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Unconventional Recycling of Aeronautical Ground Carbon Fiber Composite Wastes

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Abstract. Carbon fiber–reinforced polymer (CFRP) composites are extensively used in aerospace applications; however, their end-of-life management remains a critical challenge. This study investigates an unconventional recycling route based on the direct hot compression molding of CFRP waste powders, aiming to valorize industrial composite scraps without the addition of virgin polymers or binding agents. The material investigated corresponds to the finest fraction (~300 µm) obtained from a sieving process applied to industrial CFRP scrap powders derived from trimming residues and partially cured aeronautical prepregs. The use of this fine powder fraction promotes effective particle aggregation and consolidation during molding, preventing powder loss during demolding and enabling the fabrication of relatively thick panels despite the absence of additional bonding agents. Compression molding was carried out at 250 °C and 1.5 bar for 20 min. Two material configurations were analyzed: uncoated compression-molded panels and panels coated with a thin polyester layer. The recycled materials were characterized through morphological, thermomechanical, and mechanical analyses. The results indicate that the polyester-coated panels exhibit improved mechanical performance compared to the uncoated configuration. In comparison with previous studies focused on coarser powder fractions (≤1 mm), the present work highlights the potential of the finest powder fraction for effective consolidation, demonstrating the strong influence of particle size on the processability and properties of compression-molded recycled CFRP. These findings confirm the viability of direct compression molding as a sustainable and scalable recycling strategy for tailoring CFRP waste reuse as a function of powder size.

Introduction

Industrial manufacturing processes generate substantial quantities of powder-based waste, particularly in sectors such as metallurgy, ceramics, additive manufacturing, and mineral processing. These waste powders often consist of high-value raw materials, including metals, alloys, ceramics, and composite residues, but are frequently discarded due to contamination, irregular particle size distributions, partial degradation, or the absence of economically viable recycling routes [1–3]. Therefore, large volumes of potentially recoverable material are rerouted to landfilling or incineration, practices that not only impose significant environmental burdens but also result in the irreversible loss of resources and energy [4,5].

In recent years, increasing regulatory pressure and the global push toward decarbonization have driven industries to adopt circular economy principles, emphasizing material recovery, waste minimization, and resource efficiency [2,6]. Within this framework, the valorization of industrial powder waste has emerged as a critical challenge and opportunity. Powder-based residues are particularly attractive candidates for recycling due to their intrinsic form, which is already suitable for shaping and consolidation processes, potentially bypassing several intermediate manufacturing steps [7].

Conventional recycling approaches for industrial powders typically rely on energy-intensive reprocessing methods, such as remelting, high-temperature sintering, or chemical treatments aimed at restoring material purity [8,9]. While effective in some cases, these strategies often involve high energy consumption, complex separation procedures, and significant operational costs, which can undermine their overall sustainability and limit large-scale implementation [10]. Moreover, repeated thermal or chemical processing may lead to material degradation, further reducing the performance of recycled products [11].

In contrast, direct molding and consolidation of waste powders represent a promising alternative recycling route. This approach enables the conversion of industrial residues into functional components with minimal preprocessing, relying on powder compaction mechanisms such as hot pressing, compression molding, or hybrid thermo-mechanical techniques [12,13]. By avoiding melting or extensive chemical modification, direct molding can significantly reduce energy demand while preserving the intrinsic properties of the original material. Previous studies have demonstrated the feasibility of producing structural and semi-structural components from recycled powders with competitive mechanical, thermal, and functional properties [14].

Despite these advantages, several challenges should be solved in the direct molding of industrial waste powders. Variability in particle morphology, size distribution, chemical composition, and the presence of residual binders or contaminants can strongly influence powder flowability, compaction behaviour, and interparticle bonding [15,16]. Furthermore, the optimization of processing parameters, such as pressure, temperature, dwell time, and binder or coating content, is essential to ensure adequate mechanical integrity, dimensional stability, and reproducibility of the final components.

In this context, the objective of this study is to assess the direct molding approach as a sustainable and scalable non-conventional process for the valorization of industrial powder waste. Aeronautical powder scraps are transformed into panels through direct molding technology, and the resulting materials are characterized in terms of their thermal, mechanical, and morphological properties. This characterization aims to verify the suitability of the recycled panels for potential industrial applications and to identify key parameters governing their performance. By advancing the understanding of direct powder molding from industrial waste streams, this work seeks to contribute to the development of sustainable manufacturing practices and to support the implementation of circular economy strategies within powder-based industries. Consequently, the present work explores an alternative route for the valorization of carbon fiber–reinforced polymer (CFRP) machining residues, focusing on their application as a functional material for panels. The feedstock is mechanically milled waste generated during aerospace-grade composite machining processes, containing short carbon fibers (CF), fragmented thermoset matrix, and minor residual impurities. The recycled powder was consolidated via direct compression molding, deliberately avoiding the addition of external binders, virgin reinforcements, or supplementary curing agents. The consolidation mechanism is driven by a combination of thermo-mechanical effects activated during grinding and compression molding [17-19]. Mechanical milling generates localized shear forces and frictional heating, which can activate residual chemical functionality within the thermoset matrix, promoting matrix softening and interparticle adhesion during molding at elevated temperature [20-22].

Compared to the coarser powder fractions investigated in earlier studies by the authors for CFRP powders with particle sizes ≤1 mm, the finest powder fraction examined in the present work exhibits enhanced aggregation behaviour, leading to improved packing, reduced powder loss during handling and demolding, and more uniform consolidation [23]. This improved aggregation enables the fabrication of relatively thick panels without the use of additional binders or virgin resin systems, highlighting the strong influence of particle size on processability and structural integrity. These results demonstrate that tailoring the recycling strategy as a function of powder size is a key factor in maximizing the effectiveness of direct compression molding as a sustainable route for CFRP waste valorization.

Materials and Methods

Materials. A carbon fiber–reinforced sandwich panel was manufactured using exclusively recycled, commercially available materials. The carbon fiber–reinforced polymer (CFRP) scraps were derived from mechanically processed CFRP wastes sourced from an aerospace production facility, where it originated from dismantling operations and end-of-life treatment of composite components. As the waste was generated through machining and grinding of certified aeronautical structures, the resulting material exhibits intrinsic heterogeneity, consisting of a mixture of short carbon fibers, cured epoxy matrix fragments, and minor residual impurities. Given the complex and variable nature of the recovered material, no detailed ultimate or proximate chemical analyses were performed. Nevertheless, the composition is representative of conventional aerospace-grade CFRP systems based on epoxy matrices reinforced with carbon fibers. The waste material was collected immediately following the grinding process, a stage at which both particle size distribution and contamination levels are typically broad and poorly controlled. To obtain a powder suitable for further processing, the recovered CFRP scraps were classified via mechanical sieving using a Retsch AS 200 basic sieve shakes (Retsch GmbH, Haan, Germany). A three-step sieving procedure was employed, consisting of an upper sieve with a 4 mm aperture followed by a lower sieve with a 1 mm mesh size and a final one with 300 μm mesh size. This classification yielded a fine fraction with particle sizes below 300 μm. The pronounced heterogeneity of the resulting powder fraction was qualitatively assessed through stereomicroscopic observations carried out with a Leica S9i stereo microscope (Leica Camera AG, Wetzlar, Germany) (Fig. 1a). In addition, the same instrument was used to evaluate the particle size distribution of the sieved powder.

Fabrication of Recycled CFRP Panels. Recycled CFRP panels were manufactured by direct compression molding of industrial CFRP powder without the addition of virgin polymer or binding agents. A square specimen (200×200 mm^2) was produced in a monolithic recycled CFRP panel from 500 g of powder. Molding was performed using a hydraulic hot press (ATS FAAR; maximum load 264 kN, platen size 300×300 mm^2). The upper and lower platens were set at 250 °C and 220 °C, respectively, to accommodate mold geometry and promote effective consolidation. The recycled CFRP powder was placed in an aluminum mold with an internal cavity of 200×200 mm^2 and compressed at 1.5 bar for 20 min. Fluorinated ethylene propylene (FEP) films were used as release layers on both mold interfaces. After molding, samples were cooled to room temperature inside the press for 120 min prior to demolding. The fabrication procedure is schematically illustrated in Fig. 1a. One half of the resulting panel was subsequently coated with a thin polyester layer applied by spray deposition.

Thermomechanical analysis. Dynamic mechanical analysis (DMA) was conducted using a TA Instruments DMA Q800 (New Castle, DE, USA) operating in dual cantilever bending mode. Measurements were performed over a temperature range from 30 °C to 250 °C at a heating rate of 3 °C/min. Rectangular specimens with nominal dimensions of $10 \times 60 \times 3$ mm^3 were tested, and five samples were analyzed to ensure repeatability.

Thermal analysis. Thermogravimetric analysis (TGA) was performed on both raw powder samples and compacted specimens using a TA Instruments TGA Q500. The tests were carried out under a nitrogen atmosphere with a constant heating rate of 10 °C/min over a temperature range from 30 °C to 900 °C.

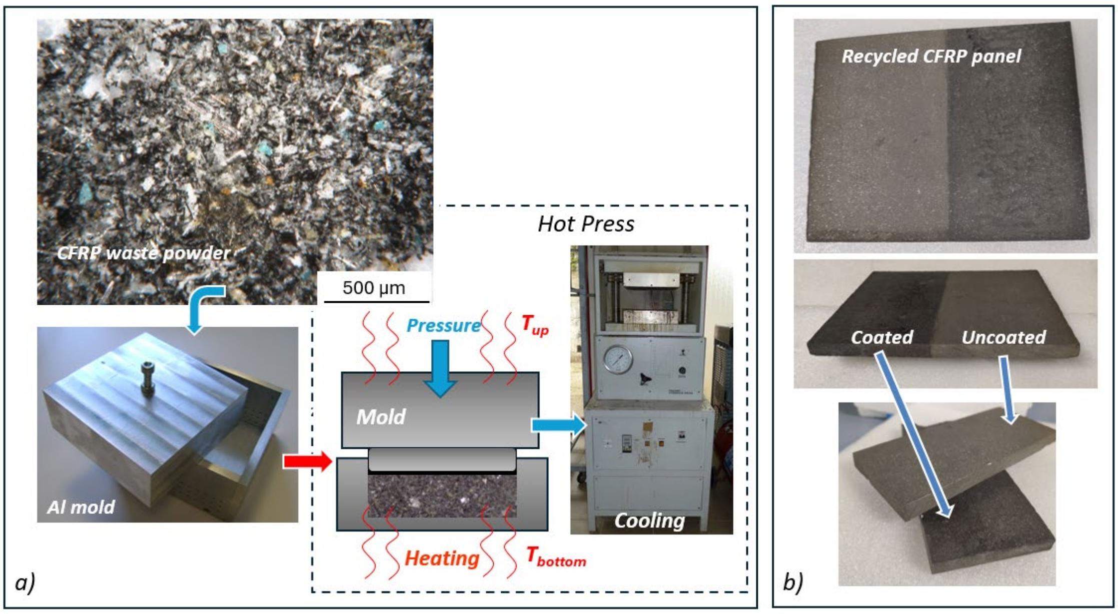

Fig. 1. Fabrication process scheme (a), recycled CFRP panel coated and uncoated (b).

Microscopic and morphological observations. A first microscopic observation of the CFRP panels surfaces with and without coating were carried out by a digital 3D microscope (Hirox HRX-01, HIROX EUROPE, JYFEL Corporation, Limonest, France). The 3D microscope also enabled a preliminary qualitative analysis of the three-dimensional surface morphology, with extraction of surface parameters for both coated and uncoated CFRP printed panel samples. A more accurate microstructural characterization was performed with scanning electron microscope (SEM) to compare the morphology of unprocessed powders and consolidated materials. Prior to analysis, the samples were sputter-coated with a thin gold–palladium conductive layer to minimize charging effects. Observations were conducted using a field-emission scanning electron microscope (FE-SEM, FEI Quanta 200 F, Zurich, Switzerland), operating under high-vacuum conditions at an accelerating voltage of 30 kV. Finally, to evaluate the effect of the coating on the surface properties, particularly the wettability, measurements were performed using an optical tensiometer (Attension Theta Lite, by Biolin Scientific). A 3 µL drop was deposited on the surface, and the average contact angle was measured by OneAttension software both at 1 s after deposition and after 30 s.

Mechanical tests. The flexural behavior of the manufactured specimens was evaluated through three-point bending tests conducted in accordance with ASTM D7264. Experiments were performed on an electromechanical universal testing system (MTS Insight 5, MfigTS Systems S.r.l., Torino, Italy) operating under displacement-controlled conditions at a constant crosshead velocity of 1 mm/min. The span length between supports was fixed at 40 mm, and an initial preload of 1 N was applied to ensure proper specimen seating. Throughout the tests, the applied force and corresponding mid-span displacement were continuously monitored. The acquired data were subsequently analyzed to determine flexural strength, flexural modulus, and deformation at failure using the formulations specified in the ASTM standard.

Results and Discussion

Recycled CFRP panels. The recycled CFRP panel exhibited an average thickness of 12.7 ± 0.32 mm and a bulk density of approximately 1.18 g/cm³. Compared to the recycled panel produced in earlier work from CFRP powders with particle sizes ≤1 mm (density ≈ 1.3 g/cm³) [23], the panel fabricated in this study exhibits a lower apparent density (≈ 1.2 g/cm³), likely associated with the presence of differences in powder packing and consolidation behavior due to the sieved powder and the dimensions. In particular, the use of powders with more uniform and finer particle sizes (< 300 µm) tends to reduce packing efficiency and increase apparent porosity in the consolidated panel, because a narrow size distribution and lack of large particles limit the ability of smaller particles to fill interstitial voids effectively. This is a consolidated concept in the literature, with narrower and more uniform size distributions generally leading to lower random packing densities compared to broader, multimodal distributions that better fill void spaces [24]. After consolidation, the recycled panel displayed a largely continuous and homogeneous surface, indicating good cohesion across the panel (Fig. 1b). Only limited surface defects were detected, mainly localized cracks attributed to stresses induced during the demolding stage.

The surface morphology of the panels fabricated via compression molding, both coated and uncoated, was further examined using optical microscopy to corroborate the visual assessments. The microscopic images are shown in Fig. 2. Microscopic observations reveal effective consolidation and agglomeration of the recycled constituents during direct compression molding. At higher magnification, clusters composed of randomly oriented short carbon fibers, fragmented epoxy matrix, and dispersed metallic inclusions, originating from machining operations on composite components, are clearly identifiable. These metallic residues, commonly present in aerospace-grade CFRP waste, contribute to the intrinsic heterogeneity of the recycled material. Importantly, the absence of large voids or unbonded regions indicates a high degree of densification, demonstrating efficient utilization of the recycled powder and supporting the potential of this approach for producing structurally consistent materials from CFRP waste.

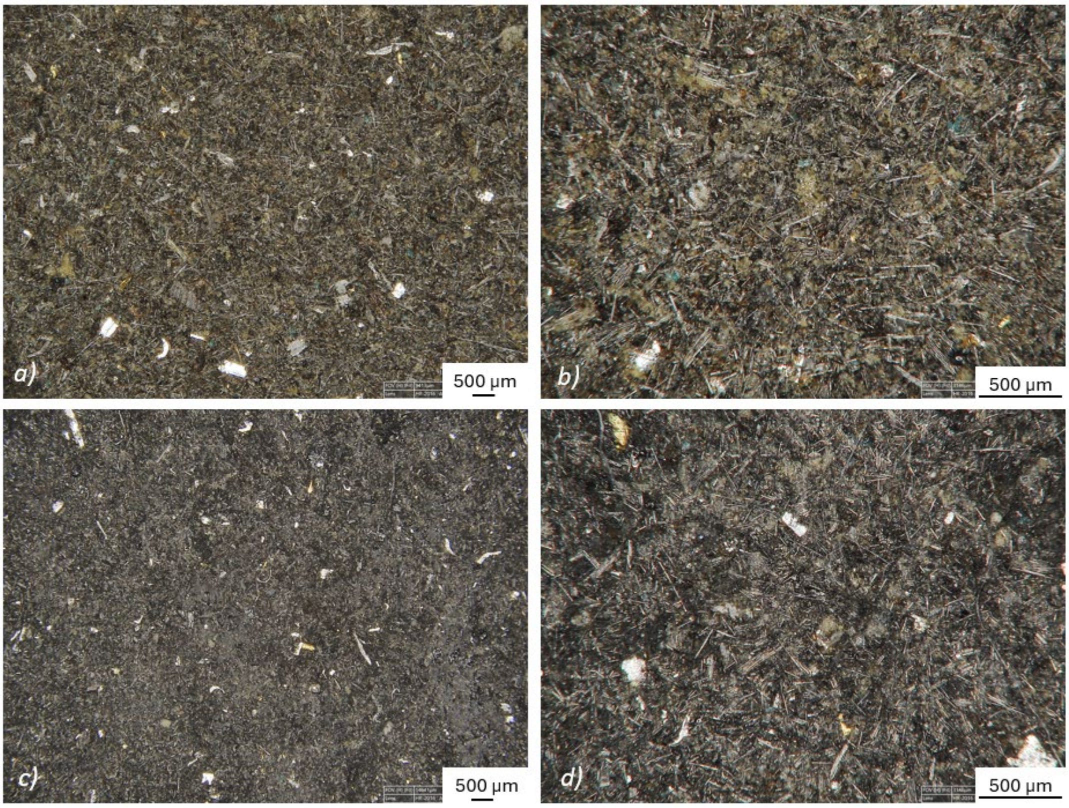

Fig. 2. Microscopic images of the panel surface for the uncoated one (a,b) and coated one (c,d).

An in-depth analysis of the surface morphology was conducted using optical profilometry, and the data for the different profiles examined are reported as mean values with standard deviations in Table 1. The surface parameters highlight a pronounced modification of the surface topography induced by the coating. The areal roughness parameters Sa and Sq are significantly reduced in the coated panel, decreasing from 322 μm to 123 μm and from 413 μm to 149 μm, respectively. This reduction indicates an effective smoothing and leveling of the surface after coating application. Similarly, the peak-to-valley parameter Sz exhibits a substantial decrease, from 2973 μm for the uncoated surface to 878 μm for the coated one, reflecting a marked reduction in overall surface height variations. Consistent with this trend, both the maximum peak height (Sp) and maximum pit depth (Sv) are considerably lower for the coated surface, confirming that the coating effectively fills surface valleys and attenuates prominent asperities. The skewness parameter (Ssk) shifts from a negative value (−1) in the uncoated surface to approximately zero after coating, suggesting a transition from a valley-dominated topography to a more symmetric height distribution. In addition, the kurtosis (Sku) decreases from 4 to 3, indicating a reduction in sharp, extreme surface features and a surface height distribution closer to a normal profile. Overall, these results demonstrate that the coating produces a more uniform and leveled surface morphology, which is expected to influence functional properties such as wettability and interfacial behavior. Furthermore, wettability measurements indicate that the uncoated surface demonstrates a higher contact angle, and thus lower wettability, compared to the coated surface (Table 2). This behavior is consistent with literature reports showing that surface coatings can modify surface roughness and topography, leading to changes in wettability; smoother and more uniform surfaces produced by coatings typically exhibit altered solid–liquid interactions and lower apparent contact angles due to increased effective solid–liquid contact area and surface energy modifications [25]. Moreover, the decrease in the contact angle for the coated sample occurs more rapidly, highlighting a stronger spreading effect. The influence of surface roughness and coatings on wettability is well documented in surface and coatings research, where the interplay between morphology and contact angle is shown to govern wetting behavior.

Table 1. Surface parameters for the uncoated and coated recycled CFRP panel surfaces

Parameter	Uncoated	Coated
Sa	322 µm	123 µm
Sq	413 µm	149 µm
Sz	2973 µm	878 µm
Ssk	-1	0
Sku	4	3
Sp	997 µm	364 µm
Sv	1975 µm	514 µm

Table 2. Contact angle measurements on uncoated and coated recycled CFRP panel surfaces

	CA (°) after 1 s	CA (°) after 30 s
Uncoated	146.7 ± 6.7	138.9 ± 4.9
Coated	108.4 ± 5.7	86.8 ± 5.5

Dynamic-mechanical analysis. Given that, as expected, preliminary analyses have shown that the presence of the coating does not alter the viscoelastic behaviour of the materials considered, the results of the dynamic-mechanical analysis are summarised in Fig. 3 in the form of representative curves. In particular, the dynamic-mechanical analysis of 5 specimens cut from CFRP panels showed the variation of storage modulus (E') and loss factor (Tan δ) as a function of temperature, and the processing of the curves returned the values of the same parameters collected in Table 3. Clearly, the compression-molded material exhibits a high initial stiffness at room temperature (E′ ≈ 1180–1620 MPa) with a progressive drop in stiffness, up to approximately 120–140 MPa, with increasing temperature, particularly marked in the temperature range between 100 and 175 °C (glass transition). The amplitude of this transition phase between the glassy and rubbery states, centered at approximately 167 °C, as evidenced by the Tan δ peak, reflects the heterogeneity of the base waste powders including, among others, short carbon fibers and partially degraded or post-cured thermoset phases.

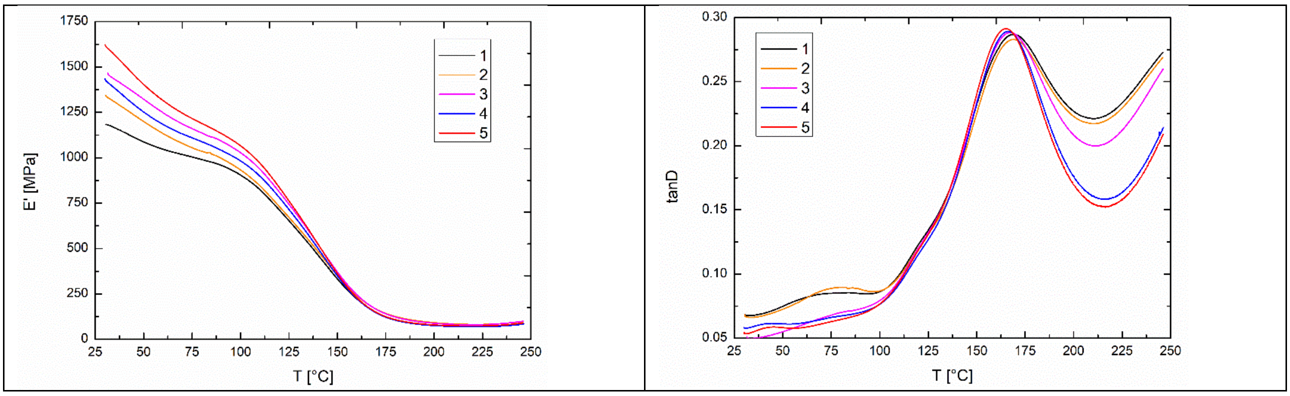

Fig. 3. a) Storage modulus (E’), b) Loss factor (Tan δ).

Table 3. Results of the dynamic mechanical analysis

Sample	E’ at 30 °C [MPa]	E’ at 175 °C [MPa]	T at Tan δ peak [°C]
1	1182.66	141.72	168.64
2	1345.52	142.32	169.84
3	1467.15	140.14	167.26
4	1433.01	121.18	166.11
5	1622.49	124.98	164.97

Thermogravimetric Analysis (TGA). Fig. 4 shows representative TGA curves for processed and unprocessed CFRP powders. Again, the curve processing provided the values of some thermal degradation parameters specific to the CFRP waste before and after the direct molding process (Table 4). Both powders show a multistep decomposition pattern, likely due to concurrent phenomena such as volatile evaporation, resin breakdown, and the formation of stable char and carbon-fiber residue. The processed powder shows higher decomposition temperatures, indicating greater thermal resistance and a more consolidated, fully cured matrix. The lower final residue for the processed sample suggests different char formation behavior due to thermomechanical history.

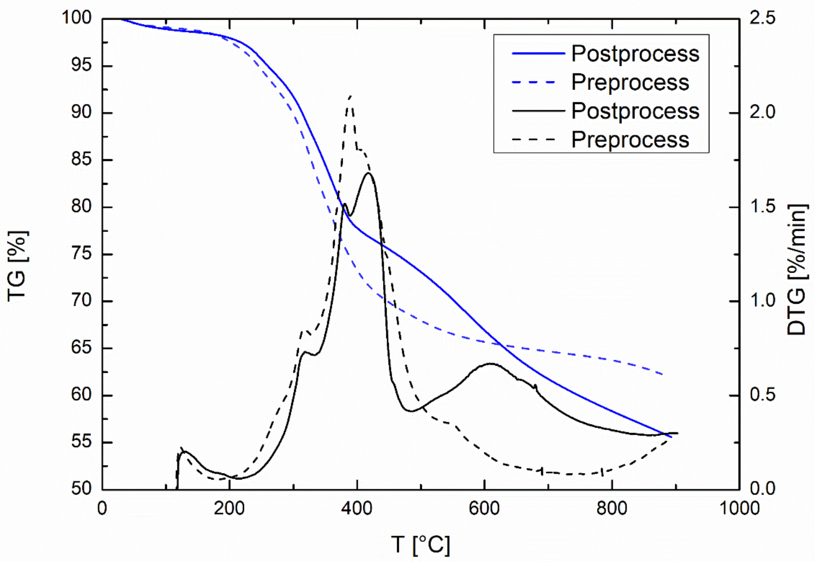

Fig. 4. TGA graph of processed and unprocessed composite powders.

Table 4 Thermogravimetric analysis parameters.

Sample	$T_{2\%}$ weight loss [°C]	T_{peak} [°C]	Residue at 900 °C [%]
Preprocess	188.44	325.28	61.87
Postprocess	198.46	359.23	55.59

Mechanical results. The results of the three-point bending tests are shown in Fig. 5 as load-displacement (Fig. 5a) and stress–strain (Fig. 5b) curves for four representative samples of each composite panel type. The coated samples exhibited a maximum load of 146.8 ± 14.7 N, a maximum flexural stress of 6.1 ± 0.4 MPa and an average flexural modulus of 401.0 ± 12.0 MPa, significantly higher than the 117.4 ± 16.4 N, 4.5 ±0.5 MPa and 332.0 ± 13.8 MPa measured for the uncoated samples, corresponding to an increase of about 21%. The flexural modulus of the recycled CFRP panel without coating was approximately 330.0 MPa. Although significantly lower than that of continuous-fiber CFRP laminates, this value is consistent with the highly discontinuous and porous nature of the recycled material. The short, randomly oriented fibers and limited consolidation efficiency result in a matrix-dominated bending response and reduced load-transfer efficiency. The use of a three-point bending configuration further emphasizes the influence of surface defects and local heterogeneities, which are intrinsic to compression-molded recycled CFRP panels produced from powdered feedstock. The panels with and without coating behaved in a brittle manner, showing no significant plastic deformation or damage precursors prior to fracture, typical of a discontinuous material like this.

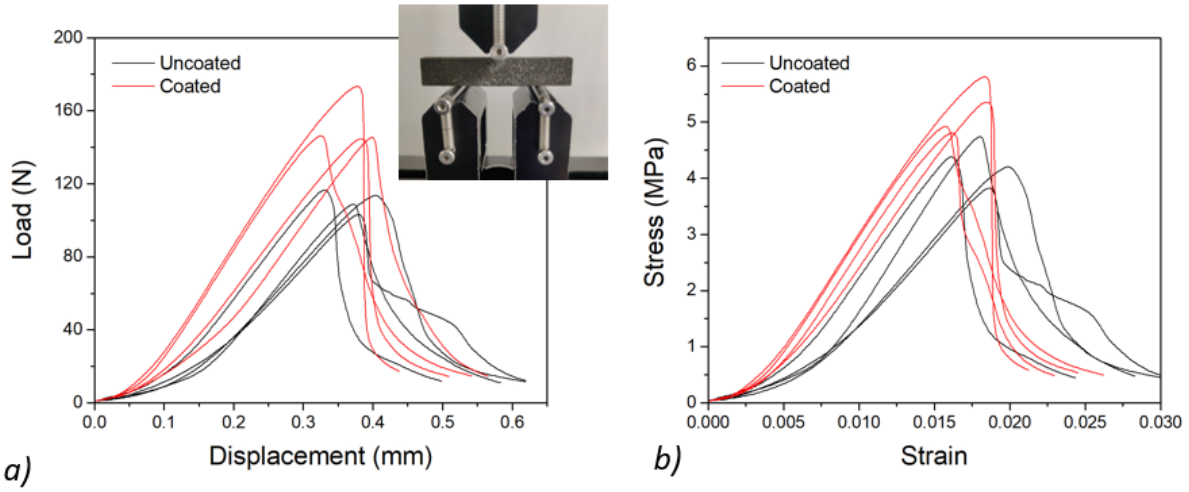

Fig. 5. Load vs displacement (a) and stress vs. strain (b) curves for both panels uncoated and coated.

These findings suggest that, beyond the observed mechanical and surface modifications, the presence of the coating contributes to the development of a more continuous and resistant surface, thereby enhancing the overall performance of the panel. Importantly, the simple application of a thin coating on the top and bottom surfaces of relatively thick recycled panels may significantly expand the potential application range of this class of materials, offering an effective and low-complexity strategy to improve surface-related properties without altering the bulk manufacturing process.

Summary

This work demonstrates that the application of a thin surface coating effectively enhances the surface quality and functional performance of recycled CFRP panels produced via a non-conventional compression molding process based on CFRP powder waste. Surface analyses revealed a significant reduction in roughness and height-related parameters, indicating effective surface leveling and improved uniformity in the coated panels. Mechanical testing under three-point bending confirmed that the recycled panels exhibit a matrix-dominated flexural response, consistent with their highly discontinuous and porous microstructure resulting from the nature of the feedstock material. The application of the coating enhances the bulk mechanical properties, as evidenced by slight increase in the flexural modulus from 330 MPa for the uncoated panel to 400 MPa for the coated one. In addition, the coating markedly improves surface integrity and wettability, contributing to more sturdy and functional panel surfaces. Overall, the results highlight that the simple application of thin coatings on the top and bottom surfaces of thick recycled CFRP panels represents an effective, scalable strategy to extend the applicability of materials produced through non-conventional compression molding, without increasing process complexity or compromising the sustainability advantages of recycled composites.

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