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Assessment of reclaimed carbon dust utilization as a filler in thermoset polymer composites: analysis of strength properties and curing effects

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ABSTRACT

Carbon dust (CD) emerged as a by-product during the machining of carbon fibre reinforced polymer (CFRP) composites, generally relegated to landfills or subjected to partial recycling. The utilization of CD as a filler material in polymer composites is still in its early stages, hindered by difficulties in the reclamation process and in managing the distribution of CD during polymer processing. This study examined the feasibility of utilizing reclaimed carbon dust (rCD) as a substitute filler for virgin carbon fiber in thermoset polymers. The study evaluated the mechanical properties of rCD-filled composites, examined the impact of several curing techniques (vacuum bagging and autoclave), and analyzed the dispersion of carbon dust by scanning electron microscopy (SEM). Samples with rCD content between 0% and 30% were produced, and different curing conditions were assessed. The findings demonstrated that an increase in rCD content resulted in diminished tensile strength, whereas compression strength was enhanced. SEM research indicated that increased rCD content led to insufficient adhesion between the resin and rCD particles, hence lowering tensile strength. Nonetheless, autoclave curing enhanced tensile strength by minimizing void content and porosity. While rCD showed potential for enhancing compression strength, challenges with tensile strength and adhesion highlighted the need for further optimisation of processing parameters and resin compatibility for broader industrial applications.

Keywords: *Reclaimed carbon dust; Mechanical properties; Polymer composite; Thermoset polymer; Curing effects*

1. INTRODUCTION

Carbon fibre composites are extensively utilized across various high-performance industries, including aerospace, automotive, medical devices, sporting goods, and musical instruments, owing to their exceptional strength-to-weight ratio, high tensile strength, substances inertness, and thermal resistance. Carbon fibres are often incorporated into thermoset polymer matrices, yielding advanced composites that satisfy the high requirements for performance of these industries [1-2]. However, the incorporation of thermoset polymers presents a significant challenge for recycling due to their cross-linked molecular structures, which are difficult to decompose once cured. This constraint restricts the improvement of sustainable recycling techniques for carbon fibre composite materials [3-4]. The machining of carbon fibre composites—via techniques such as milling, trimming, or drilling—generates harmful carbon dust. This dust generally varies from 2.2 to 99 μm in diameter and presents multiple health and safety issues. Inhalation of tiny particles might result in respiratory difficulties, whereas contact with the skin can lead to irritation. Moreover, owing to its electrical properties, carbon dust can cause faults in electronic devices if not properly maintained. Existing techniques for managing carbon dust, such as landfilling, inadequately address these issues and frequently increase environmental degradation. Despite carbon's recognized high strength, recycled carbon fiber undergoes mechanical processing, resulting in variations in size and strength compared to virgin fiber [2,6]. While the recycling of carbon fibre has been investigated, the majority of initiatives concentrate on fibre recovery instead of repurposing carbon dust as a multifunctional filler [7].

With the rising global demand for carbon fibre goods, especially in high-technology industries such as aircraft and on-shore sectors mainly for wind energy, the necessity for sustainable management and recycling of carbon fibre machining waste is becoming increasingly critical. Recent studies have examined the integration of recycled carbon dust (rCD) as a filler material in thermoset composites to address this gap. Studies indicate that the incorporation of rCD will improve the mechanical characteristics of composites, including an increase in elastic modulus and enhancement of electromagnetic properties [1]. The research conducted by Francesco et al. [8] revealed that an important variable affecting the mechanical mainly in strength properties of composite materials is the existence of voids or air pockets created during the curing process. During curing, the filler must be uniformly distributed inside the polymer matrix to ensure homogeneity in the final product [9]. This uniform dispersion is particularly vital when incorporating filler materials, as it directly

affects the structural stability and consistency of mechanical properties across the composite. Improper regulation of processing parameters during curing may result in void development, degrading material performance. There is a lack of study on polymer composites with reclaimed carbon dust, which is produced in substantial quantities during aluminum manufacturing, and there is an absence of adequate performance data. Therefore, comprehending the correlation among curing conditions, mixture uniformity, and void formation is crucial for enhancing the strength properties of carbon dust-reinforced composites.

Previous research by Luigi et al. [11] indicated that pressure control during autoclave curing substantially influences void content and, as a result, the mechanical strength of composite structures. Additionally, Darshil et al. [12] presented similar results, highlighting the significance of pressure regulation, while McNally et al. [13] investigated regenerated short carbon fibers in polyethylene as matrices in composites. Notwithstanding these insights, the behavior of composites with carbon fiber dust under identical conditions remains unexamined. Due to the fine and easily dispersible nature of carbon dust, it is vital to examine the impact of curing parameter modifications on its distribution inside thermoset matrices. Poor bonding between the rCD filler and the matrix, resulting from uneven dispersion, results in decreased tensile strength. The irregular distribution generates weaknesses that impair the material's ability to transmit stress, hence compromising its overall efficacy [14-15]. A systematic experimental methodology is necessary to ascertain the appropriate processing conditions, perhaps leading to a dependable technique for curing polymers strengthened with recycled carbon dust filler. Nonetheless, limitations continue in refining the filler loading and curing techniques to attain the required characteristics of performance [16-17].

Due to its easy dispersion into the atmosphere, studies show that carbon dust poses more handling and environmental issues than fiber form. However, because of its small particle size and large surface area, reclaimed carbon dust has substantial advantages over fiber form as a fine filler material in composite applications. Because of this, carbon dust is very useful for improving the qualities of composites while also lowering waste and environmental effect. This study aims to assess the impact of different rCD loadings and curing techniques on the mechanical characteristics and microstructure of thermoset composites. The study intends to determine an optimal combination of filler content and curing conditions using field emission scanning electron microscopy (FESEM) and acoustic non-destructive testing (NDT). The new approach has the potential to establish a systematic recycling process that transforms hazardous carbon dust waste into high-performance composite materials. The study promotes circular economy concepts by converting industrial waste into value-added products.

2. METHODOLOGY

2.1. Restoration Process of Carbon Dust (CD) waste

The composition of the carbon dust (CD) waste used in this study is not reported due to confidentiality and it was sourced from the aircraft industry. The maximum percentage purity of the carbon dust sample can be achieved by eliminating residual substances from the carbon fibre-reinforced polymer (CFRP) laminate where the material underwent a detailed sieving using mesh sieve shakers with sizes of 35 µm, 63 µm, and 75 µm (Figure 1(a)). Extraneous elements in carbon waste may compromise the accuracy of experimental results. Consequently, the carbon dust was characterized through X-ray Diffraction (XRD) and Field Emission Scanning Electron Microscopy (FESEM) to verify its purity and higher carbon content, as depicted in Figure 1(b).

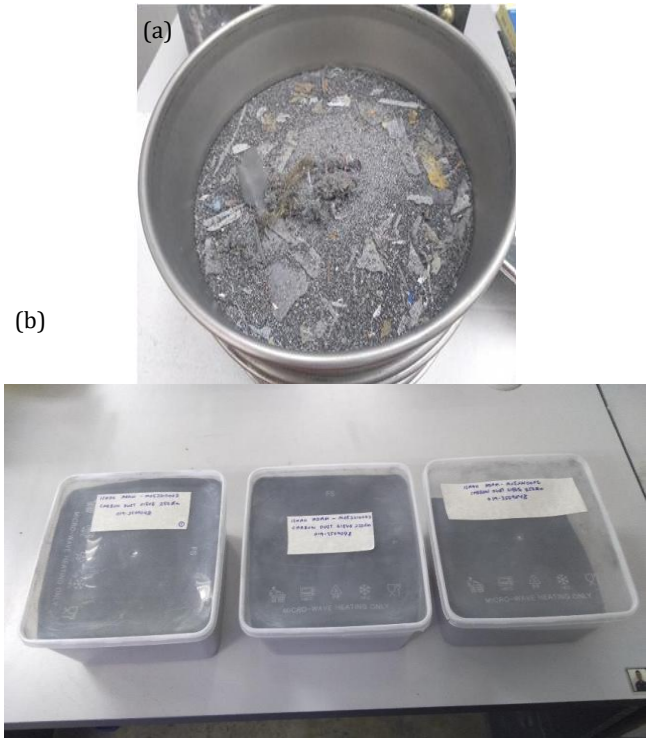


Fig. 1. (a) Sieving of carbon dust waste using 35 µm, 63 µm, and 75 µm mesh sieve shakers to remove foreign particles and ensure sample purity (b) reclaimed carbon dust (rCD) after sieved.

The elemental composition and surface morphology of the reclaimed CD were examined using a field emission scanning electron microscope equipped with energy dispersive X-ray spectroscopy (FESEM-EDX, Hitachi SU5000). Phase identification of the reclaimed carbon dust was performed via X-ray diffraction (XRD, Rigaku MiniFlex), using Cu Kα radiation (λ = 1.54050 Å) under a scanning range of 20° to 80° (2θ) at a scan rate of 2° per minute with a fixed step size. The crystallographic structures and

associated peak intensities were evaluated to determine the presence of carbon and any residual phases. In cases where non-carbonaceous impurities were detected post-characterisation, an additional sieving cycle was conducted to improve purity. Once the material was confirmed to be free of foreign contaminants, it was categorised as reclaimed carbon dust (rCD). The average particle size distribution of the rCD was subsequently quantified using a particle size analyser (PSA).

2.2. Reclaimed Carbon Dust (rCD)/thermoset polymer composite

The sample fabrication process in this research was carried out in four phases: material preparation, lay-up, curing, and machining. Each phase was executed sequentially to ensure the production of test specimens in the required final geometry for subsequent mechanical testing. An overview of the fabrication procedure is illustrated in Figure 2.

Epolam 2017 epoxy and Epolam 2018 hardener were chosen to complement the resin, offering suitable reactivity and compatibility for the intended applications. The resin and hardener were mixed by weight as tabulated in Table 1.

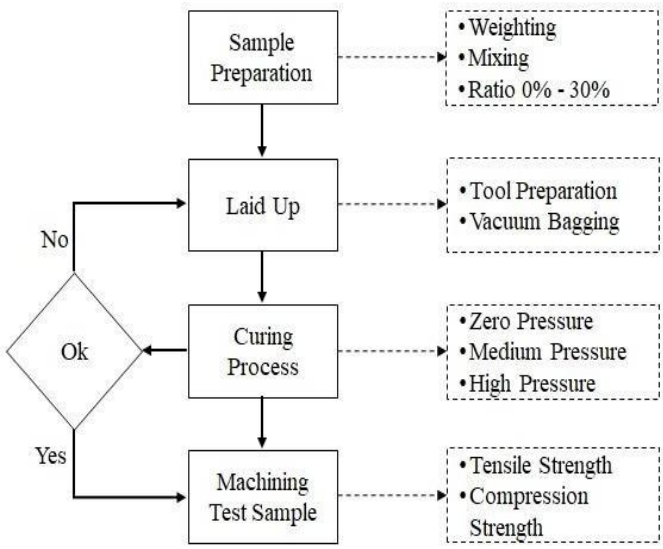


Figure 2. Flow of the fabrication

The mixing process involved weighing the components using an analytical balance and combining them in a clean container. Reclaimed carbon dust (rCD) was then incorporated into the resin-hardener mixture at varying volume fractions (0%, 10%, 20%, and 30%) to evaluate its effect as a filler material. The mixtures were stirred manually at consistent movement for 3 minutes at room temperature to prevent bubbles, and degassed under vacuum for 5 minutes.

During preliminary trials, a mixture containing 40% filler loading was attempted; however, the high viscosity and insufficient mixing led to a dry, lumpy consistency, indicating poor dispersion and inadequate homogeneity. Consequently, a 30% filler loading was determined to be the maximum viable concentration for achieving uniform distribution and maintaining processability.

Table 1 The ratio of mixing for matrices

Epoxy Resin/Hardener	Mixing Ratio by Weight	Mixing Ratio by Volume
Epolam 2017	100	30
Epolam 2018	100	35

The fabrication process is detailed in Figure 3. The curing parameters employed during the autoclave process were established in accordance with the selected epoxy resin, supplemented by experimental requirements related to process control. As outlined in Table 2, the primary variable under investigation during autoclave curing was the applied pressure. To evaluate the influence of pressure on the quality and mechanical properties of the composite, three distinct curing trials were conducted, each applying a different pressure level: 0 kPa (atmospheric), 400 kPa, and 600 kPa. These variations were selected to assess their impact on void content, resin flow, and the homogeneity of the composite material.

Figure 3. Schematic representation of the experimental methodology performed in this study

Table 2 Parameter of curing process

Parameter/Trial	1st	2nd	3rd
Cure Temperature, °C	120	120	120
Heating Rate, °C/min	0.5 – 1.0	0.5 – 1.0	0.5 – 1.0
Cure Time, min	120	120	120
Cure Pressure, kPa	0 (zero pressure)	400 (medium pressure)	600 (high pressure)
Cooling Rate, °C/min	0.5 – 1.0	0.5 – 1.0	0.5 – 1.0
Vacuum, kPa	Vent to Atmosphere	Vent to Atmosphere	Vent to Atmosphere

2.3. Analysis of Strength Properties and Fractography

Samples were examined using FESEM to assess the distribution of rCD within epoxy polymer before vacuum bagging processes to prepare specimens for mechanical testing using a universal tensile machine (Shimadzu), following ASTM D3039 standards, and the modulus value was measured via NDT measurement using standard E494-95 (Olympus Epoch 600 NDT A-Scan Equipment). Five specimens from each batch composition were evaluated, and average strength properties and NDT were recorded.

A field emission scanning electron microscope (FESEM, Hitachi SU500) was used to observe fractography on initiation failure and morphological behaviour of the samples. A gold sputter was used to coat all specimens and observations were conducted at magnifications ranging from 10× to 500×. The correlation between the strength properties and the microstructure of each sample was examined.

3. RESULTS AND DISCUSSION

3.1. Reclamation of Carbon Dust Analysis

Figure 4(a) provides a detailed analysis of the particle size distribution of reclaimed carbon dust (rCD), illustrating a wide size range from 0.634 µm to 174.1 µm. The particle size distribution indicates that the majority of rCD volume is concentrated between 15.16 µm and 24.70 µm, accounting for approximately 23.66% of the total, which demonstrates a relatively fine and narrow size band within the broader distribution.

This concentration is beneficial for composite applications, as it supports consistent dispersion within the epoxy matrix, reducing the risk of agglomeration. The sieving through 35 µm, 63 µm, and 75 µm meshes further ensured particle uniformity and prevented the inclusion of oversized debris. The values of 8.071 µm, 22.97 µm, and 53.66 µm, respectively—emphasize the fine nature of the powder, suggesting a suitable particle gradation for composite manufacturing. The comparison with Irshidat *et al.*, [10], who reported 50% of carbon dust particles under 80 µm, emphasizes the compatibility and improved refinement of the current rCD, remaining well below this benchmark and supported by Eckart & Paul [18]. The particle size analysis reveals that most carbon dust particles range between approximately 100–200 µm indicating a broad and coarse distribution. Compared to previous studies [10;18], recycled or mechanically ground carbon dust typically shows a wide and irregular size range due to fragmentation and agglomeration during processing, while finer particle sizes (below 100 µm) are often achieved through additional milling or sieving. This relatively coarser carbon dust may affect dispersion uniformity, interfacial bonding, and ultimately the mechanical performance of composites.

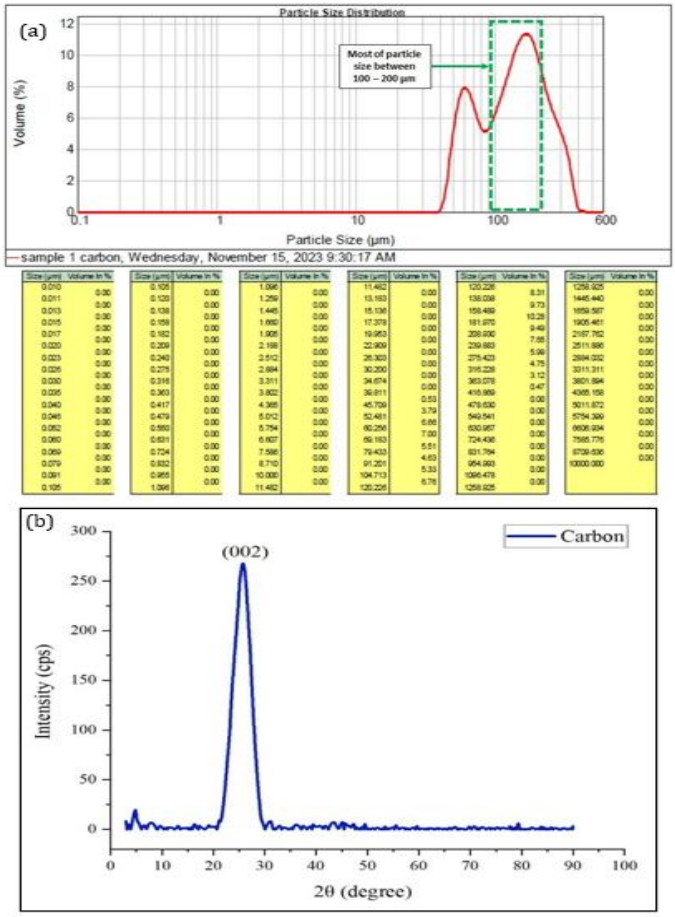
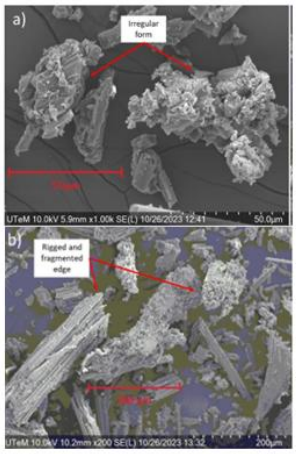


Figure 4. Characterization of the carbon dust via a) particle analyser and b) x-ray diffraction

The FESEM images, captured at magnifications of 1000X and 200X (Figure 5(a)), provide valuable insights into the size, shape and surface characteristics of the particles. The images reveal that the majority of rCD particles exhibit rigid edges and irregular forms, with an average size range between 50 µm and 200 µm. These irregular shapes are likely a direct consequence of the rough machining process used to generate the rCD from CFRP (carbon fiber reinforced polymer) waste.

The irregularity in particle shape is an expected result of the trimming and crushing processes applied to CFRP, which are inherently rough and likely to produce fragmented, jagged particles rather than uniformly shaped ones. This finding aligns with Dominic *et al.,* [19] and aligned with Irshidat *et al.* [10] who also reported that rCD particles exhibit fragmented, irregular shapes with ragged edges when captured via FESEM. Such irregular shapes, while not ideal for uniform dispersion in some applications, may still offer potential advantages in composite materials, where the interlocking of angular particles could improve mechanical properties. However, the irregularity also introduces challenges, especially in terms of particle dispersion and agglomeration. As noted in the images, some rCD particles appear agglomerated, a phenomenon that can occur due to electrostatic interactions between the particles. During sieving, particles often acquire an electrostatic charge, which can cause attractive forces to overcome repulsive forces, leading to particle clustering. This agglomeration can complicate the homogeneous mixing of rCD in matrix materials like epoxy resins, potentially reducing the effectiveness of the material as a filler in composite applications.

The data presented in Figure 5(b) show that the average atomic percentage of carbon in rCD is around 90%, which is considered high purity. Although the weight percentage of carbon is reported as 75.70%, the atomic percentage is emphasized as a more accurate representation of the carbon content, given its direct correlation to the number of carbon atoms in the rCD mixture. This high carbon content suggests that rCD is predominantly composed of carbon, which is a favorable characteristic for its application as a carbon dust filler in composite materials [19].



No Sample	Carbon Element	
	Weight, %	Atomic, %
1	79.90	90.60
2	66.87	87.87
3	67.83	85.57
4	74.37	91.97
5	70.90	90.23
6	79.03	89.73
7	81.03	91.30
8	78.17	90.43
9	83.63	92.27
Average	75.70	90.00

Figure 5. FESEM micrograph shows (a) a microstructure and (b) summary elemental analysis of reclaimed carbon dust

Referring to Figure 5(b), the high carbon content further suggests that the purification process during sieving has been effective in isolating a carbon-rich material from the CFRP waste, making rCD a viable candidate for reinforcing polymers. It is also worth noting that the purity and crystalline structure of rCD, previously confirmed by X-ray diffraction (XRD) analysis, likely contribute to the enhanced performance of rCD as a filler material.

3.2. Correlation Between Tensile Strength-Microstructure and Curing Pressure

The influence of reclaimed carbon dust (rCD) filler content and curing pressure on the tensile strength of thermoset composites was critically analyzed by testing samples cured at 0 kPa (no pressure), 400 kPa (medium pressure), and 600 kPa (high pressure), across varying rCD loadings (0 wt.%, 10 wt.%, 20 wt.%, and 30 wt.%). Results revealed a clear and consistent decline in tensile strength with increasing rCD content, regardless of curing pressure, with the highest strength always observed in the 0 wt.% sample as illustrated in Figure 6.

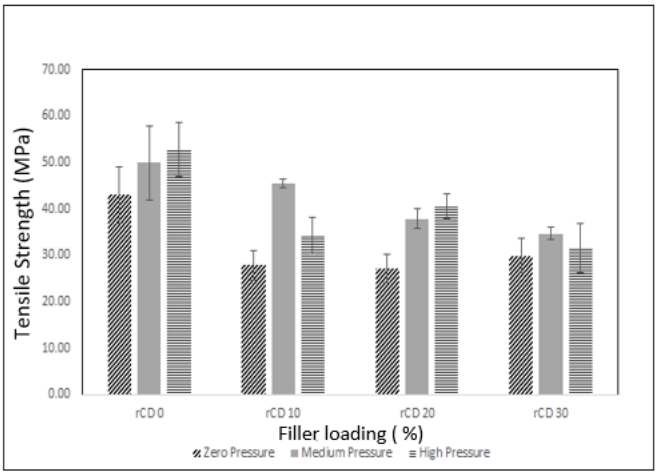


Figure. 6. Summary of comparison for tensile strength between each pressure condition.

This trend aligns with previous studies, such as those by Azmi [20] and Hardinnawirda & Aisha [21], which attribute the reduction in strength to poor filler–matrix adhesion and increased micro-spaces at higher filler contents. Fractography analysis (Figure 7) further confirmed these observations: samples with higher rCD content exhibited progressively more severe structural defects, including weak interfacial bonding at 10 wt.%, significant porosity and debonding at 20 wt.%, and major voids, cracks, and surface degradation at 30 wt.%. Although increasing the curing pressure improved compaction and marginally enhanced tensile strength, it was insufficient to counteract the negative effects of excessive rCD, as interfacial quality remained the dominant factor. Additionally, higher filler loadings led to surface defects and potential moisture entrapment, which can serve as initiation points for premature failure. Therefore, the declining tensile strength with increasing rCD content is attributed to poor interfacial bonding, increased porosity, higher defect density, and incomplete stress transfer.

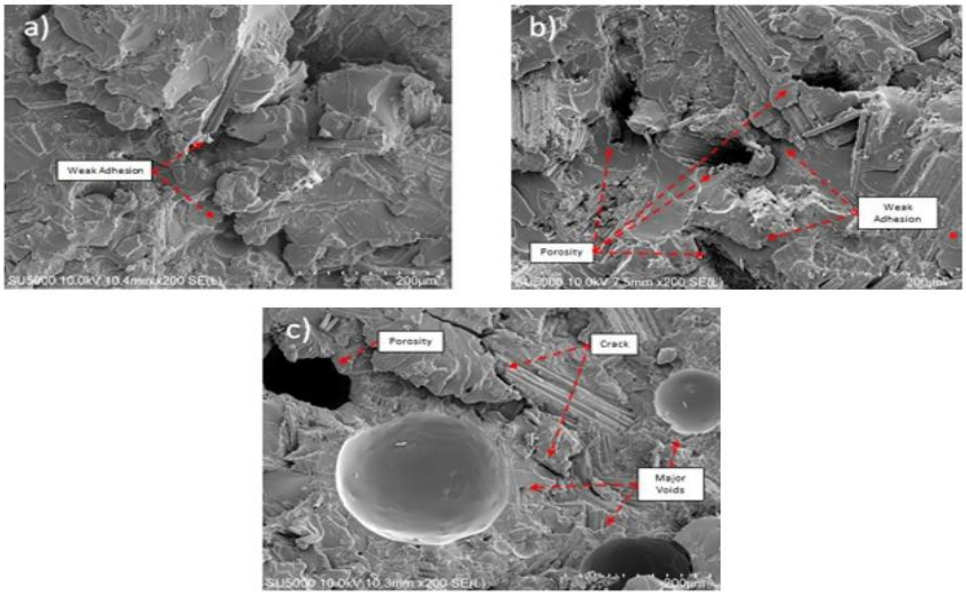


Figure. 7. Images of fractography surface at a) rCD 10 wt.%; b) rCD 20 wt.%; c) rCD 30 wt.%

This can be related to the Figure 5(a) where irregular and jagged rCD particles increase the interfacial area which can enhance compressive load or stress transfer. However, these jagged morphologies also introduce sharp edges and corners and non-uniform stress distribution around the particle, which act as local stress raisers.

While curing pressure offers some improvement, it cannot fully compensate for the structural issues caused by excessive filler, highlighting the need to limit rCD loading to below 10 wt.% to ensure a balance between sustainability and mechanical performance [21] These findings contrast with those reported by McNally *et al.* [13], who observed an increasing trend of tensile strength in PE/rCF composites as the content of recycled carbon fiber was raised approximately to 30 wt.%. According to Figure 6, there is a clear correlation between curing pressure and tensile strength, where increasing the curing pressure generally leads to higher tensile strength in thermoset composites. Across all rCD content levels, tensile strength tends to improve with higher curing pressures, except for the samples containing 10% and 30% rCD under high pressure.

These exceptions are likely due to internal defects, as discussed earlier, which may have caused premature failure. Overall, the results indicate that increasing rCD content reduces tensile strength, while increasing curing pressure enhances it, emphasizing the need to balance filler loading and processing conditions to achieve optimal mechanical performance. Some results did not follow the expected decreasing trend in tensile strength, such as the 10 wt.% rCD sample at zero pressure and the 30 wt.% rCD sample at high pressure. For these outliers, Figure 8(a) and Figure 8(b) present the corresponding fractography surfaces. In Figure 8(a), the surface of the 10 wt.% rCD sample at medium pressure appears smooth with minimal voids, which likely contributes to its relatively higher tensile strength and affects the overall group average. Conversely, the 30 wt.% rCD sample at high pressure, shown in Figure 8(b), displays numerous defects including voids, porosity, and a rough surface texture. These flaws may have weakened the sample and resulted in lower-than-expected tensile strength, deviating from the general trend observed in other samples.

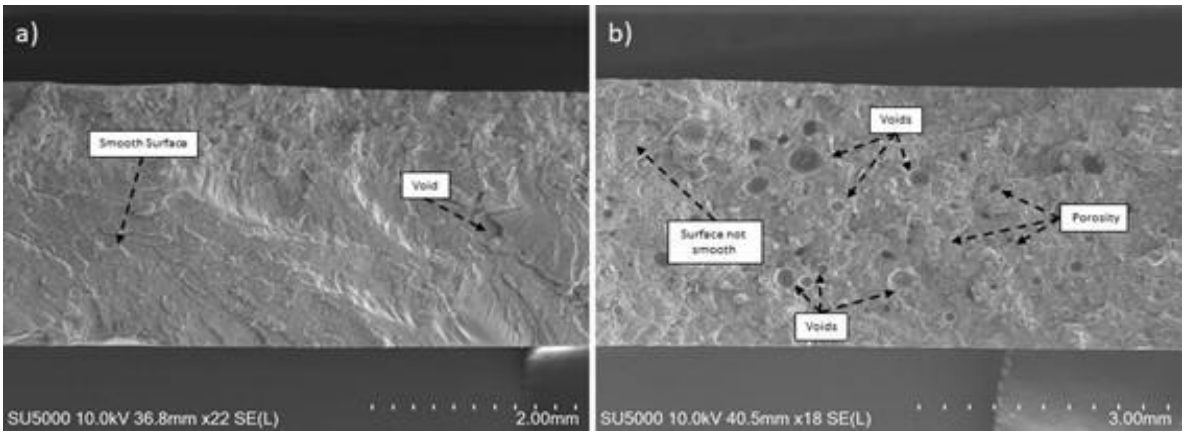


Figure 8. Images of fractography for a) rCD wt.10% at medium and b) rCD wt.30% at high pressure.

3.3. Correlation Between Compression Strength-Microstructure and Curing Pressure

For compression strength properties, the sample data were first analyzed based on curing parameters, namely zero pressure, medium pressure, and high pressure and before evaluating the overall effect of rCD content within the test samples. Based on Figure 9(a), the compression strength shows an increasing trend as the rCD content rises. The mean value for the sample group with zero rCD content (0.00%) with curing at zero pressure, shows the lowest compression strength at 76.94 MPa. When the rCD content increases to 10 wt.%, the strength rises to 87.50 MPa, an increase of 13.72%. The compression strength continues to increase to 89.94 MPa, a 2.75% rise, when the rCD content is further increased to 20 wt.%. However, at 30 wt.% rCD content, the compression strength drops to 80.16 MPa, a decrease of 10.88%. According to Figure 9(b), the compression strength shows an increasing trend as the rCD content rises after sample cured at medium pressure. The mean value for the sample group with zero rCD content (0.00%) shows the lowest compression strength at 82.66 MPa. The strength value slightly increases to 82.78 MPa, a 0.13% rise, when the rCD content is increased to 10 wt.%. The compression strength continues to increase to 85.93 MPa, a 3.81% rise, when the rCD content is increased to 20 wt.%, and ultimately reaches its maximum value of 88.77 MPa, a 3.30% increase, when the rCD content is raised to 30 wt.% under medium pressure. All compression strength data were derived from the mean values of each sample, based on the percentage of rCD particle content, as shown in Figure 9 (c).

From the overall comparison, the data reveals an increasing trend in compression strength as the rCD content rises. The sample with zero rCD content (0.00%) shows the lowest compression strength at 78.69 MPa. When the rCD content is increased to 10 wt.%, the compression strength rises to 85.28 MPa, representing an 8.37% increase. For the sample with 20 wt.% rCD content, the compression strength slightly increases again to 85.87 MPa, a 0.70% rise. However, at 30 wt.% rCD content, the compression strength drops to 82.88 MPa, a 3.41% decrease, which deviates from the previous trend of increasing strength. The variation at increased rCD content may be attributable to various variables, such as potential difficulties in the dispersion of rCD particles within the matrix or the formation of flaws at increased filler loadings. As the content of rCD increases, there may be greater porosity or reduced interfacial bonding between the rCD particles and the matrix, which could result in weaker overall mechanical properties. This peculiarity emphasizes the need of optimizing filler content to prevent diminishing returns in material performance, as excessive filler can compromise the structural integrity of the composite [22]. The identified trend highlights the necessity for thorough regulation of rCD loading to properly balance enhancements in strength with possible material limitations. Overall, rCD fillers improve compressive strength by densifying the matrix, as particle–matrix interfaces are less critical under compression, but under tension, weak bonding or particle agglomeration can cause debonding and cracks, reducing tensile strength unless dispersion or surface treatment is optimized.

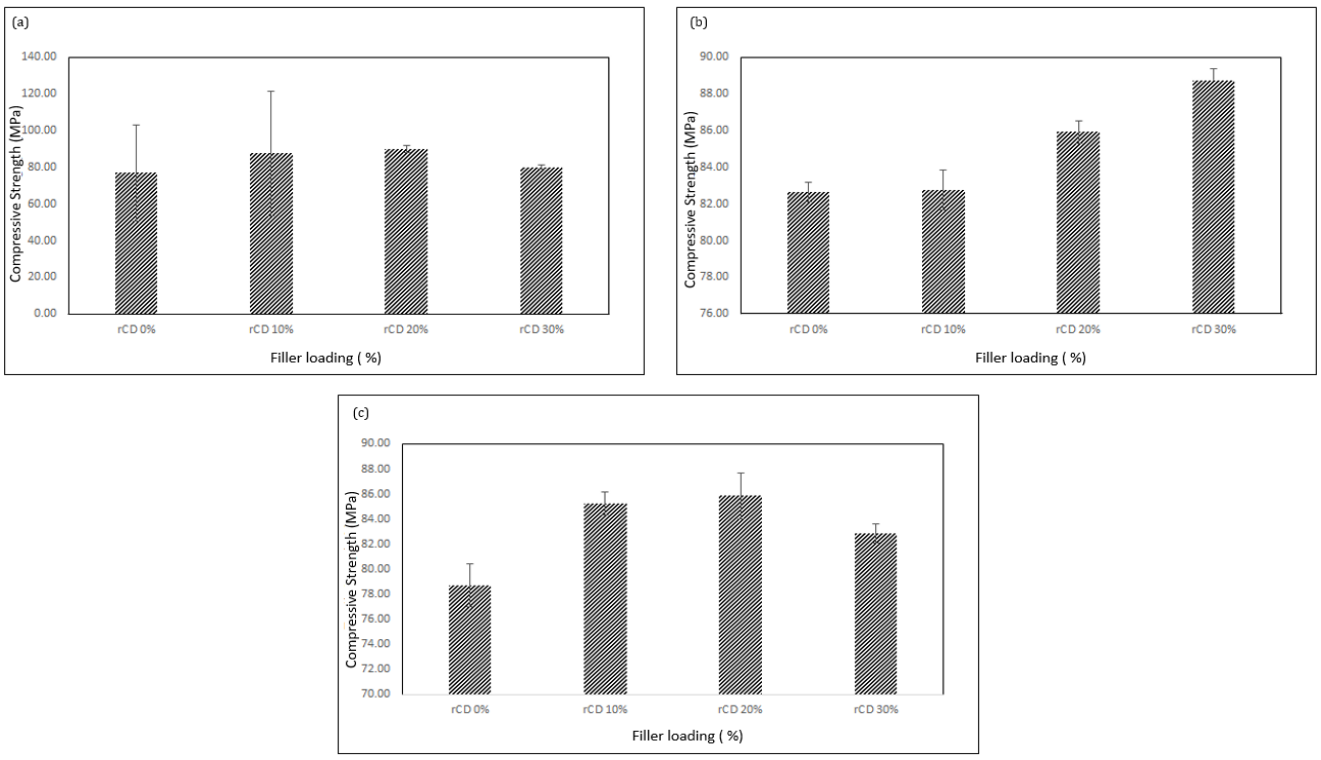


Figure. 9. Compressive strength with varying curing pressures a) zero b) medium c) high pressure

3.4. Modulus Via Non-Destructive Testing

The Young's modulus values were calculated according to standard E494-95. Each test specimen was scanned using Non-Destructive Testing (NDT) A-Scan, and its wavelength image was captured. The details from these NDT scan images were then analyzed to extract the necessary parameters for calculating Young's modulus. The mean value for each test specimen was tabulated as shown in Table 3. Analysis from this data, indicates that the Young's modulus values at medium pressure curing conditions are the highest compared to zero and high-pressure curing conditions. Specifically, the sample AC1.4 achieved the highest mean Young's modulus value at 47.92 MPa, while the lowest mean value was observed in sample ST3.0 under zero-pressure curing, at only 5.62 MPa. Across all curing pressure parameters, the sample with the highest rCD content (30%) consistently exhibited the lowest Young's modulus values, as illustrated in Figure 10. Using autoclave curing more effectively reduces voids because the applied pressure compresses trapped gases, improves resin infiltration, and enhances consolidation between the fillers and the matrices.

The lower porosity of autoclave-processed composites may lead to improved load transfer, which directly affects tensile strength and Young's modulus as compared to vacuum-bagging approach. However, higher void content can be developed from the agglomeration of rCD particles that can weaken the matrix–particle interface and reduce these mechanical properties [22]. This trend suggests that increasing rCD content results in a reduction in the stiffness of the composite material, particularly at higher filler loadings. The decrease in Young's modulus with increasing rCD content may be attributed to poor interfacial bonding between the rCD particles and the epoxy matrix, leading to a more flexible and less rigid material. Additionally, the lower modulus values observed at zero-pressure curing conditions highlight the potential impact of curing pressure on the material's overall stiffness (Figure 10). Medium pressure seems to enhance the interaction between the filler and matrix, resulting in increased stiffness values, but high-pressure factors may cause excessive compaction that adversely influences the material's structural attributes. The result emphasizes the significance of rCD content and curing conditions in influencing the mechanical characteristics of the composite material.

Table 3 Variation of Young's modulus as a function of curing pressure

No.	Sample Code	Curing Pressure (kPa)	rCD content (%)	Young Modulus, (MPa)
1	AC0.0		0%	7.46
2	AC1.0	Zero Pressure	10%	11.58
3	AC2.0	(0)	20%	16.16
4	AC3.0		30%	5.62
5	AC0.4	Medium Pressure	0%	29.13
6	AC1.4	(400)	10%	47.92
7	AC2.4		20%	29.42
8	AC3.4		30%	13.80
9	AC0.6	High Pressure	0%	12.06
10	AC1.6	(600)	10%	15.84
11	AC2.6		20%	11.23
12	AC3.6		30%	7.04

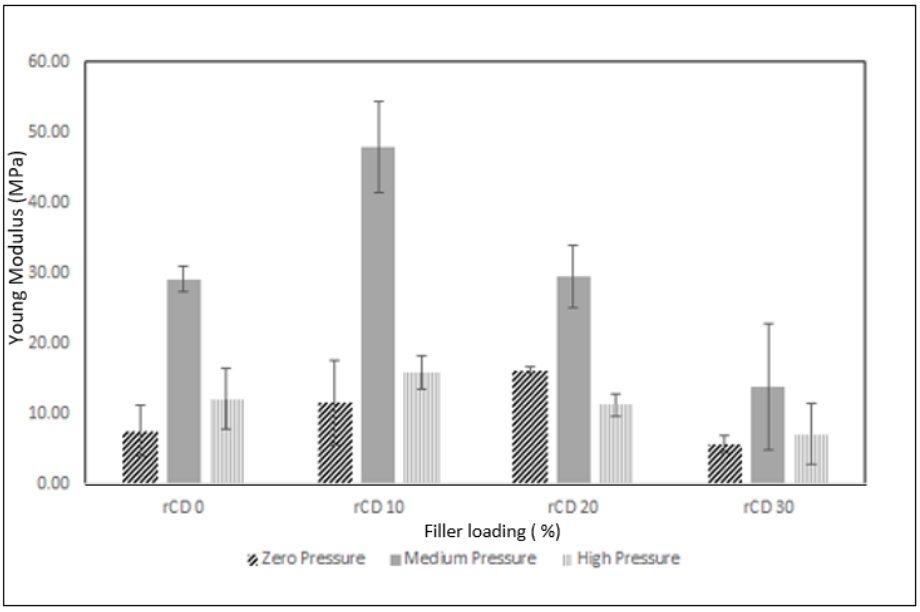


Figure. 10. Compression strength at different curing pressure a) zero b) medium c) high pressure

4 CONCLUSIONS

The research effectively met its goals by illustrating the influence of varying rCD loading and curing pressure on the strength properties of thermosets, with results from multiple methodologies verifying one another to offer a thorough comprehension of the material's behavior under different conditions. Future investigations may concentrate on examining the long-term durability and sustainability of thermoset composites with varying recycled content levels and curing pressures. Research should focus on optimizing filler content and curing conditions to achieve a balance between mechanical performance, cost-effectiveness, and sustainability, while also exploring the possibilities of integrating rCD with other fillers to improve material attributes. The results indicate that thermoset composites with regulated rCD content and optimum curing conditions possess considerable potential for industrial applications, including automotive, construction, and packaging, where high compressive and tensile strength are critical. Moreover, employing recycled carbon dust (rCD) as a filler enhances mechanical qualities while fostering sustainability through the integration of waste materials into valuable goods. With additional refinement, these composites demonstrate significant promise for commercialization, yielding both economic and environmental advantages.

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