presented in Figure 8.

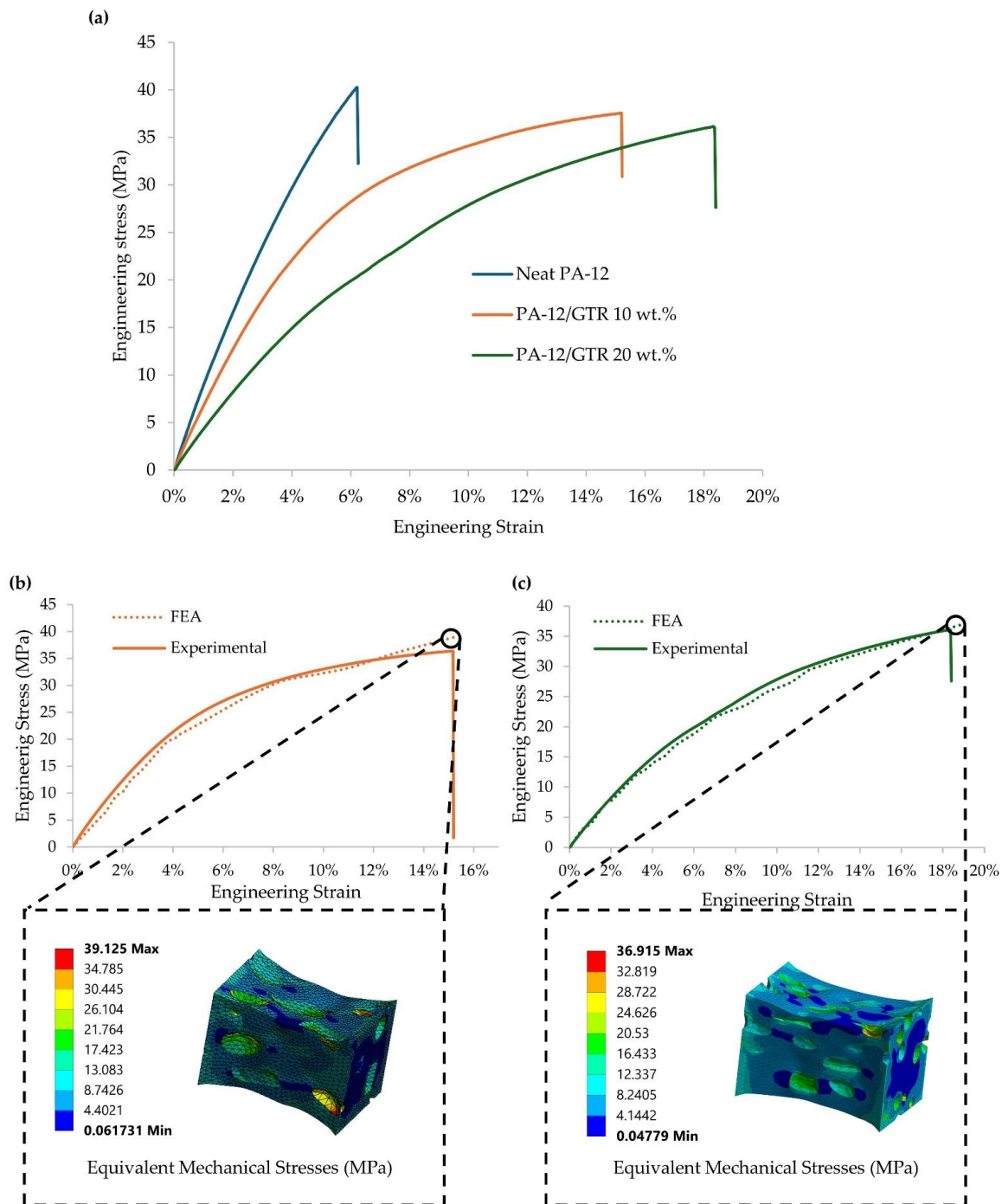


Figure 7. Stress–strain response curves: (a) overall response of the matrix material and the PA-12/GTR composites; (b) tensile response of PA-12/GTR 10 wt.% composite compared to the equivalent;

lent RVE model; (c) tensile response of PA-12/GTR 20 wt.% composite compared to the equivalent RVE model.

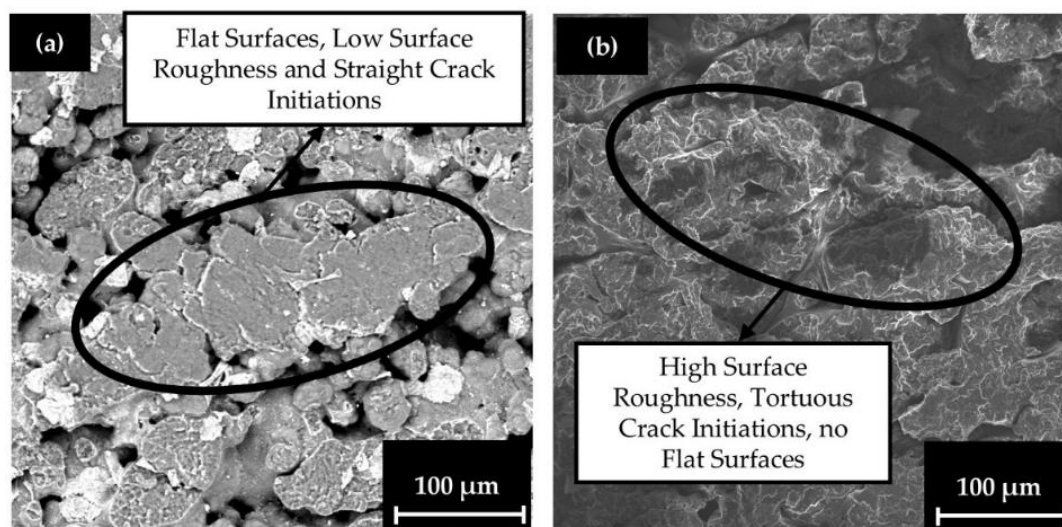


Figure 8. Fractural mechanisms: (a) neat PA-12; (b) hybrid PA-12/GTR with 20 wt.% filler.

The SEM observations of the crack initiation mechanisms confirm the hypothesis of a more ductile or hybrid fracture in the composite material. The existence of rough facets and the rounded crack initiations hints at the existence of significant plastic deformation regions. The absence of air gaps in Figure 8b, despite the visible ductility, indicates that the structure handled significant plastic deformation. It is also observed that the interfacial bonds were not destroyed, and the initiation happened in a random area of the composite. This behavior was expected since the printing temperature (higher than GTR's melting point) allowed the development of a more unified structure without significant air gaps and highlights a significant benefit of the SLS AM for the treatment of cross-linked materials and elastomers. This behavior is also visible in Figure 8, where the interfacial bonding and the crack initiation mechanisms are presented. The compatibility due to the printing conditions allowed the development of the specimens without the need for chemical compatibilizers or stabilizers for the process. In Table 3, the overall results regarding the mechanical properties of the 3D-printed specimens are presented by illustrating the key factors of Ultimate Tensile Strength (UTS), yield strength, elastic modulus (E), and the elongation at break.

Table 3. Main mechanical properties of PA-12/GTR composites extracted from tensile testing.

Material	Elastic Modulus (MPa)	Yield Strength (MPa)	UTS (MPa)	Elongation at Break
Neat PA-12	820 ± 75	20.9 ± 2.3	40.2 ± 3.9	6 ± 0.5%
PA-12/GTR 10 wt.%	630 ± 60	19.9 ± 2.1	37.6 ± 3.5	15 ± 1.2%
PA-12/GTR 20 wt.%	440 ± 40	18.1 ± 1.9	36.1 ± 3.3	18 ± 1.4%

3.3. Energy Absorption Capabilities

The built specimens were subjected to uniaxial compression testing in order to determine the PA-12-based composites' capacity to absorb energy. The energy that the material is absorbing is shown by the region beneath the compressive stress–strain curves. The specimens presented identical dimensions, so the calculation process for the overall energy absorption was similar in all cases. To assess the capabilities per mass unit, different definitive densities were calculated for each composite since PA-12 and GTR presented different specific densities. In all cases, similar loads were applied and translated to an

equivalent stress of around 350 MPa at the peak of the densification state. The results regarding the compression testing and the energy absorption capabilities are presented in Figure 9, with the overall energy absorption (EA) and the Mean Crash Force (MCF) utilized to characterize the material and the structure's absorption properties at 50% of the total strain.

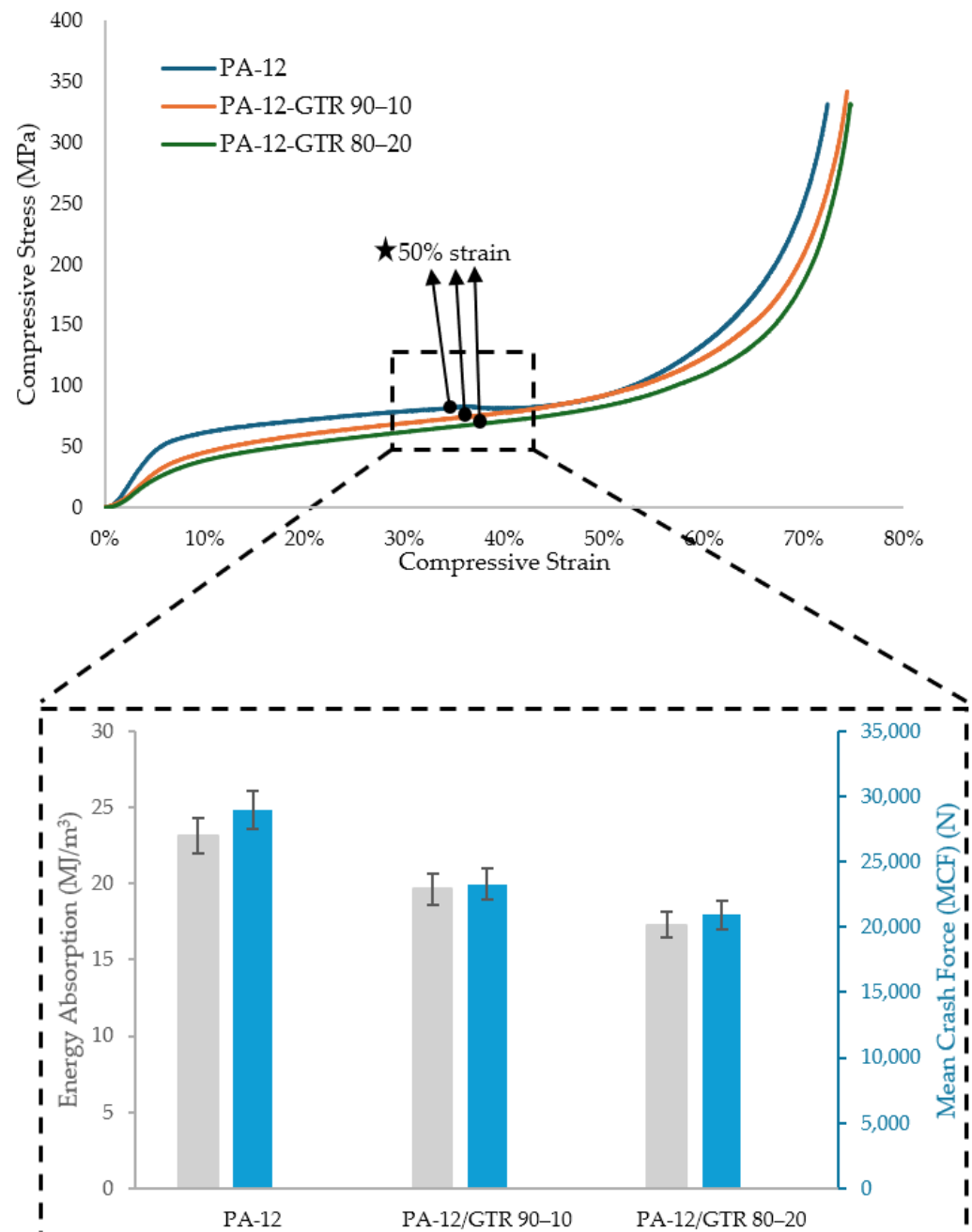


Figure 9. Compressive response of the composites and the equivalent energy absorption properties up to the 50% strain point (circles).

Reduced energy absorption properties result from the insertion of reused GTR into the matrix material, as can be shown from the examination of the compression curves in Figure 9. This behavior was expected due to the fact that GTR presents completely different material behavior compared to PA-12. GTR is an elastomer with soft bonds, which is capable of obtaining high deformations, while PA-12 is one of the strongest thermoplastics with high strength capabilities and minimal elastic behavior. When the repurposed GTR

is inserted into the matrix, a hybrid with marginally less absolute absorbing capabilities was developed due to the small contribution in the plastic deformation region of the GTR, leading to stress concentrations and debonding in the mechanical interlocking areas and resulting in lower energy dissipation capabilities. In Table 4, an overview of the compression results for the PA-12/GTR composites is displayed.

Table 4. Energy absorption properties overview of the PA-12/GTR composites.

Material	Energy Absorption, EA (MJ/m ³)	SEAm	Mean Crush Force (N)	Efficiency, η (%)
Neat PA-12	23.1 ± 2.2	24.1 ± 2.3	28,921 ± 270	76.9 ± 6.5%
PA-12/GTR 10 wt. %	19.6 ± 1.8	20.1 ± 2.1	23,298 ± 230	67.1 ± 6.2%
PA-12/GTR 20 wt. %	17.3 ± 1.6	17.3 ± 1.6	20,914 ± 200	67.4 ± 6.4%

3.4. Vibration Isolation Capabilities

In order to evaluate the composites' viscoelasticity and vibration isolation capabilities, three different types of testing were carried out: a static loading/unloading test for a small number of cycles (5–10), a frequency-dependent Dynamic Mechanical Analysis (DMA) to assess the elastic damping capabilities and modal analysis to assess the viscous damping factor. For the loading/unloading, a stable load was applied and unloaded when the structure reached the 60% mark that represents the elastic region's yield point strain. The static experiment's findings are shown in Figure 10. In Figure 10a, the experimental extracted curves are indicated, and in Figure 10b, the equivalent total loss factors are illustrated after the first full cycle.

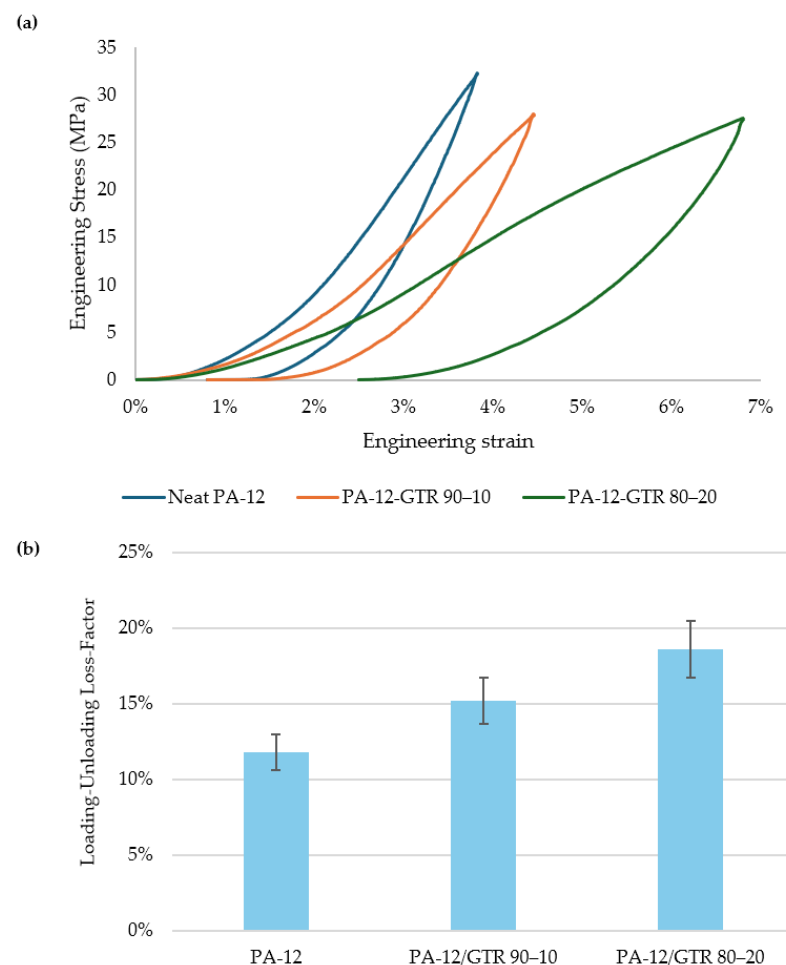


Figure 10. Loading/unloading response of PA-12 and PA-12/GTR composites: (a) loading/unloading curves for the 1st cycle; (b) equivalent damping factor of each composite.

The insertion of waste GTR into the PA-12 matrix resulted in significant improvement in the vibration isolation capabilities, which is visible from the significant rise in the total damping coefficient from Figure 10. The difference in the material behavior between the matrix and the filler is visible in this case, and the effect of the filler on the composite's response. The constructed hybrid material could work in a structure where suppression of the vibrational phenomena due to constant or sudden loads is demanded. A prime example of that is the development of protective equipment such as shin or elbow guards or helmets for contact sports (e.g., American football). In the results of the DMAs, an isothermal frequency sweep is presented for the range of 0.1–100 Hz, mainly described by the storage modulus (E'), the loss modulus (E''), and the equivalent elastic damping factor ($\tan \delta$, n) (Figure 11).

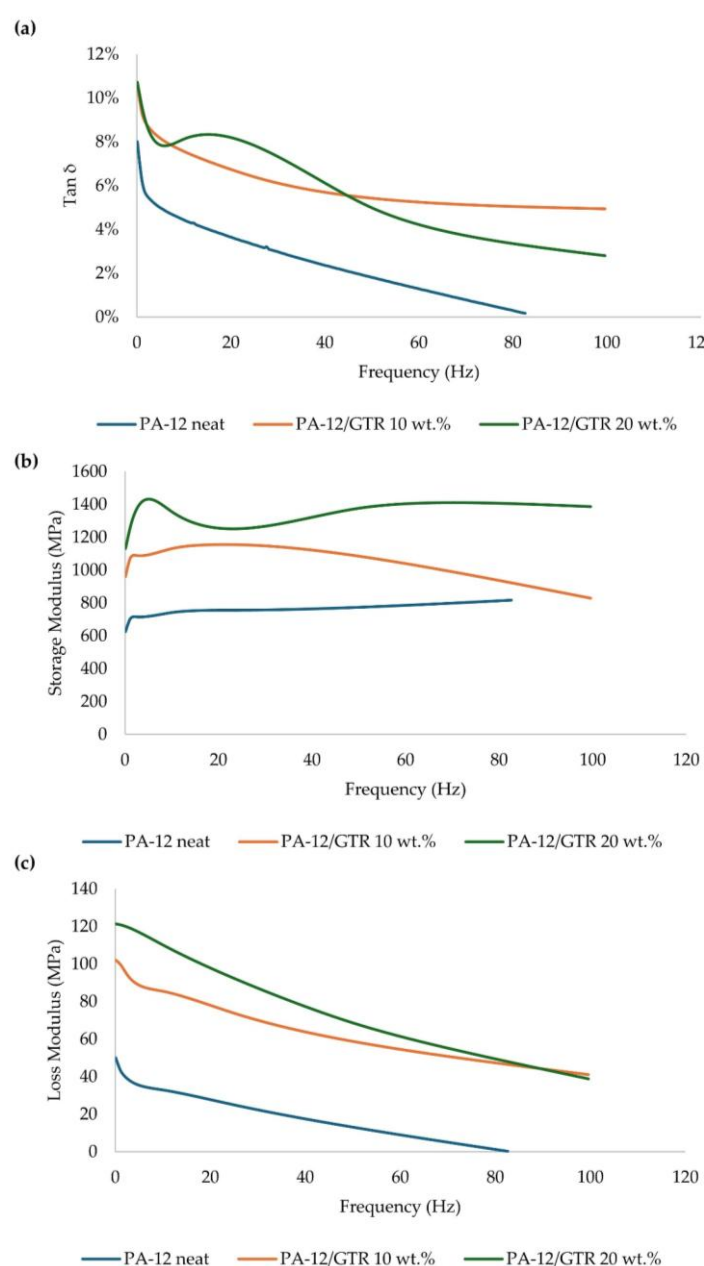


Figure 11. Isothermal frequency sweep response of PA-12/GTR composites extracted from DMA testing: (a) storage Modulus (E'); (b) loss Modulus (E''); (c) loss factor ($\tan \delta$, n).

From Figure 11, it is evident that the loss factor is positively impacted by the addition of reused GTR, as it is indicated in the $\tan \delta$ frequency sweep. The elevated absolute value is also evident in the metrics of the storage modulus (E') and the loss modulus (E''). Both values were expected to increase, as the loss modulus indicates higher energy mitigation and vibration isolation capabilities, which was evident from the static testing as well, while the absolute storage modulus was expected to be elevated since the composites presented higher deformation and extended plastic regions, especially in values that are not near the fractural point, therefore similar to the applied loads on the DMA testing. Also, the storage modulus is elevating with the insertion of GTR at near-zero frequency. This elevation is contradictory to the Young's modulus, which indicates that in dynamic loads the composite materials present both elastic and viscous deformation. The viscoelastic properties of the inserted reinforcement and the small relaxation time of the dynamic phenomena result in this deviation between the storage modulus and the equivalent Young's modulus of each material. The rate of the loss modulus increase is more intense compared to the equivalent increase rate of the storage modulus, meaning that the ratio between those two absolute values ($\tan \delta$) is expected to depend on the concentration of the filler material. In higher frequencies, the vibration isolation capabilities of the matrix are almost diminished, and the absolute $\tan \delta$ value approaches near-zero values, while in the composite structures, this value seems to reach a certain plateau after a certain frequency. This drop is mainly explained due to the vibrations happening between the bonds, as frequency elevates, the relaxation time is lower, and therefore the viscoelastic capabilities that lead to the energy dissipation properties are diminished. In high frequencies, the structure mainly functions as a string and is not capable of storing further energy. The plateau region in the composites is expected since, from the static testing, the composites presented higher deformations and increased elasticity. The GTR insertion transformed the brittle matrix material to a composite with better elastomeric behavior. On the contrary, the neat polymer presented a glass-like behavior throughout the deformation region and brittle fracture mechanisms. The absence of the elastomeric GTR resulted in a sharp fallout of the energy dissipation properties when the soft segments between the molecular chains were frozen, which is evident in frequencies above 30 Hz. Regarding the $\tan \delta$ response of the 20 wt.% composite, it is evident that some bumps diverge from the overall behavior of the other two tested materials. This bump is evident due to interfacial frictions between the particles, and this peak was also observed in the previous literature during the identification of the $\tan \delta$ and the storage modulus on fiber, resin or particle-reinforced particles (interfacial relaxation peak) [37,38]. Higher concentration of GTR would be expected to result in a sharper peak. This bump could be useful in applications where relaxation time is relatively low (e.g., turbines). From the results of Figure 11, it is evident that the optimal weight fraction that leads to optimized properties without significantly transforming the matrix behavior is between 10 and 20 wt.%. In cases where strength and energy dissipation capabilities are demanded simultaneously, low filler concentrations are suggested. For applications where damping capabilities are demanded on relatively lower dynamic loads and load frequency, the insertion of higher filler percentage could lead to localized regions with high vibration isolation properties and stand as an identical candidate for the use case. The PA-12/GTR composite's frequency response function under various GTR weight fractions, extracted from the modal experiments, is illustrated in Figure 12, and the key characteristics obtained from these experiments are summarized in Table 5.

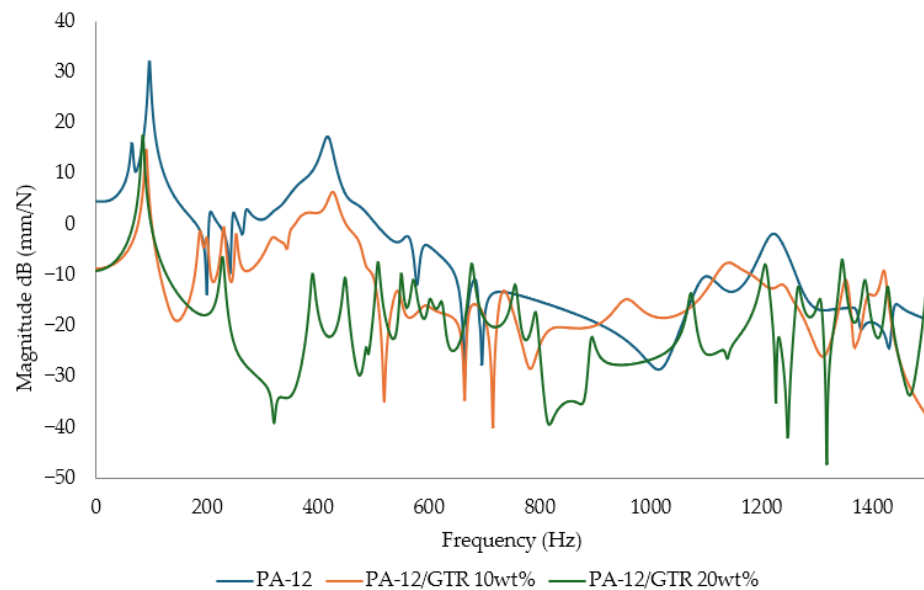


Figure 12. PA-12/GTR composite's frequency response function under various GTR weight fractions.

Table 5. Resonant frequencies, loss factors, and E modulus of PA-12 specimens loaded with different weight fractions of GTR.

Material	Resonance Frequency (Hz)	Viscous Loss Factor (ζ)	Storage Modulus (MPa)	E Modulus (MPa) from Modal Testing	E Modulus (MPa) from Tensile Testing	Increase in the Damping Factor (%)		
						Loading–Unloading	DMA	Modal Tests
Neat PA-12	96	7.5%	625 ± 52	752 ± 62	820 ± 75	-	-	-
PA-12/GTR 10 wt. %	91	10.9%	930 ± 79	646 ± 59	630 ± 60	28.9	26.6	45.3
PA-12/GTR 20 wt. %	84	11.8%	1130 ± 93	488 ± 43	440 ± 40	57.8	48.4	57.3

Figure 12 indicates the frequencies of resonance for various modes over a continuous frequency range. The sole polymer curve consists of high, sharp peaks and the highest resonance frequency, which indicates significant vibration transmissibility, meaning less energy dissipation. On the contrary, both composites present smoother peaks and broader peaks, which means higher damping capabilities. Especially in the high-weight fraction composite (20 wt.%), the resonance reduction is visible, indicating strong vibration suppression and isolation. The modal results confirm the behavior that was exported from the static and dynamic mechanical testing. In the lower weight fraction, a degree of vibration suppression was achieved, and an approximate 30% increase in the damping capabilities was observed. At weight fractions of 20 wt.% and above, the system dissipates energy much more effectively over a broader range, as shown by the significant 57% increase in the absolute damping factor values, making it a suitable candidate for applications with frequent dynamic loads or where acoustic damping is demanded. The 10 wt.% composite seems to be an adequate candidate for applications where moderate damping is demanded and where the energy produced from the vibrations is somewhat advantageous, for example, in energy harvesting processes. In Table 5, the key features taken from the modal testing curves are shown and compared with the hysteretic damping identified through the loading–unloading and DMA tests.

Overall, it is observed that the addition of reused GTR led to a structure with higher elasticity, which is indicated by the significant decrease in the Young's modulus and confirmed by the material's ability to dissipate energy under dynamic conditions as expressed

by the increase in Storage Modulus from the isothermal DMA testing. In Table 5, the reference point of 0.1 Hz was used to express a direct comparison between the static and the dynamic testing. In the resonance region, the composites' prominent peaks suggest that the loss modulus heavily influences the material's behavior in this region, which is adequate for applications where rapid restoration is required. The proposed PA-12/GTR composite seems to stand as a suitable solution for applications where high strength tolerance and medium energy dissipation properties are required, such as suspension brackets in automotive systems or for protective equipment in contact sports. The hybrid materials seem to be able to stand as a standalone structure without the need for a protective shell for these types of applications. Regarding the correlation between the calculated loss factors (static and dynamic), there is no relevant direct comparison between them; however, the modal testing method's dependability was confirmed by the observed agreement between the two distinct damping factors.

3.5. Discussion

Figure 13 displays the primary static and dynamic characteristics of the PA-12/GTR composites. The primary material characteristics from uniaxial tensile testing were retrieved in order to evaluate the static response and impact of the GTR on the stiffness of the structure (E Modulus, Yield Strength, UTS). The overall energy absorption (EA) and overall damping factor from the loading–unloading testing (n), the $\tan\delta$ at near 0 Hz frequency (hysteretic) from DMA testing and the damping ratio at the resonance frequency from the modal testing (viscous damping ratio, ζ) were analyzed to evaluate the dynamic properties and the general vibration isolation characteristics that are crucial for further upcycling and future applications.

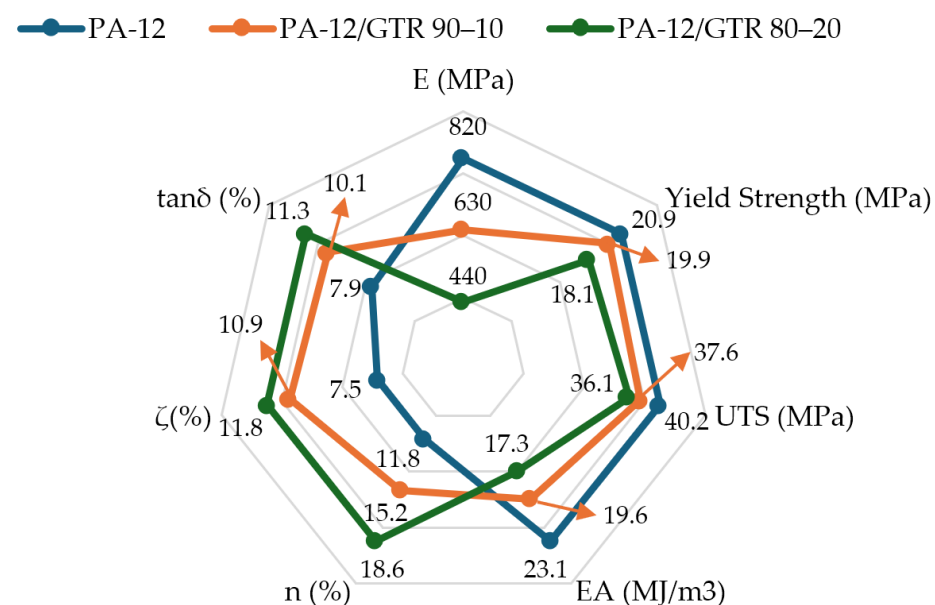


Figure 13. Multi-property comparison of PA-12 (blue) and PA-12/GTR composites (orange: 10 wt.% GTR, green: 20 wt.% GTR), including elastic modulus, strength, energy absorption and damping response.

The GTR's insertion into the PA-12 matrix resulted in a material with high elasticity, as shown by the significant drop in the Young's modulus. The maintenance of the overall strength and yield strength, as indicated in Figure 13, despite the incorporation of a material with relatively lower stiffness compared to the matrix, indicates that good homogeneity was achieved and minimal air gaps were present in the final structures. The SLS's

manufacturing printing capabilities regarding the layer height and the bed temperature aided in the efficient exploitation of the matrix's stiffness with the reinforcement elasticity, achieving optimal results in both and minimizing possible defects due to air gaps despite the irregular shape and size of the rubber. The Ji model provides an effective analytical framework for estimating the overall elastic response of the PA-12/GTR composites. Nevertheless, its formulation relies on idealized assumptions, including simplified particle geometry, homogeneous filler dispersion, and uniform interphase thickness and mechanical properties. These assumptions cannot fully account for the irregular morphology, particle-size variability, local agglomeration, and spatial variations in interfacial bonding associated with recycled GTR particles. Therefore, although the model satisfactorily captures the overall reduction in Young's modulus with increasing GTR content, it does not explicitly resolve the local microstructural heterogeneities and stress concentrations present in the actual composite. Regarding the energy absorption capabilities, a minimal drop was observed in the low-weight fraction composite. On the contrary, higher GTR concentrations led to significantly reduced overall energy absorption and exploited the differences between the non-polar GTR and the polar PA-12. This resulted in possible localized stress concentration zones where early debonding was observed. Also, the nature of the reinforcement could lead to disruptions in the overall degree of crystallinity of the structure compared to the matrix material, resulting in less energy dissipation properties. The damping parameters obtained from DMA, modal analysis, and loading–unloading testing are not directly comparable because each method involves different frequencies, strain amplitudes, deformation modes, and boundary conditions. The DMA loss factor was approximately 11.3% at 0.1 Hz and increased with frequency, confirming the frequency dependence of the viscoelastic response. The higher loading–unloading damping factor of 18.3% is attributed to the greater strain amplitude, which activates additional nonlinear hysteretic and interfacial dissipation mechanisms. The modal damping ratio of approximately 11% corresponds to an equivalent loss factor of about 22% according to $\eta \approx 2\zeta$, although modal damping is also influenced by specimen geometry, resonance conditions, and supports. Similar differences among damping methods have been reported in the literature [39,40]. Overall, the analysis of the damping capabilities indicated that the elastomer's vibration isolation capabilities were significantly absorbed by the matrix material in the final structure and led to high-strength vibration isolators that could stand as a standalone structure in various automotive systems or in wearable protective gear.

4. Conclusions

In this research paper, an overall evaluation of the static and dynamic mechanical response of SLS-manufactured PA-12 composites with reused GTR as a reinforcement material was conducted. The main focus was to identify the optimal manufacturing technique and the optimal methodology process to convert unknown waste materials into reusable printable feedstocks by exploiting the AM's advantages regarding rapid manufacturing and to promote a sustainable model for long-term viable manufacturing processes aligned with the future global environmental goals. It is worth noting that, especially in the case of vulcanized cross-linked materials, such as the Ground Tire Rubber, where extensive pre-treatment is not a viable solution, SLS AM can work as an immediate method for converting those wastes to a utilizable feedstock material. The dynamic response of the composites compared to the matrix polymer material indicated that the final damping properties are suitable for use in applications where significant vibration isolation properties are demanded, along with highly concentrated stresses, such as protective equipment or in suspension brackets in automotive systems. The incorporation of GTR into the polymer matrix enhanced the vibration isolation properties and improved the elasticity properties while maintaining good overall strength and energy absorption capabilities.

The selected manufacturing process and the printing parameters (0.075 mm layer height, print bed temperature of around 180 °C) aided in the satisfying degree of sintering between the matrix material and the irregularly shaped and sized reinforcement without the need for chemical compatibilizers, therefore minimizing the air gaps and the defects in the structure. The high degree of homogeneity between the matrix and the reinforcement was visible via SEM on the surface, by the deformation mechanisms of the composites compared to the neat polymer, and was also evident by the fact that despite the low-stiff high-elastic nature of the GTR, the structure's overall UTS was maintained. Regarding the dynamic response, GTR concentrations at the 20 wt.% region resulted in significant differences in the energy absorption capabilities and in irregularities in the frequency sweeps extracted from the DMA and the modal testing. Those irregularities were evident due to the potential increase in the interfacial frictions between the neighboring particles and especially in the case where those particles were the friction was between a matrix and a reinforcement particle. This friction created concentration points with unique and localized relaxation points. Those localized relaxation points would be ideal for structures where high noise vibration mitigation is demanded at high frequencies.

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