Penerbit Akademia Baru

Journal of Advanced Research in Micro and Nano Engineering

Journal homepage: https://www.akademiabaru.com/submit/index.php/armne/index
ISSN: 2756-8210

Assessing the Correlation Between the Physico-Mechanical Characteristics and Microstructure of Reclaimed Carbon Dust Reinforced ABS Polymer Composite in the Extrusion Process

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ARTICLE INFO

Article history:
Received 5 May 2024
Received in revised form 11 June 2024
Accepted 27 July 2024
Available online 31 August 2024

Keywords:
Reclaimed carbon dust; CFRP waste; polymer composite; strength properties; extrusion process

ABSTRACT

ABS polymer has limited stiffness and will fracture upon reaching this limit. Reinforcing ABS with reclaimed carbon dust (rCD) from CFRP waste, which has superior stiffness in both compression and tension, can prevent this failure. This study evaluates the impact of varying rCD filler content and screw extruder speeds on the physico-mechanical properties of the composite. rCD content ranges from 0 wt.% to 40 wt.% and screw speeds of 20 rpm and 40 rpm are used. The rCD was sieved and its quality was verified using particle size analysis (PSA), field emission scanning electron microscopy with energy dispersive X-ray (FESEM-EDX), and X-ray diffraction (XRD) before composite fabrication in a single screw extruder. The physico-mechanical properties, including tensile strength, Young's modulus, and density, were tested using a universal testing machine (UTM) and Archimedes technique. All samples appeared undistorted prior to UTM evaluation. Results indicated that composites processed at 40 rpm with 40 wt.% rCD exhibited superior physico-mechanical properties compared to those processed at 20 rpm. Fractography of tensile fracture samples showed well-dispersed rCD within the ABS matrix, with minimal large pores at 40 rpm. Additionally, the highest tensile strength (31.48 MPa) and Young's modulus (1.603 GPa) indicated good dispersion of rCD and strong interfacial bonding between the matrix and fiber. Thus, a 40 rpm screw speed is more effective for mixing ABS/rCD composites. In conclusion, rCD was successfully reclaimed and integrated into ABS, resulting in a composite with enhanced strength properties suitable for assistive medical device application.

1. Introduction

In recent years, industries worldwide, including oil and gas, aerospace, medical technology, alternative energy, food handling, and material conveying, have increasingly adopted acrylonitrile butadiene styrene (ABS) polymer for various applications. ABS is valued for its affordability, reliability,

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https://doi.org/10.37934/armne.22.1.1125

and versatile properties suitable across diverse sectors [1]. It excels in applications needing strong, rigid plastics with high impact resistance, heat resistance, and stiffness, making it a viable substitute for metal in medical devices' structural components as stated by Rankouhi [2] and Harris *et al.,* [3]. However, ABS's limited stiffness can cause fractures when its threshold is exceeded. Research by Sabah *et al.,* [4] shows that ABS's mechanical properties degrade under stress, particularly due to notches. This issue can be mitigated by reinforcing ABS with materials like reclaimed carbon dust (rCD), derived from the trimming of carbon fiber reinforced polymer (CFRP), which offers superior stiffness in compression and tension [5].

Various industries effectively recycle CFRP waste through methods such as electrical, chemical, thermal, and mechanical processes [6]. Meredith *et al.,* [7] have mentioned that mechanical recycling was the simplest method, involving grinding CFRP into powder, particularly suitable for thermoplastic polymers. This process allows shredded composites to blend with virgin polymers, reheating them to form new materials. It includes steps like grinding and sieving to separate carbon fibers from the resin matrix which is supported by Khalil [8]. However, mechanically recycled carbon fiber typically varies in size and strength compared to fresh fiber [6,9]. Despite this, recycling CFRP waste remains crucial to obtain reclaimed carbon fiber, known as carbon dust, generated significantly in aluminum production [10]. Converting carbon dust into reclaimed carbon dust (rCD) requires precise methods to separate it from other CFRP trimming waste. Studies suggest that incorporating recycled carbon fiber improves the mechanical properties of polymers [11]. It is anticipated that reclaimed carbon dust will enhance ABS's mechanical properties, addressing limitations in applications due to improved strength.

The strength of composites significantly depends on filler content, with rCD used as reinforcement in this study according to the rule of mixtures. However, exploring reclaimed carbon dust's applications requires further investigation, given that polymer composites vary widely in reinforcement types, especially fiber forms. For example, Rezaei *et al.,* [12] studied short carbon fiber reinforced polypropylene composites, while Fernández *et al.,* [11] focused on long recycled carbon fiber reinforced polypropylene. McNally *et al.,* [13] examined recycled short carbon fiber in polyethylene composites. Limited research exists on polymer composites using reclaimed carbon dust, with insufficient performance data available. The challenge lies in ensuring uniform distribution and dispersion of rCD within the matrix to achieve high-performance particulate-polymer composites. This requires breaking down particle agglomerates into primary particles during processing, controlled by extruder screw speed.

Screw speed plays a crucial role in filler distribution within the polymer matrix. Optimal screw speeds enhance filler dispersion, crucial for improving ABS polymer and rCD interaction. Inadequate dispersion, resulting in lower tensile strength, signifies poor filler-matrix bonding [14,15]. Moreover, different extrusion temperatures will produce various dispersions of fillers loading in polymer composites [16,17]. Furthermore, mechanical properties and composite interactions hinge on rCD's homogeneous distribution, influenced by processing parameters such as filler loading. Thus, there is a gap in knowledge regarding the fabrication processes and implementation of reclaimed carbon dust with polymer composite. This study focused on filler loading and extruder screw speed as primary parameters, fabricating samples via single screw extrusion for standard mechanical testing. Scanning electron microscopy (SEM) and field emission SEM analyzed fractured sample morphologies to correlate filler loading and processing parameters with rCD/ABS composite mechanical properties.

2. Methodology
2.1 Preparation of Reclaimed Carbon Dust (rCD)

The waste carbon dust used in this study was sourced from the aerospace industry, as depicted in Figure 1(a). To ensure the purity of the carbon dust sample from other components in the carbon fibre reinforced polymer (CFRP) laminate, it underwent sieving through 35 µm, 63 µm, and 75 µm sieve shakers, as shown in Figure 1(b). The presence of other elements in the carbon waste could potentially affect the accuracy of results. Subsequently, the carbon dust underwent characterization using XRD and FESEM to verify its purity and high carbon content.

(a) (b) (c)

Fig. 1. (a) CFRP waste in powder form (b) impurities from CFRP waste and (c) reclaimed carbon dust (rCD) after sieved

The composition of the sieved carbon dust was analyzed using a field emission scanning electron microscope with energy dispersive X-ray (FESEM-EDX Hitachi SU5000), and the phases present in the reclaimed carbon dust were identified using X-ray diffraction (XRD Rigaku Mini Flex), based on peak intensity (crystalline) and other phases. FESEM-EDX and X-ray diffraction analyses were conducted within a scan range of 20°-80°, with a rate of 2° per minute and 2θ step sizes, using Cu Kα radiation (1.54050 Å). If any impurities from other materials were detected after characterization, the sieving process was repeated. Once free from impurities of other materials, the carbon dust was classified as reclaimed carbon dust (rCD) as illustrated in Figure 1(c). The average particle size of the reclaimed carbon dust was determined using a particle size analyzer (PSA).

2.2 Fabrication rCD/ABS Composite

The ABS polymer and reclaimed carbon dust (rCD) were mixed in various weight percentages. The weight percentages of reclaimed carbon dust were 0%, 10%, 20%, 30%, and 40%, while ABS polymer constituted 100% by weight. The control sample consisted solely of 100% ABS polymer. The ABS/rCD composite was produced through single screw extrusion, varying screw speed, and filler ratios as tabulated in Table 1.

The ball mill method involved batch mixing of acrylonitrile butadiene styrene (ABS) pellets with reclaimed carbon dust (rCD) to ensure uniform material dispersion. The batches of ABS/rCD composite were extruded into filament using a single screw extruder machine (HAAKE). Extrusion was conducted at a consistent processing temperature using HAAKE Rheomix Lab Mixers.

Table 1
Parameter of the extrusion process

Temperature (°C)	Speed screw (rpm)	Filler loading of rCD (%)
200	20	0, 10, 20, 30, 40
200	40	0, 10, 20, 30, 40

2.3 Assessing Physico-Mechanical Properties and Morphological

Some of the extruded samples, as depicted in Figure 2, were examined using FESEM to assess the distribution of rCD within ABS polymer before undergoing the crushing and hot press processes to prepare specimens for mechanical testing using a universal tensile machine (Shimadzu), following ASTM D3039 standards, and density measurement according to ASTM D792. Five specimens from each batch composition were evaluated, and average strength properties and density values were recorded.

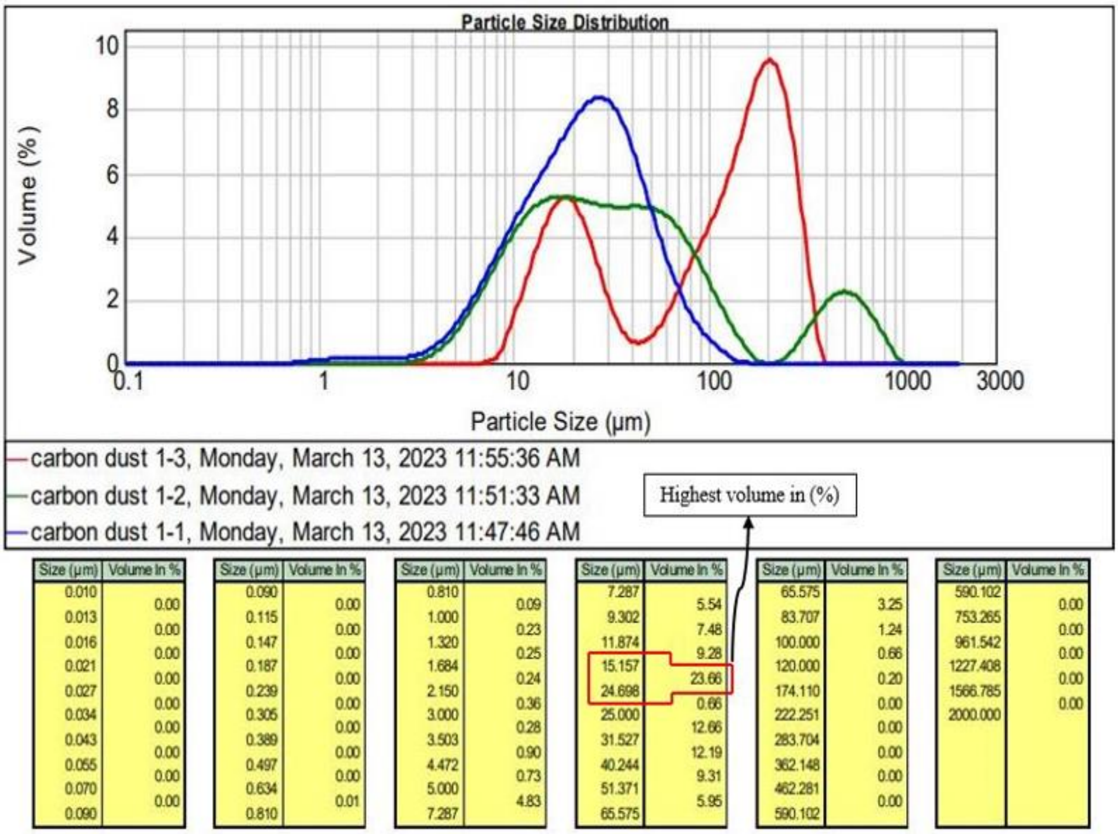
Fractography observations on initiation failure and morphological behaviour of the samples were conducted using a field emission scanning electron microscope (FESEM, Hitachi SU500). All specimens were initially coated with gold sputter, and observations were conducted at magnifications of 6x, 7x, 8x, 250x, and 500x. The correlation between the physico-mechanical properties and the microstructure of each of the samples was discussed.

Fig. 2. Extruded samples of rCD/ABS

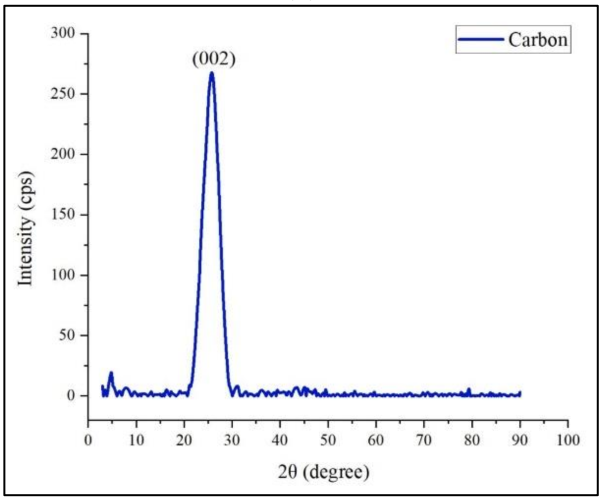
3. Results
3.1 Reclamation of Carbon Dust Analysis

Figure 3(a) illustrates the particle size distribution of rCD, ranging from 0.634 µm to 174.1 µm, with the predominant volume falling between 15.16 µm and 24.70 µm, constituting approximately 23.66% of rCD. The carbon dust underwent sieving through 35 µm, 63 µm, and 75 µm sieve shakers, ensuring particles did not exceed 174.1 µm (75 µm). Despite potential clustering during analysis, 10% and 50% of rCD particles measured smaller than 8.071 µm and 22.97 µm, respectively, while 90% were below 53.66 µm, suitable for this study. Previous research by Irshidat *et al.,* [10] noted that 50% of carbon dust particles were under 80 µm, maintaining relevance given rCD particles remain below this threshold. The smaller particle size of rCD facilitates homogeneous distribution within the ABS matrix. Notably, these particle sizes differ from previous studies due to the origin of carbon dust from CFRP waste trimming and crushing, which lacks controlled sizing.

Figure 3(b) presents the XRD pattern of reclaimed carbon dust, showing sharp diffractogram peaks indicative of its crystalline structure. The pattern reveals a carbon peak at 2θ = 25°, corresponding to the (002) plane, confirming the presence of carbon and crystalline material. This finding aligns with a study made by Gangil *et al.*, [5] where the composition of carbon elements in reclaimed carbon dust is almost the same, affirming that rCD predominantly comprises carbon with a crystalline structure. Thus, Figure 3(b) confirms that the carbon dust was effectively recovered through sieving steps without additional treatment.



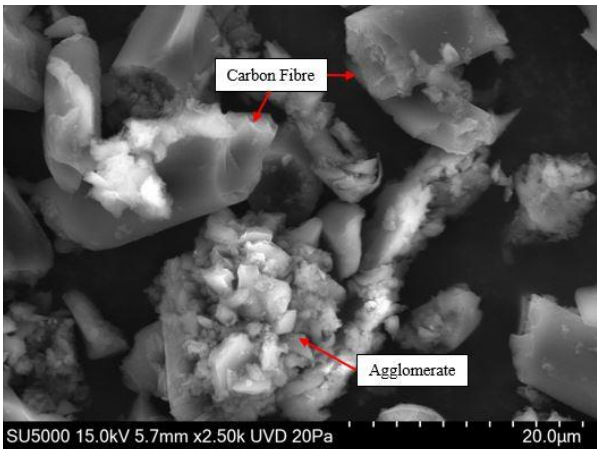
(a)



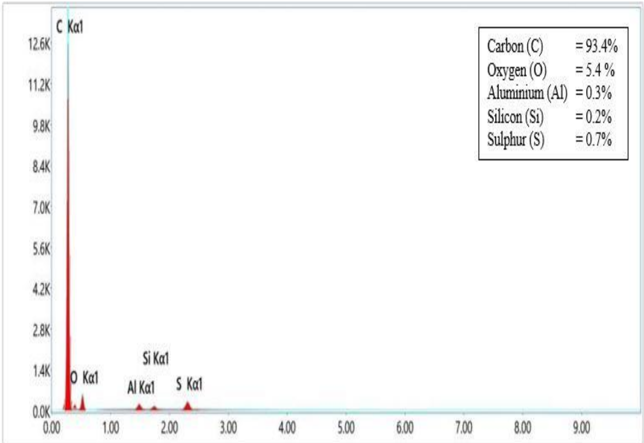
(b)

Fig. 3. Characterization of the carbon dust via (a) particle analyser and (b) x-ray diffraction

The microstructure of reclaimed carbon dust (rCD) is characterized based on particle shape, size, and distribution. Figure 4(a) presents an image of rCD post-reclamation, revealing angular and irregular particle forms with an average size of 20 µm. The irregular shape of rCD results from the small particle size generated during the trimming and crushing of CFRP, which tends to produce irregular rather than uniform shapes. This finding is consistent with Irshidat *et al.,* [10] research, which also observed angular and irregular forms in carbon dust particles (Figure 4(a)). Some rCD particles are seen agglomerated with others, likely due to electrostatic interactions among carbon particles. During sieving, particles can acquire an electrostatic charge, and if attractive forces exceed repulsive forces during vibration, agglomeration occurs.



(a)



(b)

Fig. 4. Characterization shows (a) an image microstructure and (b) elemental analysis of reclaimed carbon dust

According to Figure 4(b) result of EDAX, elements detected in rCD include carbon, oxygen, aluminum, silicon, and sulfur. While other elements are present in small percentages, carbon constitutes the predominant element at 93.4% by weight. Despite the presence of these minor elements, their percentages (oxygen 5.4%, aluminum 0.3%, silicon 0.2%, sulfur 0.7%) are negligible and do not affect the physico-mechanical properties studied, as carbon remains the dominant component in rCD.

3.2 Correlation Between Density-Microstructure and Parameter Processing

Figure 5 illustrates the density of ABS/rCD composites for each composition with varying screw speeds. According to Figure 5, ABS/rCD composites extruded at 40 rpm show higher density compared to those extruded at 20 rpm. Specifically, the density of ABS/rCD composite with 40% rCD at 40 rpm is 1.158 g/cm³, whereas at 20 rpm it is 1.069 g/cm³. This difference suggests that the higher screw speed of 40 rpm effectively facilitates the mixing of reclaimed carbon dust with ABS polymer, resulting in a denser surface of the ABS/rCD composite sample compared to 20 rpm.

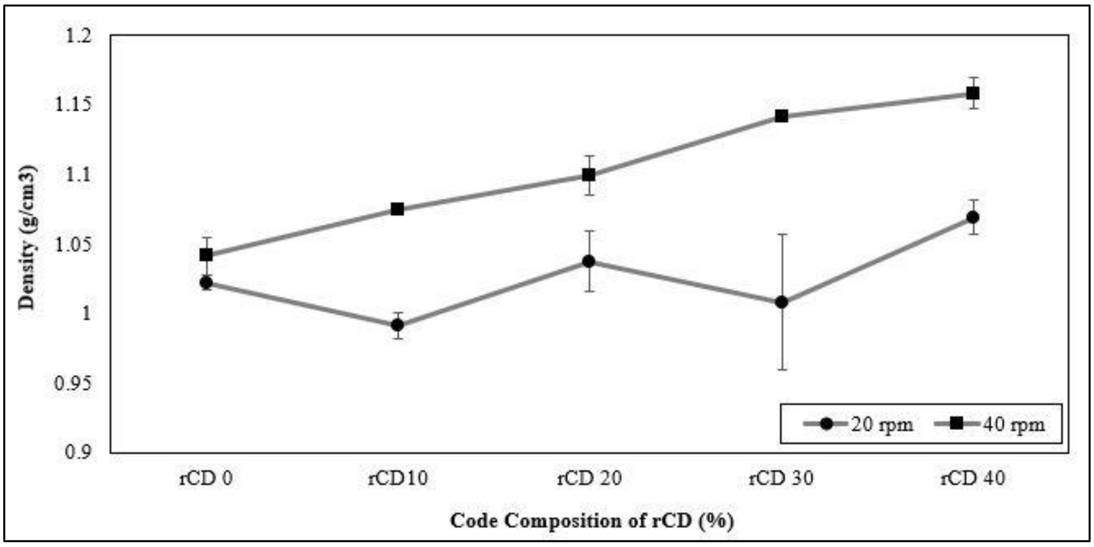


Fig. 5. Density of each composition at different speed screw and filler loading of rCD

Meanwhile, Figure 6 presents the surface morphology of ABS/rCD composites at (a) 20 rpm and (b) 40 rpm with 40% rCD content. In Figure 6(a), the surface exhibits significant porosity and voids, indicating insufficient densification. In contrast, Figure 6(b) shows a densified surface compared to Figure 6(a), suggesting improved mixing of reclaimed carbon dust with ABS polymer at 40 rpm compared to 20 rpm. The density of ABS/rCD composites with 10 wt.% and 30 wt.% of rCD at 20 rpm may have decreased below that of the control sample due to the presence of numerous pores and voids in the extruded samples, as depicted in Figures 7(a) and 7(b). At 20 rpm, the screw speed may not adequately mix the rCD within the ABS polymer melt, leading to agglomeration and clustering. This non-uniform distribution across the sample area could contribute to porosity and void formation. Density reflects the compactness of the ABS/rCD composite sample; an increased presence of pores will lower its density. Overall, enhancing filler loading percentage and screw speed, while ensuring uniform distribution, can improve composite density by reducing pore formation [18].

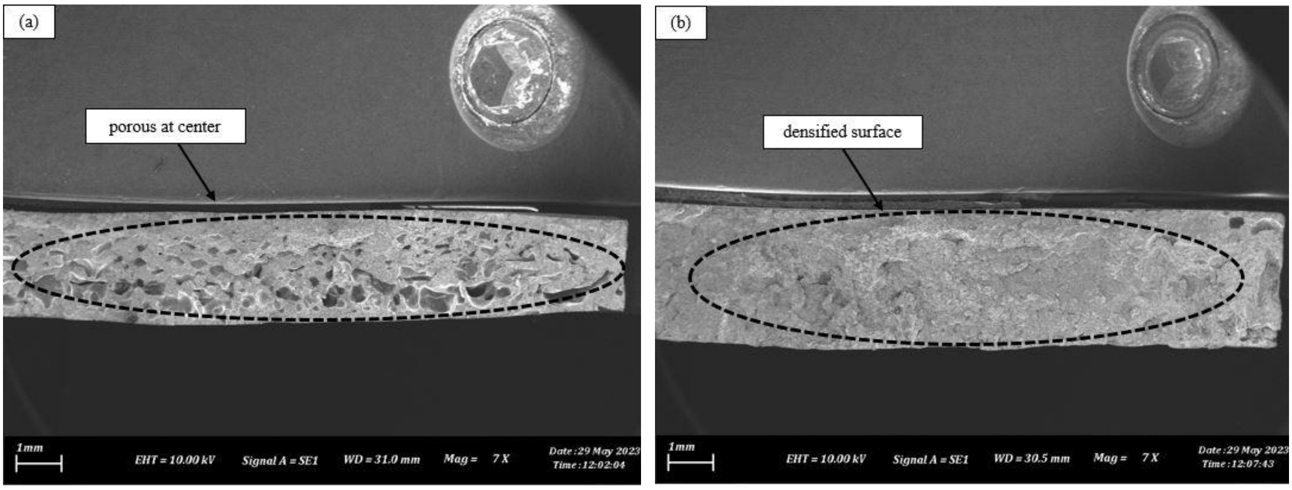


Fig. 6. Skin area sample fractured from tensile testing of ABS/rCD composite for (a) 20 rpm and (b) 40 rpm with 40 wt.% of rCD

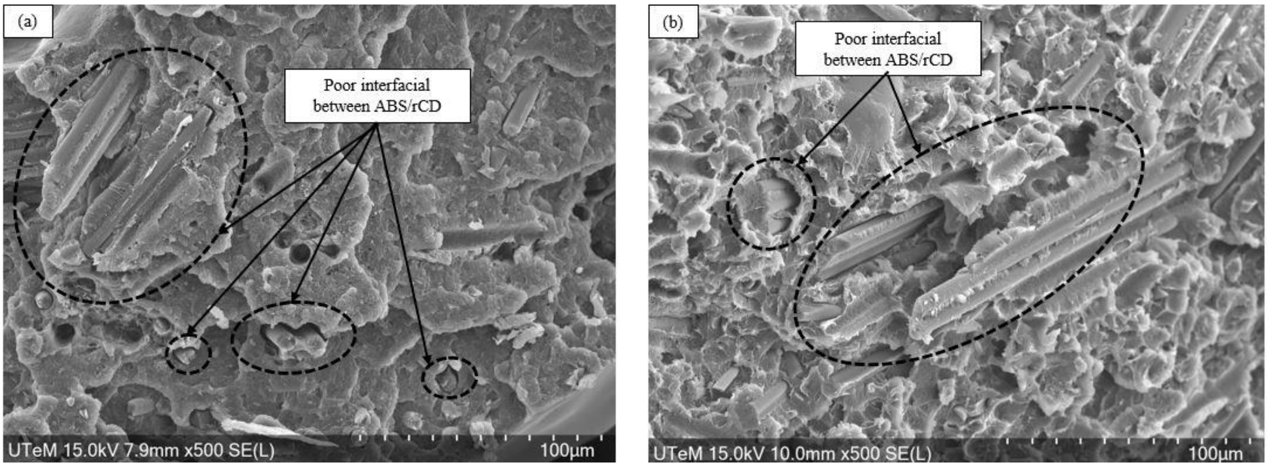


Fig. 7. Images of fractography surface of rCD/ABS composite at speed screw of 20 rpm with (a) 10 wt.% and (b) 20 wt.% of rCD

3.3 Correlation Between Strength Properties-Microstructure and Parameter Processing

Figure 8 clearly shows that adding reclaimed carbon dust (rCD) content increased tensile strength at both rpms. However, the tensile strength for 20 rpm and 40 rpm with 20 wt.% of rCD decreased by 19% and 12%, respectively. Specifically, the tensile strength for 20 rpm with 20 wt.% of rCD decreased from 16.00 MPa to 12.96 MPa, and for 40 rpm with 20 wt.% of rCD, it decreased from 28.95 MPa to 25.30 MPa. These findings differ from those of McNally *et al.,* [13], who reported an increase in the tensile strength of PE/rCF composites when the percentage of recycled carbon fiber content was increased up to 30 wt.%. However, the results align with those of Hardinnawirda and Aisha [23], who observed a decrease in the tensile strength of polymer composites as the percentage of filler increased. The reduction in tensile strength for both rpms and 20 wt.% rCD could be attributed to several factors, including rCD agglomeration, which can lead to matrix cracking. When the matrix cracks, the fractography surface becomes flaky and porous, resulting in voids.

Figures 9(a) and (b) illustrate the fractography surfaces at 20 rpm and 40 rpm with 20 wt.% rCD. Figure 9(a) reveals a flaky, uneven surface with spaces and some rCD particles agglomerated. This observation clearly indicates a reduction in tensile strength for both rpms with 20 wt.% rCD. The tensile strength was assessed using a tensile test, where the sample was subjected to static loading.

Consequently, if the ABS/rCD composite sample has any flaws, scratches, or moisture, fractures can occur earlier than anticipated. Although the polymer composite sample with 20 wt.% rCD had few pores, the agglomeration of rCD at specific points can cause high stress in those areas, leading to premature failure when the sample is pulled. Therefore, rCD agglomeration is likely one of the main causes of the lower tensile strength at 20 wt.% and this can be supported by features of the rCD depicted in Figure 4(a). The particle size analyzer shows that rCD particles vary in size, with only 10% falling below 8.071 µm. Consequently, larger rCD particles tend to agglomerate, making it challenging to regulate their distribution within the ABS polymer. The tensile strength for 40 rpm with 40 wt.% of rCD is 31.48 MPa, whereas the tensile strength for 20 rpm with 40 wt.% of rCD is 19.46 MPa. This indicates that the tensile strength at 40 rpm is greater than at 20 rpm, likely because 40 rpm can enhance the interfacial bonding between the ABS polymer and reclaimed carbon dust. Moreover, this indicates that the tensile strength of polymer composites increases as the filler loading increases which tally to the research made by Amrishraj *et al.,* [19] which states that the addition of fillers into polymer improves the mechanical properties of the composites.

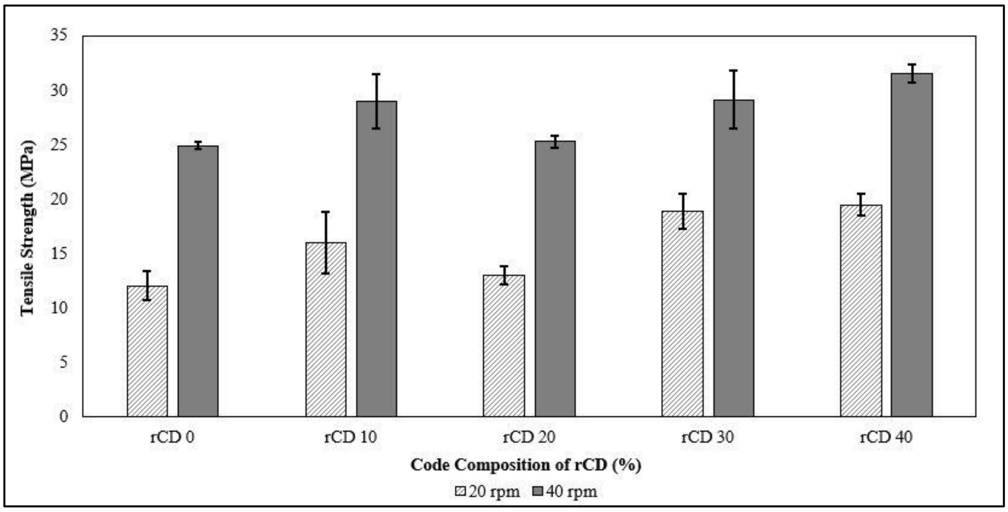


Fig. 8. Tensile strength of rCD/ABS composite at different speed screw

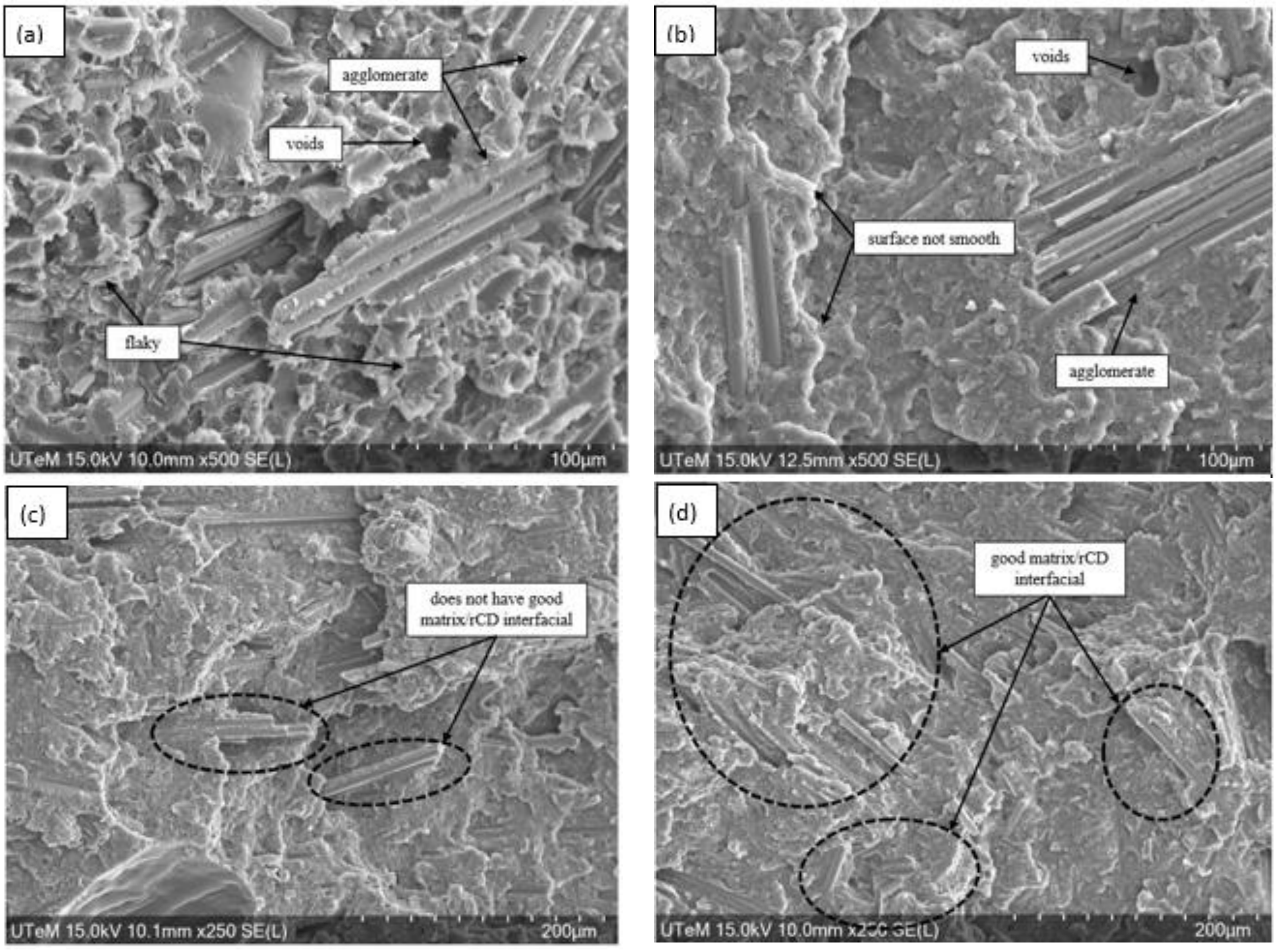


Fig. 9. Fractography surface for (a) 20 rpm (b) 40 rpm with 20 wt.% of rCD and (c) 20 rpm (d) 40 rpm with 40 wt.% of rCD

Figure 9(c) demonstrates that the fractography surface for 20 rpm with 40 wt.% of rCD does not exhibit good interfacial bonding between the ABS polymer and rCD, whereas Figure 9 (d) shows that the fractography surface for 40 rpm with 40 wt.% of rCD has improved interfacial bonding between the matrix and rCD. Furthermore, according to Figure 10, Young's modulus for 40 rpm gradually increased, consistent with the findings of Simpson *et al.,* [20] and Fernández *et al.,* [11], who discovered that stiffness increased as the percentage of fiber content increased. However, Young's modulus for 20 rpm fluctuated, contradicting the findings of McNally *et al.,* [13] and Fernández *et al.,* [11]. Even though Young's modulus for 40 rpm with 20 wt.% improved, the tensile strength for that composition was reduced due to stress concentration and failure mechanisms between the matrix and the filler. The filler concentration of 20 wt.% could offer stress concentrations and failure mechanisms if rCD agglomeration occurs, reducing tensile strength.

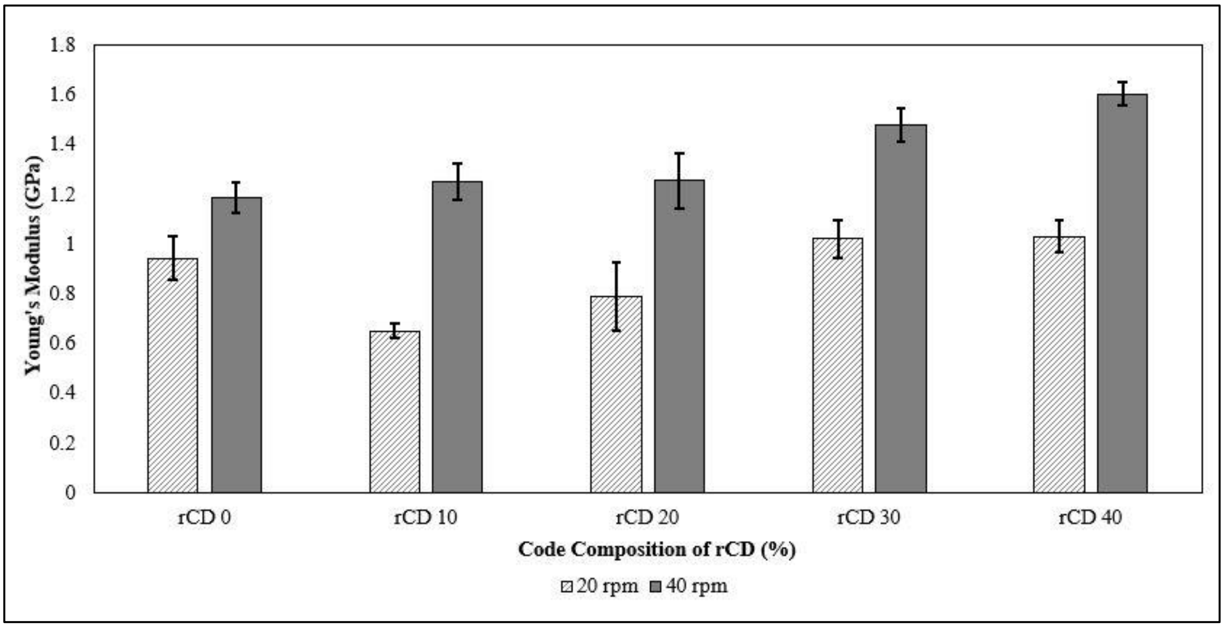


Fig. 10. Young's modulus of rCD/ABS composite at different speed screw

Adding 20 wt.% of rCD is to be seen improves the stiffness of the ABS/rCD composite sample because rCD is a stiffer material than ABS polymer. The Young's modulus at 20 rpm with 10 wt.% and 20 wt.% rCD dropped below the Young's modulus of the control sample, which was 0.941 GPa. With 10 and 20 wt.% rCD, the Young's modulus fell by 31% and 16%, respectively. The addition of rCD is intended to improve the Young's modulus. However, the compositions of 10 wt.% and 20 wt.% for 20 rpm result in poor interfacial contact between the matrix and rCD, as demonstrated in Figures 11(a) and 11(b), limiting load transmission between the ABS polymer and rCD. As a result, the poor interface might reduce the stiffness of the ABS/rCD composite sample. The Young's modulus for 40 rpm with 40 wt.% rCD is greater than that for 20 rpm, with the Young's modulus for 40 rpm with 40 wt.% rCD being 1.603 GPa versus 1.030 GPa for 20 rpm. At 40 rpm with 40 wt.% can offer superior interfacial bonding and well-distributed rCD sizes within the ABS polymer compared to 20 rpm (Figure 9(d)). The findings presented above are consistent with those of other study by Salmah *et al.,* [21], while the tensile strength and elongation at break have reduced with increasing filler loading, the composites' adhesion and filler-matrix interaction have improved, resulting in an increase in the composites' Young's modulus. As a result, the tensile strength and Young's modulus for 20 rpm fluctuated and were lower than those for 40 rpm because the screw speed of 20 rpm is not ideal for this process.

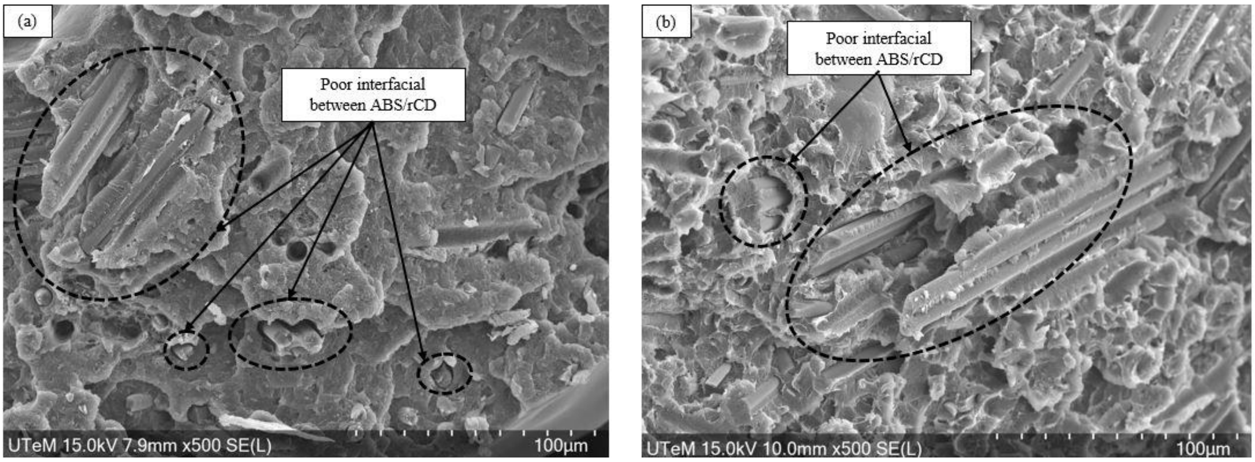


Fig. 11. Fractography surface for 20 rpm with (a) 10 wt.% and (b) 20 wt.% of rCD

3.4 Fractography Analysis

The microstructure of the control sample in this investigation, which is pure ABS polymer at 20 rpm, exhibits the roughest surface as shown in Figure 12(a) whereas pure ABS polymer at 40 rpm shows the smoothest surface as shown in Figures 12(b). Furthermore, Figure 12(a) reveals that the core of the specimen sample appeared to be ductile due to its rough and irregular surface. In contrast, Figure 12(b) illustrates that the core of the specimen sample appeared to be brittle due to its smooth and flat appearance. This aligns with Ding *et al.,* [22] stated that the behaviour of ABS will show different characteristics at different parameter processing and different effects under tensile stress. As the strain increases, ABS experiences both elastic deformation and plastic deformation.

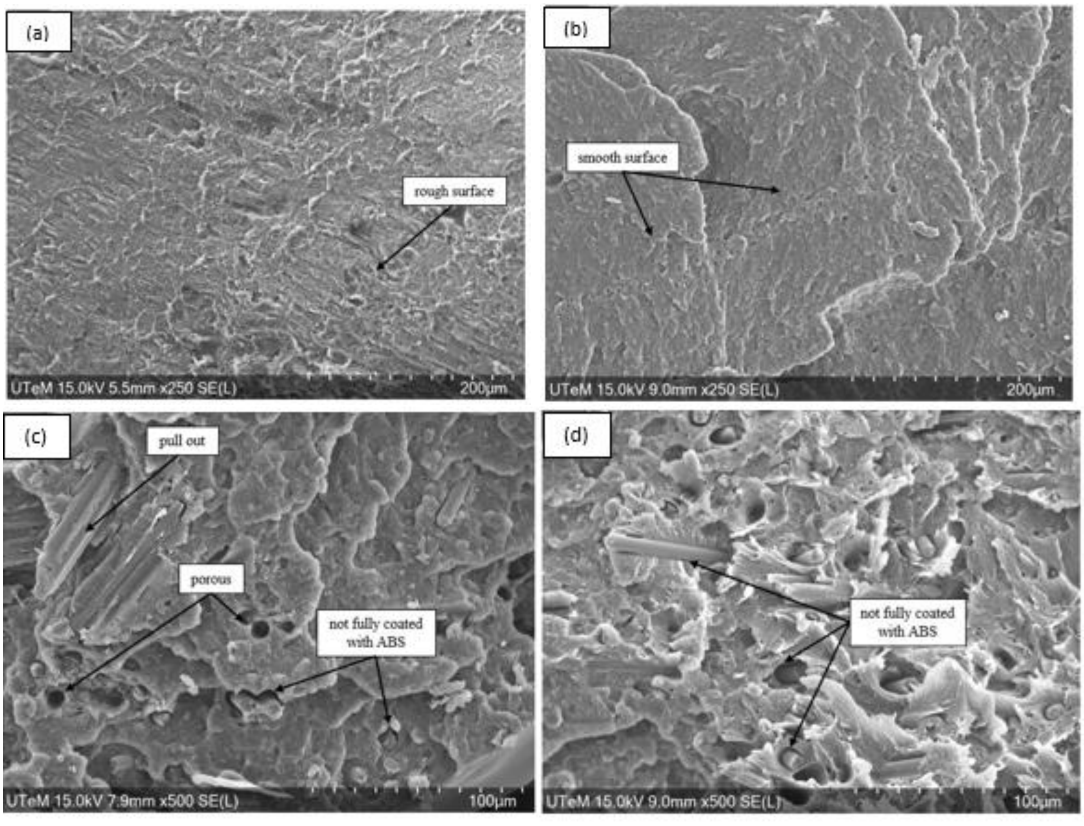


Fig. 12. Images of pure ABS (a) 20 rpm, (b) 40 rpm, and 10 wt.% rCD at (c) 20 rpm, and (d) 40 rpm

With 10 wt.% of rCD at 20 rpm, there are many pores and voids, as shown in Figure 12(c). In contrast, the surface at 40 rpm is more densified with fewer pores and voids, as shown in Figure 12(d). The core of the specimen at 20 rpm shows a lack of consolidation, leading to these pores and voids. As a result, the sample at 20 rpm has lower density and mechanical properties compared to the sample at 40 rpm, which achieves better dispersion and fewer agglomerations. The specimen with 20 wt.% of rCD at 20 rpm showed fewer voids compared to the sample with 10 wt.% of rCD, seen in Figure 13(a). At 40 rpm, the surface appearance for 20 wt.% of rCD was similar to that of the 10 wt.% sample, as shown in Figure 13. However, despite higher density, mechanical properties were compromised due to issues like fiber pull-out and rCD particle agglomeration, illustrated in both Figure 13. These problems, noted by Chen *et al.,* [24], affect matrix adhesion and bonding, leading to gaps that reduce overall mechanical strength.

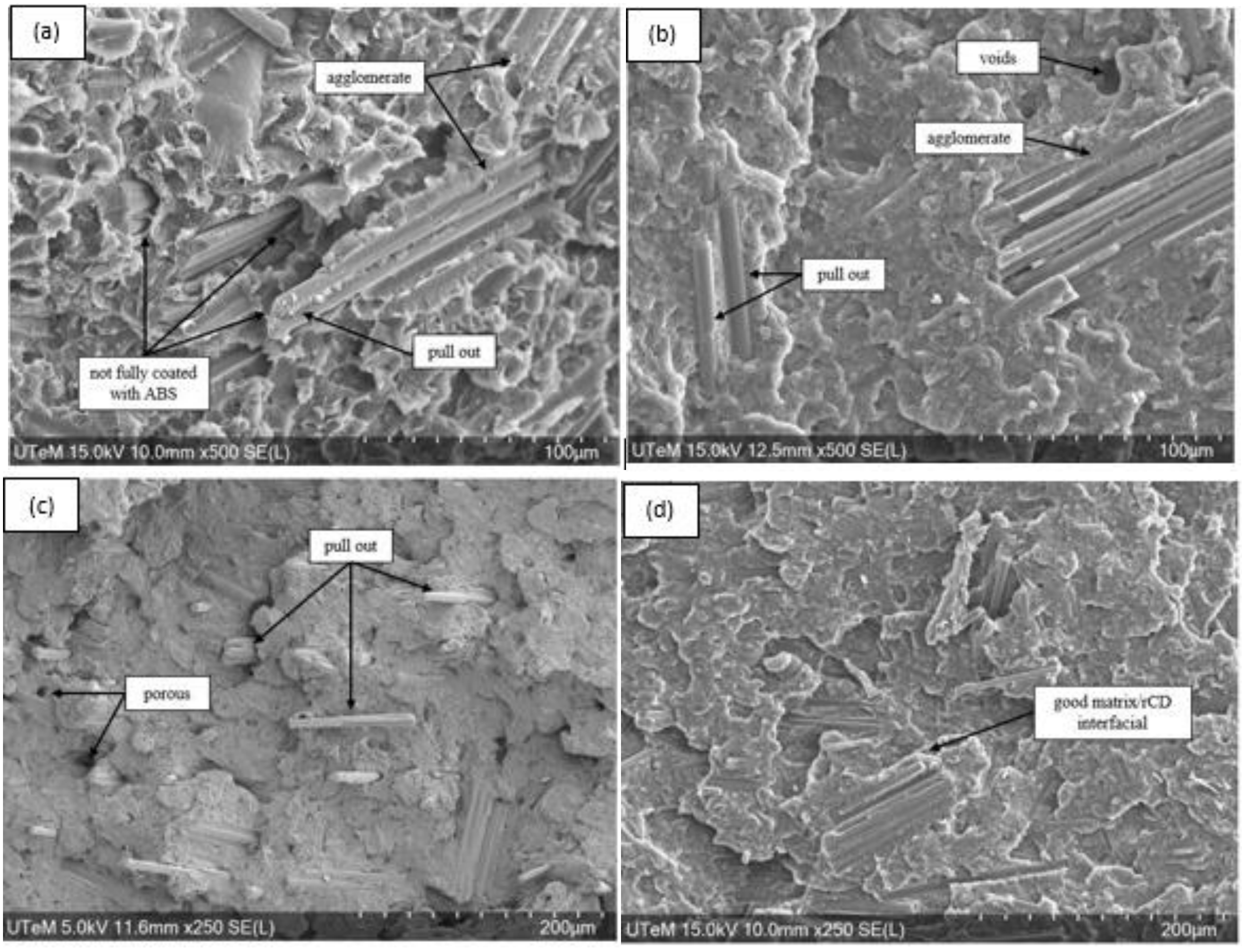


Fig. 13. Images of ABS with 20 wt.% rCD at (a) 20 rpm, (b) 40 rpm and 30 wt.% rCD at (c) 20 rpm (d) 40 rpm

At 30 wt.% and 20 rpm, numerous pores are visible at the core of the specimen, as shown in Figures 13(c) and (d). Figure 13(c) highlights fiber pull-out due to weak interface bonding between ABS and rCD, leading to lower density and mechanical properties compared to the sample processed at 40 rpm. In contrast, the specimen with 30 wt.% at 40 rpm exhibits a densified surface and improved interfacial bonding between ABS and rCD, as depicted in Figure 13(c) and (d), resulting in enhanced physico-mechanical properties compared to 20 rpm.

For 40 wt.% at both 20 rpm and 40 rpm, the surface appearance remained consistent with that of the 30 wt.% rCD sample. At 20 rpm, Figure 14 (a) shows central specimen porosity, whereas at 40 rpm, Figure 14(c) depicts a densified surface. Despite being porous, the density of the 40 wt.% sample at 20 rpm increased slightly compared to other compositions at the same speed. Conversely, the 40 wt.% sample at 40 rpm exhibited the highest density due to the enhanced densification achieved by the ABS polymer and rCD interaction. This observation resonates with findings from the research conducted by Mostovoy *et al.,* [16]. Mechanical properties were notably superior in the 40 wt.% samples at both speeds because of the uniform dispersion of rCD particles within the ABS polymer, as seen in Figure 14(b) and (d). However, mechanical properties were highest in the 40 wt.% sample at 40 rpm, as shown in Figure 14(c), where rCD particles were well-distributed but not fully coated with ABS polymer, leading to a somewhat flaky microstructure surface [24]. This is in line with research conducted by Shamsudin *et al.,* in 2024 [25], investigations were carried out with particles ranging approximately size with 40% loading where the outcome revealed equally well dispersed which leads to higher mechanical strength.

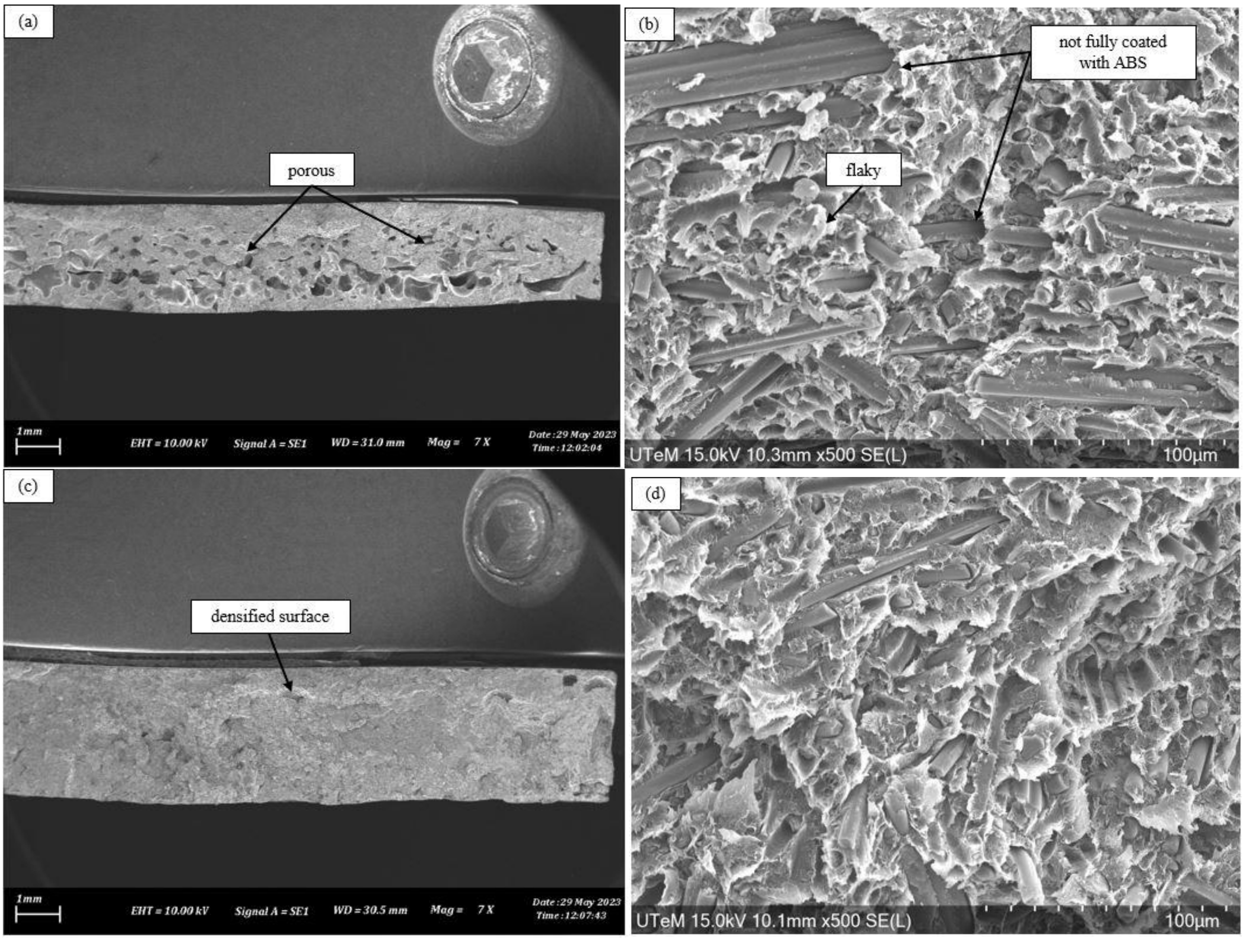


Fig. 14. Images of ABS with 40 wt.% rCD at (a) overview and (b) core for 20 rpm, (c) overview and (d) core for 40 rpm

4. Conclusions

The primary objective is to assess how varying filler loading percentages of recycled carbon dust and screw speeds affect the physical and mechanical properties. The study involves several processes, including sieving carbon dust waste from CFRP trimming, characterizing the reclaimed carbon dust, conducting the extrusion process, measuring density, and performing tensile testing.

The testing phase successfully characterized rCD and evaluated both the physical and mechanical properties of the rCD/ABS composite. Key findings include:

i. At 20 rpm, lower properties (12.96 MPa, 0.650 GPa) indicate poor rCD dispersion and agglomeration.
ii. Effective rCD dispersion at 200°C and 40 rpm without a compatibilizer.
iii. Using rCD at 40 rpm enhances ABS properties compared to 20 rpm, suggesting optimal processing conditions.
iv. Samples with better properties (31.48 MPa, 1.603 GPa) showed well-dispersed rCD and robust bonding between the matrix and fibers.

Acknowledgement
The authors would like to acknowledge the support of Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan (FTKIP) and Centre for Research and Innovation Management, Universiti Teknikal Malaysia, Melaka. This research was not funded by any grant.

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