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Effects of infill density on mechanical properties of additively manufactured chopped carbon fiber reinforced PLA composites

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In this present study, the fused deposition modeling (FDM) method was used to fabricate the composites. Before three-dimensional (3D) printing, samples were designed according to the ASTM D256, D790 and D3039 standards for impact, flexural and tensile tests, respectively, using Onshape software before conversion to an STL file format. Afterward, the digital file was sliced with infill densities of 60%, 80%, and 100%. The composite samples contained chopped carbon fiber (cCF) and poly lactic acid (PLA), as reinforcement and matrix, respectively. The cCF/PLA (simply called cCFP) filaments were printed into various cCFP composite (cCFPC) samples, using a Viper Share bot 3D machine with different infill densities before the aforementioned mechanical testing. The tensile strength of cCFP were obtained as 25.9MPa, 26.9MPa and 34.75MPa for 60%, 80% and 100% infill density cCFP samples, respectively. Similarly, the flexural strength of cCFP were obtained as 11.8MPa, 12.55MPa and 18.4MPa and impact strength was 47.48kJ/m^2, 48.45kJ/m^2 and 48.96kJ/m^2 for 60%, 80% and 100% infill density cCFP samples, respectively. The fractured/tested samples were examined and analyzed under a scanning electron microscope (SEM) to investigate the presence of fiber and void in the tensile sample. Based on the experimental results, it was evident that a high infill density of 100% with the highest reinforcement exhibited maximum impact strength, tensile and flexural strengths and moduli when compared with other lower carbon content of cCFPC samples. Therefore, the optimal 3D-printed cCFPC sample could be used for engineering application to benefit from properties of the polymer matrix composite materials and possibilities through additive manufacturing (AM).

Keywords: *Fused deposition modeling, 3D printing, composite, mechanical properties, scanning electron microscope, process innovation*

1. Introduction

Today, the rapid growth and widespread attention garnered by the three-dimensional (3D) printing of various polymers underscore its significance in the field of mechanical engineering. 3D-printing machines have proven invaluable for research and development, owing to their adaptability in fabricating intricate geometries without the need for expensive tooling. Since its inception in 1986, this technology stands out from conventional manufacturing methods by offering several advantages. Notably, it enables the production of complex geometries with minimal material waste and facilitates a swift prototyping process. These advantages contribute to the increasing adoption of 3D printing as a transformative tool in modern engineering and manufacturing practices. 3D printing offers additional advantages, including its ease of production through the utilization of computer-aided design (CAD) drawings. This streamlined process contributes to the creation of high-precision products.

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Various industries have established businesses centered around the use of 3D-printing machines, leveraging their capabilities to rapidly create products and manufacture components [1–4]. Over the past 25 years, significant progress has been made in the development of novel structural materials through advancements in 3D-printing technology. This continual evolution positions 3D printing as a transformative force in manufacturing and materials development across various industries [5, 6]. The designer has access to brand-new engineering outcomes using different materials, which include advanced ceramics, polymers, metals and hybrid materials, known as composites. Depending on the complexity of the design, rapid prototyping technology associated with these materials can quickly produce a prototype. This progress in materials provides designers with fresh opportunities to explore and implement creative solutions across a broad range of industries [7–9].

Furthermore, the benefits of 3D printing include the ability to create customized shapes, cost-effectiveness, minimal waste and the easy modification of materials. Various 3D printing methods, such as fused deposition modeling (FDM), liquid 3D printing (PLP), selective laser sintering (SLS), stereolithography (SLA), digital light processing (DLP) and electron beam melting contribute to these advantages. Some studies have explored the impact of input parameters, including filament diameter, extruder temperature, feed rate, raster angle, material characteristics, nozzle angle and distance between parallel faces on the output parameters. The research provided strategies to optimize these parameters for better results [10–13].

Initially, only plastics, such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) could be used for 3D printing. PLA and ABS materials were preferred due to their mechanical properties. PLA, made from corn, is eco-friendly but challenging to work with post-printing and degrades over time. ABS, though not environmentally friendly, can be recycled and is easy to manipulate. Nowadays, 3D printing employs materials such as polycarbonate (PC), polycaprolactone (PCL), polyphenylsulfone (PPSU), etc. The variety of materials allows for more diverse applications and considerations in 3D printing [14–16].

Besides, it is anticipated that AM will soon introduce innovative materials through new technologies. Research in AM is critical for driving subsequent developments that are beneficial and essential to various aspects of life. Ongoing efforts are dedicated to the development of lightweight materials with enhanced stiffness, strength and energy absorption properties for multifunctional applications. Lightweight materials, characterized by low density and a high strength-to-weight ratio, find ideal applications in the aerospace, biomedical, semiconductor and automotive sectors [17–19]. FDM, also known as fused filament fabrication (FFF), stands out as a key AM method based on solids. Its popularity has grown, both in industries and among the general public, owing to its simplicity, flexibility, rapid prototyping capabilities, cost-effectiveness, minimal waste and ease of material changes. Within FDM, two types of polymer composites can be 3D printed, namely, a composite made of continuous fiber-reinforced thermoplastic (CFRT) and short fiber-reinforced thermoplastic (SFRT). While AM is extensively used to produce short carbon fiber-reinforced polymer composites, challenges arise in controlling the orientation and alignment of short carbon fibers, limiting improvements in specific mechanical properties. Ongoing research aims to address these challenges and unlock further advancements in the field [20–23].

Thermoplastic base filaments are widely used in FDM due to their temperature characteristics. However, FDM-fabricated thermoplastics have lower properties when compared with materials produced through traditional injection molding, primarily due to their anisotropic behavior. To overcome these limitations, numerous studies have aimed to enhance the material properties of FDM-fabricated components. The study utilized FDM to assess the mechanical characteristics of 3D-printed chopped carbon fiber/polylactic acid (CF/PLA) composites. The 3D-printed products exhibited significantly improved strength when compared to the unreinforced printed counterparts. AM, including FDM, has proven to be a viable method for producing a variety of particle-polymer composites with complex architectures. Utilizing natural fibers like wool, hemp, flax, kenaf, and vegetable fibers has proven successful in replacing synthetic fibers in composite manufacturing through AM. This emerging technology offers unique capabilities for creating intricate structures with diverse material properties, expanding the possibilities for manufacturing heterogeneous components [24, 25].

Considering the aforementioned literature, it is very germane to bridge a research gap on investigation into the influences of different infill densities on the mechanical (impact, tensile and flexural) properties of 3D-printed chopped carbon fiber-reinforced PLA composites (cCFPCs), as considered within the scope of this present work. All the samples were consistently printed at a fixed temperature of 200 °C in a closed-room atmosphere. The controlled printing environment aimed to maintain a standardized condition for the investigation, allowing for a focused evaluation of the influence of varying infill densities on the mechanical characteristics of the cCFPCs. The novelty of the work is the development of 3D-printed composites' materials with chopped carbon fiber (cCF) as reinforced with PLA.

2. Materials and methods

2.1. Design of samples

Tensile, flexural and impact samples were created in Onshape software, following ASTM standards [26]. These designed samples were then produced using Viper Share bot 3D-printing machines. To thoroughly study the properties, each category of testing was replicated with five samples. The designed samples, as depicted in the Figures 1(a) and (b), served as the basis for the subsequent mechanical testing and analysis.

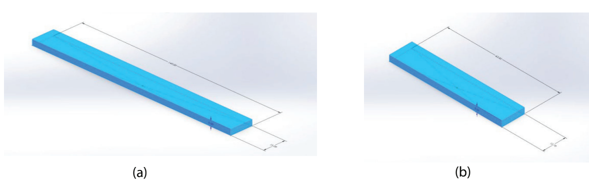

Fig. 1. (a) Tensile and (b) impact CAD samples

2.2. Materials

The cCFPC was procured from Amazon India and the cost of 3D filament material is 7500rs per 500 grams. The diameter of the cCF 3D filament is 1.75mm. The filament was manufactured by 3DXTECH, an American-based company.

2.3. Tensile test

The samples were 3D-printed following the guidelines of ASTM D3039, featuring a rectangular dimension measuring 200×20×3mm [26]. A set of five samples was selected for the tensile test. The testing was conducted using a universal testing machine and calculations were performed to estimate tensile strength, elongation at break and tensile modulus, based on parameters obtained. The conclusion of the testing process involved the presentation of the average value obtained from the results of the five samples.

2.4. Flexural test

The samples were 3D-printed in accordance with ASTM D790 specifications for flexural testing, featuring dimensions of 125.0×12.7×3.2mm [26]. A total of five samples were prepared for this purpose. The testing was conducted using a universal testing machine, employing a three-point bending test on the flexural samples to determine both flexural strengths and its moduli. The average value of the results obtained from the five samples was then recorded for analysis and documentation. Importantly, the flexural strength and modulus were calculated using Equations (1) and (2), respectively.

$$\text{Flexural strength} = \frac{3FL}{2b\,d^2} \tag{1}$$

$$\text{Flexural modulus} = \frac{mL^3}{4b\,d^3} \tag{2}$$

where F represents the maximum failure load (N), L means the length of span (mm), b and d denote the width and thickness of sample, respectively, and m stands for slope of the load-displacement curve tangent to the initial line.

2.5. Impact test

The samples were 3D-printed according to ASTM D256 without notch for impact test, having a dimension of 63.5×12.5×3.2mm [26]. The five samples were taken for this test. The test was carried out on an impact testing machine. The average value obtained from the results of the five samples were reported.

2.6. Scanning electron microscope (SEM)

A scanning electron microscope (SEM) was employed to investigate into the fractography of the ruptured surfaces of the composite samples. The samples were meticulously cut under machine specifications to ensure precision and accuracy, determining the fiber content within each sample. Subsequently, a uniform coating of golden sputter was applied to the samples before examination under the SEM. Various magnifications were obtained to inspect the tensile samples. The multi-magnification approach was used for a detailed and comprehensive analysis of the fractured surfaces, providing valuable insights into the structural characteristics and failure mechanisms of the material. This test was carried out on the CARL ZEISS model of EVO18 SEM with a voltage of 20 kV and a vacuum level of 1.5 $\times$ 10^{-3}Pa were set in machines at IRC, KARE and Srivilliputtur.

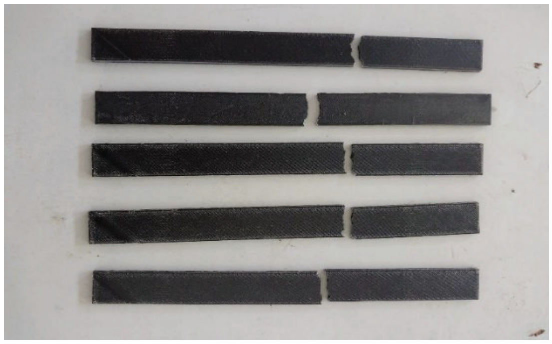

Fig. 2. Tensile fractured samples

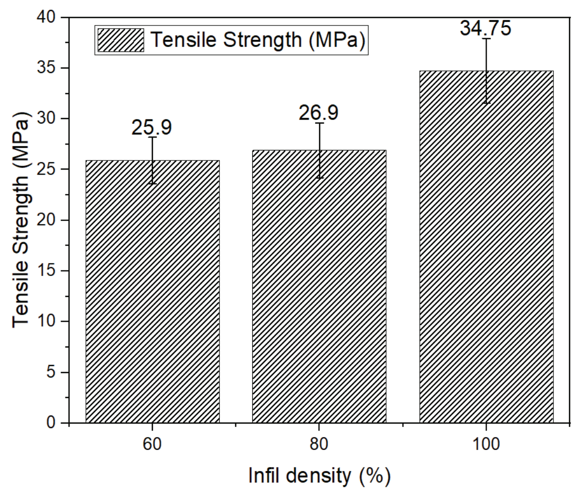

Fig. 3. Tensile strengths of the cCFPC samples

3. Results and discussion

The results obtained on the mechanical properties of the 3D-printed cCFPCs are comprehensive and subsequently elucidated. These include tensile, flexural strengths and moduli as well as impact strengths. Further morphological analysis of tensile fractured samples were also discussed.

3.1. Tensile strength

Figure 2 depicts tensile fractured cCFPC samples. Calculations of their tensile strength were conducted for the various varying infill densities of 60%, 80% and 100%. The corresponding tensile strengths and ultimate tensile stress-strain curves are later shown in Figures 3 and 4, respectively. It was observed that tensile strength increased when there was an increase in infill density of composite materials. Therefore, infill density played a significant role in the properties of the cCFPC materials.

Figure 3 shows that the tensile strength of cCFPCs with different infill densities was a main parameter. It was observed that samples with highest infill density produced the highest tensile strength of 34.75±3.2 MPa. Meanwhile, samples with 60% and 80% infill densities yielded the lower values of 25.9±2.3 and 26.9±2.7 MPa, respectively. The lower strengths can be traced to the presence of insufficient fiber content in their composite samples. For the same infill density of 60%, 80%, and 100% without reinforcement by chopped carbon (i.e., Pristine PLA), the tensile strength is measured as 19.2±1.4MPa, 20.6±2.6MPa and 42.9±3.9MPa, respectively, as reported by Mazur et al. [27]. The tensile strength of 100% infilled

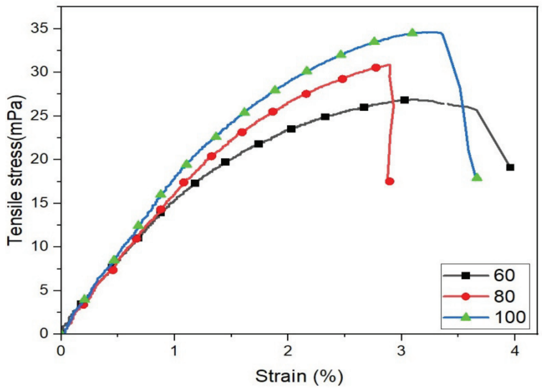

Fig. 4. Stress-strain curves from the tensile test on cCFPC samples

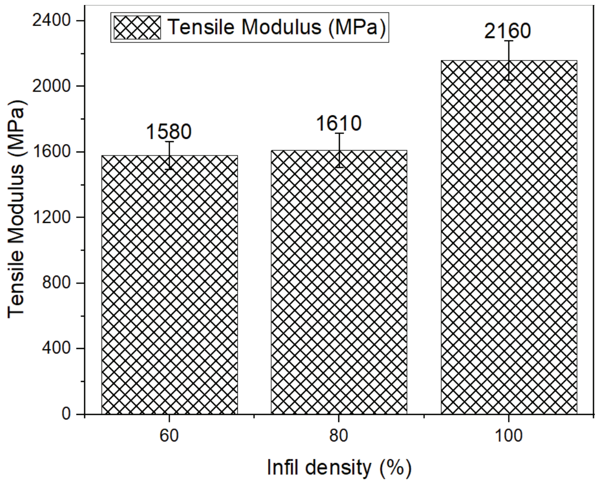

Fig. 5. Tensile moduli of the cCFPC samples

cCFPCs is decreased by 19% when compared to the 100% infill density of the PLA sample. However, the tensile strength of 60% and 80% infilled cCFPCs has increased with 26% and 23%, respectively, when compared to 60% and 80% infill density of pure PLA samples.

3.2. Tensile stress-strain

The five samples of each infill density of cCFPCs were further analyzed. The average value of each category was calculated to obtained stress-strain curves. A typical stress-strain curve of cCFPCs with different infill densities is depicted in Figure 4. It was observed that the highest tensile stress values were obtained from the sample with a 100% infill density. The cCFPC samples with 80% infill density recorded tensile stress and strain values of 30 MPa and 2.9%, respectively. Similarly, cCFPC samples with 60% produced tensile stress and strain values of 26 MPa and around 3%, respectively. Finally, a curve with an infill density of 100% exhibited maximum tensile stress and strain of 34 MPa and 4.1%, respectively. Evidently, the infill density played a major role on mechanical/tensile properties of 3D-printed cCFPC samples.

3.3. Tensile modulus

The values of tensile moduli from the different infill densities of cCFPCs are shown in Figure 5. A tensile modulus of 1580±85 MPa was obtained from the 60% cCFPC, and the 80% cCFPC produced a value of 1610±105 MPa. Similarly, the highest tensile modulus was produced by the 100% cCFPC and its value was 2160±120 MPa. The optimum tensile modulus value can be associated with more fiber content, as it acts as a load-bearing element within the composite system. Consequently, equally-distributed load within the structure had the capability of withstanding the highest load, compared with the other two cases of lower fiber contents. Moreover, samples with the highest fiber content had less void within their 3D-printed cCFPC samples. The tensile properties of 3D-printed cCFPCs such as modulus and strength are lower when compared with continuous carbon fiber reinforced 3D-printed PLA composite materials [28]. Moreover, the mechanical properties of 3D-printed PLA materials or composite materials could give lower values when compared to injection molded PLA materials or composite materials due to the presence of more microvoids on 3D-printed samples [29, 30].

3.4. Flexural strength

Flexural strengths were determined for all the 3D-printed cCFPC samples with different infill densities. The flexural fractured samples are depicted in Figure 6. The related flexural strengths are shown in Figure 7. It was observed that fiber content in cCFPCs increased with their flexural

Fig. 6. Flexural fractured samples of the cCFPCs

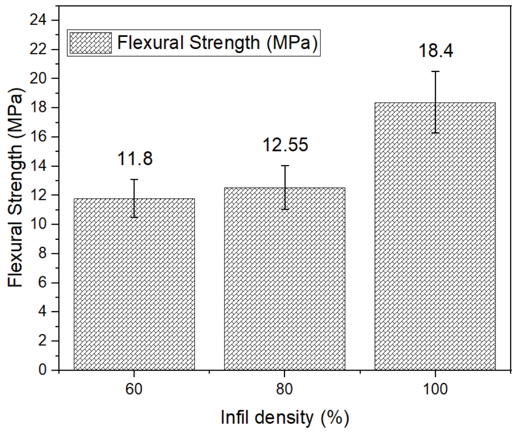

Fig. 7. Flexural strengths of the cCFPC samples

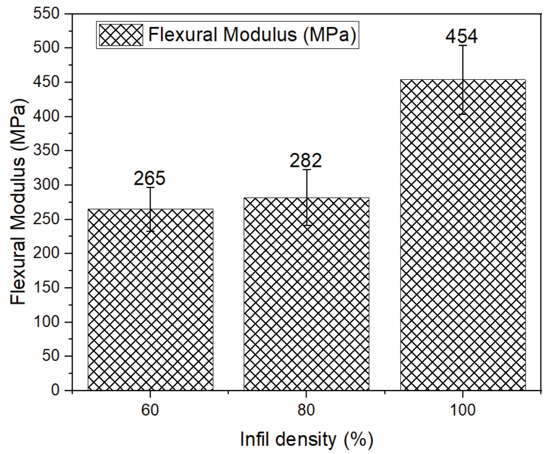

Fig. 8. Flexural moduli of the cCFPC samples

strengths gradually and significantly with the 100% sample.

The flexural characteristics demonstrated a positive correlation with the growing infill density. In particular, the flexural strength escalated from 11.8 to 18.4 MPa as the infill density increased by 20%. The trend is clearly depicted in Figure 7, showing that higher infill density was associated with an enhanced resistance to internally applied stress. The flexural strength of cCFPCs is increased by 36% when compared to lower-infilled cCFPCs with high-density filled cCFPCs materials. At the same infill densities of 60%, 80% and 100%, without reinforcement by chopped carbon (i.e., Pristine PLA), Mazur et al. [27] reported flexural strengths of 37±1.8 MPa, 42±2.3 MPa, and 101±3.4 MPa, respectively. The flexural strength of 100% infilled cCFPCs decreases by 81% compared to the 100% infill density of PLA samples. Similarly, the flexural strength of 60% and 80% infilled cCFPCs decrease by 68% and 71%, respectively, compared to the 60% and 80% infill density of pure PLA samples.

3.5. Flexural modulus

The flexural modulus is the ability of plastic material to bend. The flexural modulus of the various 3D-printed cCFPCs is depicted in Figure 8. It was observed that higher fiber content produced higher flexural modulus, as the highest value was observed from the sample with 100% infill density. While 60 and 80% of samples with lower fiber contents produced lower values of 265 and 282 MPa, respectively. The flexural properties gradually increased from the low infill density of cCFPCs to the high infill density of cCFPCs samples. The same trend is observed by Mazur et al. [27] as they investigated the mechanical properties of 3D-printed composite materials. Flexural strength and flexural modulus values are gradually increased when increasing the fiber content and infill density of the 3D-printed polymer composite materials.

3.6. Flexural stress-strain

Figure 9 shows the flexural stress-strain plots of cCFPCs with different infill densities. It was observed that at 60% infill density, the flexural stress was 4.9MPa with a strain of 10.5%. For 80% infill density, the flexural stress and strain values were 12.5MPa and 4.5%, respectively. The sample with 100% infill density exhibited the highest flexural stress at 17.5MPa with a strain of 4.6%. Specifically, at 100% infill density, the composite demonstrated the highest flexural stress, flexural

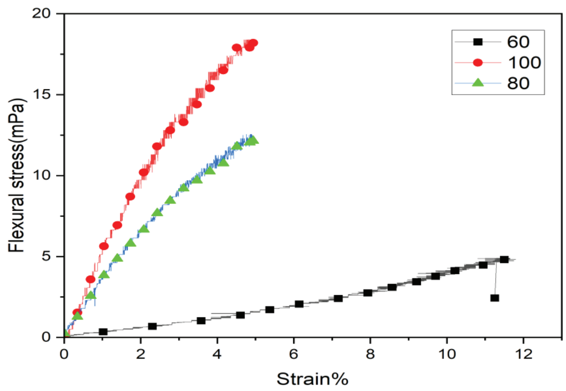

Fig. 9. Stress-strain curve from the flexural test on cCFPC samples

Fig. 10. Impact samples of the cCFPC samples

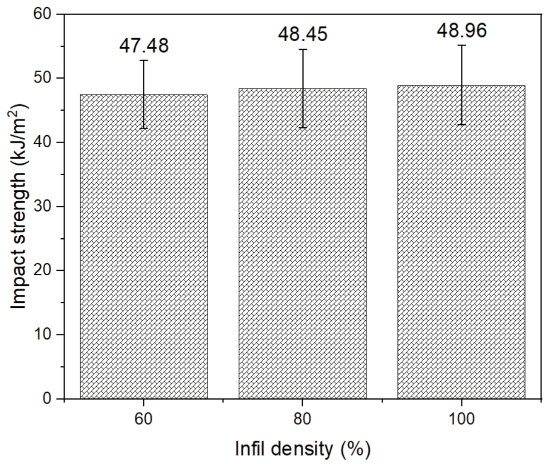

Fig. 11. Impact strengths of the cCFPC samples

strength and modulus. In contrast, lower infill densities of 60% and 80% experienced reduced strengths, due to the insufficient fiber content and the presence of voids in their polymer, highlighting the significance of addressing these factors for optimal material performance.

3.7. Impact sample

Figure 10 shows the fractured impact samples of the various 3D-printed cCFPCs. The impact strengths were determined for all the 3D-printed samples with different infill densities, as shown in Figure 11.

From Figure 11, the impact strength values were 47.48, 48.45 and 48.96 kJ/m^2 for samples with 60%, 80% and 100% infill densities, respectively. Significantly, the impact strength of the cCFPC samples improved with their infill densities, as the sample with the highest infill density of 100% recorded the highest impact strength. Therefore, it has the most suitable option for applications in lightweight mechanical scenarios. This further suggested that an optimum 3D-printed cCFPC sample with 100% infill density could serve as a viable alternative to traditional plastic materials, particularly in areas where robust impact resistance is a required critical factor. There was no major changes in the impact strength of cCFPCs for different infilled samples. The impact strength increased by only 3% when compared to lower infill density cCFPCs with high infill density cCFPCs materials.

3.8. SEM Characterization of chopped carbon fiber (cCF)

Figures 12(a)–(d) depict the SEM images of the 3D-printed tensile fractured samples. Studies on the morphological and surface microstructures of the cCFPC samples with the lowest and highest infill densities were carried out, involving infill densities of 60% at (a) 100x and (b) 500x as well as 100% at (c) 100x and (d) 500x magnifications. Figures 12(a) and (b) show that the 60% infill density with lowest fiber content possessed more uneven voids, leading to earlier mechanical failure. The sample had a major problem regarding the lowest strengths, because its infill concentration contained the lowest cCF. This was previously confirmed, considering its lowest stress-strain curve and other relative tensile properties. This type of 3D-printed cCFPC may not be a suitable lightweight component with responsibility of structural application, but it depends on the required performance.

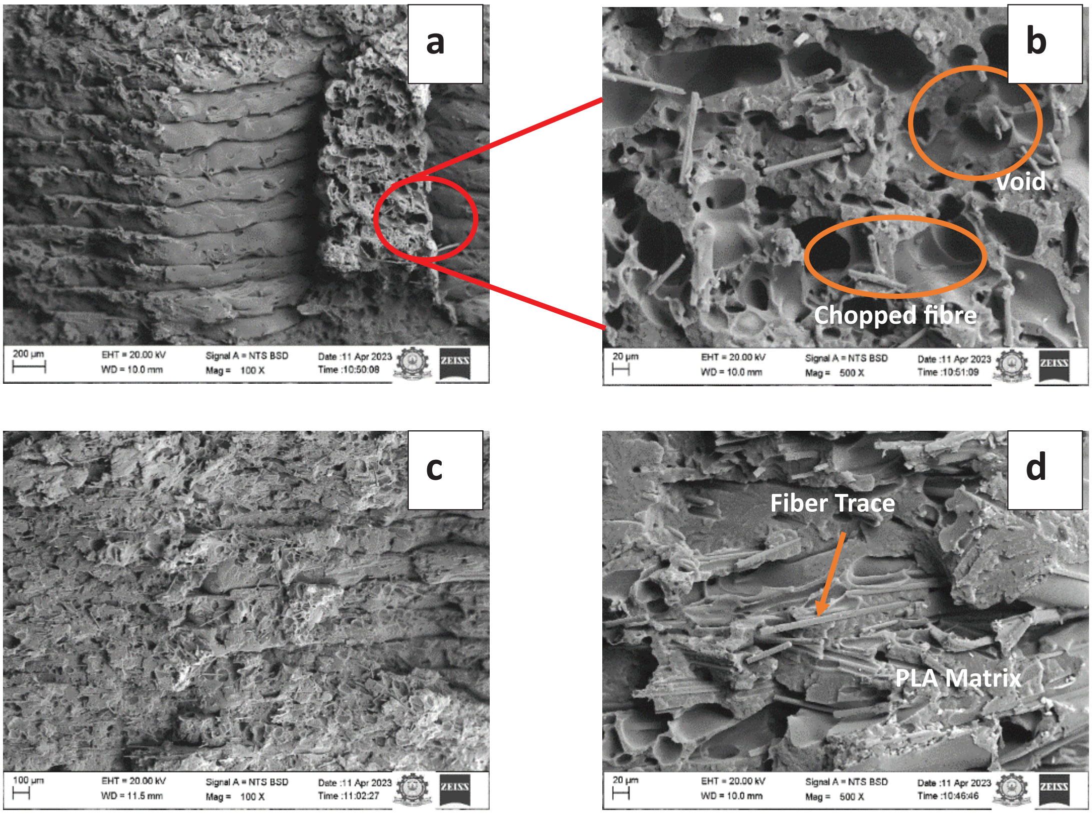

Fig. 12. SEM images of the tensile ruptured 3D-printed cCFPC samples with infill densities of 60% at (a) 100x and (b) 500x, as well as 100% at (c) 100x and (d) 500x magnifications

Figures 12(c) and (d) depict the 100% infill density with higher or more chopped fiber content and smooth fractured surface within the PLA matrix when compared with the infill concentrations of other cCFPC samples. The higher fiber content supported strong mechanical properties of the sample. Also, the sample had a cleaner fracture than other lower infill density, confirming the brittle nature of the carbon fiber. These results were previously confirmed, considering their stress-strain curves and other mechanical properties.

4. Conclusion

The cCF composite material was successfully fabricated with the Viper Share bot 3D printer, using a combination of printing parameters: various infill densities of 60%, 80% and 100% and a constant printing temperature of 200 °C. The mechanical properties of the 3D-printed cCFPC material were experimentally assessed. From the present research work, the following concluding remarks can be deduced.

- The 3D-printed cCFPC samples exhibited maximum tensile (34.75MPa), flexural (18.4MPa), and impact strength (48.96kJ/m^2) when printed with 100% infill density. In contrast, samples with 60% and 80% infill densities demonstrated lower tensile, flexural and impact strengths. This outcome can be attributed to the insufficient fiber content and the higher void content in samples with lower infill densities, as confirmed with the SEM images obtained.
- The maximum tensile modulus of 2160MPa and flexural modulus of 454MPa were obtained for a higher (100%) infill density of 3D-printed samples. The tensile modulus and flexural modulus increased by 22% and

42% when compared to the 60% infill density cCFPC samples. The tensile and flexural modulus plays a crucial role in determining the maximum deformation of the 3D-printed samples. It was observed that samples with 100% infill density consistently yield higher values for both tensile and flexural modulus, indicating enhanced stiffness and resistance to deformation, when compared to lower infill densities of cCFPC, due to the absence of sufficient fiber content in the samples and consequent presence of voids.

Summarily, it was obvious that the optimum 3D-printed cCFPC sample could be suitable materials for semi/structural applications, depending on the desired mechanical load-bearing capacity and working conditions required.

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