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REINFORCEMENT OF 3D PRINTED PLA WITH CARBON FIBER REINFORCED COMPOSITE AND INVESTIGATION OF MECHANICAL PROPERTIES

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Abstract: *While production methods with 3D printing are developing day by day, studies on this method are also increasing. 3D layered manufacturing is a method of creating layer-by-layer 3D solid models designed with computer-aided drawing (CAD) programs using melted raw material for each layer. In addition to PLA being the most commonly used filament in 3D printing, filaments such as ABS, PETG, and TPU are also used. A wide variety of products can be produced with this production method depending on the design. The mechanical properties of the products resulting from 3D printing depend on many parameters such as the number of layers, fill rate, material used, and printing speed. Various methods are also applied to further strengthen the products produced from printing. In this study, PLA samples obtained from 3D printing were reinforced with carbon fibre reinforced polymer composite (CFRP). The reinforcement process was carried out by placing CFRP material during PLA sample production, and the mechanical properties of the resulting samples were examined. Increased hardness as well as improved tensile, bending, impact, and wear strengths of the CFRP reinforced samples were observed.*

Key words: CFRP reinforced PLA,3D printer, Carbon Fiber, PLA, CFRP

1. INTRODUCTION

A 3D printer is a device that creates three-dimensional objects by depositing materials layer by layer based on digital models. This process is known as additive manufacturing. Unlike traditional manufacturing methods that remove material through cutting or drilling (subtractive processes), 3D printing adds material layer by layer only where needed, based on the 3D design. In this study, the FDM method was used. The basic principle of Fused Deposition Modelling (FDM) involves heating and reshaping the raw material to create new forms. In this process, a filament spool, which is the raw material, is gradually unwound by a mechanism typically involving a drive wheel (Dizon et al., 2018). This filament is then fed into a nozzle with controlled temperature to reach a semi-liquid state (Mitchell et al., 2018). As the filament passes through the nozzle, it is extruded in extremely fine, successive layers. The nozzle moves precisely to deposit each layer, progressively building the object from the bottom up. This movement is typically guided by a pre-programmed design created using Computer-Aided Design (CAD) software, which defines the exact path and shape of each layer. By following these CAD specifications, the FDM printer can construct complex three-dimensional structures layer by layer, with highly controlled and accurate precision (Kristiawan et al., 2021).
Initially, the FDM printer heats the nozzle to a specific temperature. The raw material, typically in filament form, is then passed through this heated nozzle. The molten filament is carefully extruded onto the printer's build platform. Upon contact, the material cools and solidifies, forming the first layer of the object. Once the first layer solidifies, the nozzle extrudes additional filament to form the next layer. As it cools, this new layer fuses with the one beneath it. This process is repeated, with each new layer adhering to the previous one, gradually building the object upward. In terms of printing patterns, FDM printers typically follow a specific order. They begin by printing the object's perimeter, outlining the outer and then inner edges. After these boundaries are established, the printer fills in the interior of each layer. This interior can be completely solid or patterned with an infill matrix, depending on the object's design and structural requirements. The printer continues this cycle of extrusion, cooling, and layer bonding until the entire object is complete. The precise movement of the nozzle, directed by the printer's software, ensures that each layer conforms to the design specifications, resulting in a finished product that matches the intended three-dimensional shape (Mwema & Akinlabi, 2020).
Low melting temperature of PLA filament, typically ranging from 200 to 220°C, makes it an accessible

material for a wide range of desktop FDM 3D printers (Szykiedans et al., 2017). This low melting point not only simplifies the printing process by reducing the likelihood of clogging but also eliminates the need for specialized printing hardware, such as heated beds or enclosures. Furthermore, PLA's low shrinkage rate minimizes the risk of warping, a significant advantage when printing large objects or designs with substantial contact areas on the print bed (Wewolver, 2024). In terms of mechanical properties, PLA exhibits a tensile strength of approximately 7,250 psi, making it a fairly strong material for lightweight applications. However, its elongation at break is about 6%, which is lower than some other filaments, such as ABS and PETG, making it more brittle (All3dp, 2024). This brittleness limits its use in situations requiring high impact resistance or load-bearing capacity (Bergström & Hayman, 2016).

A notable feature of PLA is its biodegradability. Unlike petroleum-based filaments, PLA can decompose into its components under suitable conditions, typically within a few months to years (Raja et al., 2022). This property is particularly appealing to environmentally conscious users as it addresses growing concerns about the ecological impact of 3D printing materials (Vanaei et al., 2020). Despite its numerous advantages, PLA also has some drawbacks. Its brittleness, sensitivity to high temperatures, and lower chemical resistance compared to other filaments like ABS and PETG may limit its applicability in certain situations (Lugo, 2022). Additionally, its hygroscopic nature, which leads to moisture absorption, can affect the quality and consistency of the filament, necessitating careful storage and handling (Joseph et al., 2023).

2. EXPERIMENTAL STUDIES

2.1 Materials

2.1.1. Epoxy resin and carbon fibre

Epoxy resin was used as the matrix material. The properties of the carbon fibre used in the production of the CFRP plates are shown in Table 1,

Table 1: Properties of carbon fibre (DowAksa, 2024)

Brand	**DowAksa**
Fiber Type	24K
Fiber Quality	A-42
Tex Amount	1.6 kg per 1000 meters/Nm 1.6
Tensile Strength	2040 MPa

2.1.2 PLA Filament

CBC Filament brand PLA filament was used. The properties of the PLA filament used are shown in Table 2.

Table 2: Properties of PLA filament (ileri3D, 2024)

Marka	**CBC Filament**
Renk	Beyaz
Çap	1.75mm
Çap Toleransı	±0.02

2.1.3 Cyanoacrylate

Cyanoacrylate was used as the adhesive.

2.2 Test Methods

Tensile test was performed on a Zwick Z010 model device at a test speed of 5 mm/min, and 3-point bending test was performed on the same device at a test speed of 2 mm/min. Izod impact test was performed on a Zwick device with a 5.4 Joule hammer. Tensile, impact, and bending tests were performed at room temperature and the test results were calculated by taking the average of 5 samples.

The hardness test was conducted to each sample by taking 10 measurements on a Zwick Shore D test device and the averages of the measurements were calculated.

For the abrasion test, a Pin-On-Disk Test was performed using a Devotrans GT-7012-T model Taber abrasion device and appropriate apparatus, the test was performed with CS10 abrasive wheels according to the ASTM G99 standard at room temperature at a speed of 72 rpm. Before and after each test, the disk and sample surfaces were cleaned with a brush. In this study, 3 samples from each group were tested to determine the weight loss after abrasion and the arithmetic average was calculated. The weights of each sample were measured at the beginning (before wear) and every 250 turns, for a total of 1000 turns, on a precision balance with a precision of 0.0001 g, and the weight loss (Δm) was calculated.

2.3 Manufacturing Methods

2.3.1 Carbon Fiber Reinforced Composite (CFRP) Plates

Carbon fibre reinforced composite (CFRP) sheets were produced by the pultrusion method. The produced plates were cut according to test standards using a special cutter. The flowchart of the CFRP plate production method is shown in Figure 1. The CFRP plates are 10mm wide for tensile test specimens, 6.5mm wide for other specimens, and full length for all specimens.

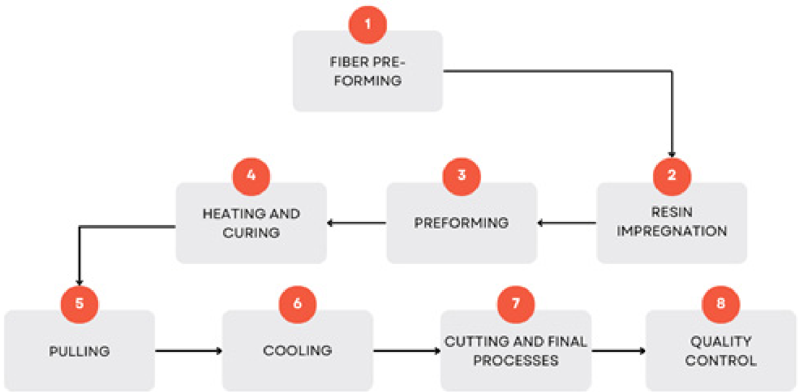

Figure 1: CFRP plate production method flow chart

2.3.2 PLA specimens containing CFRP plates

The production flowchart of the PLA specimens containing CFRP plates is shown in Figure 2.

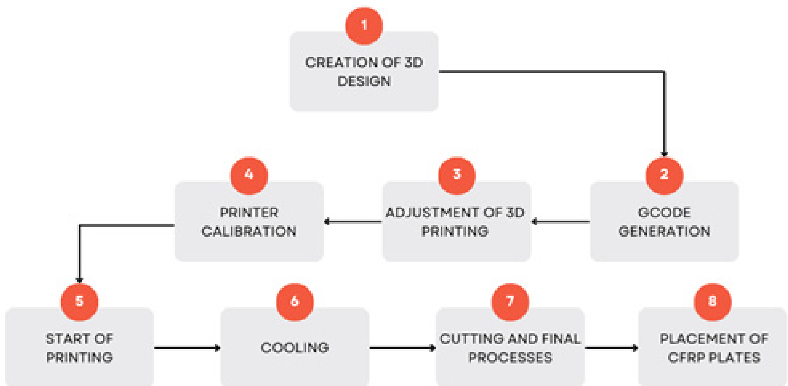

Figure 2: Production flow chart of PLA composite samples containing CFRP plate

In the first stage of the production process, the specimens were designed according to ASTM standards using the Fusion 360 CAD program (Figures 3 and 4).

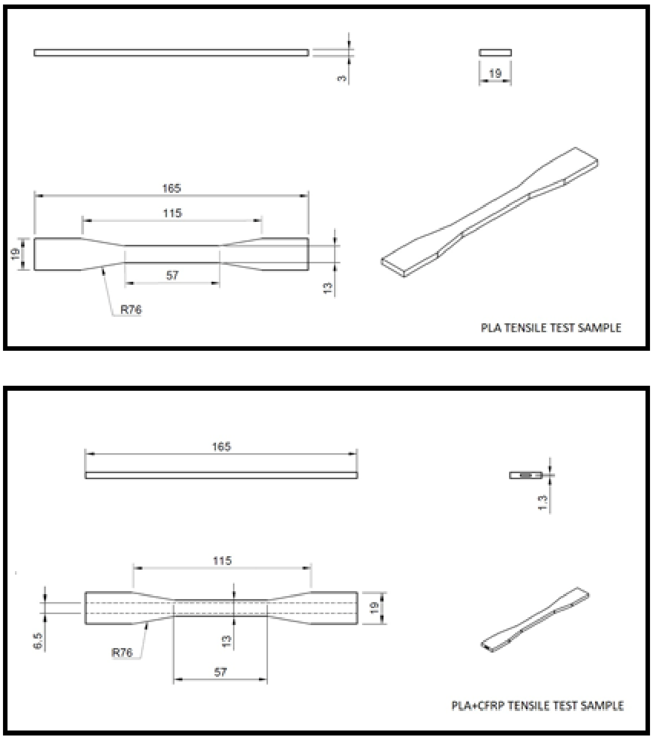

Figure 3: Technical drawing of the tensile specimens

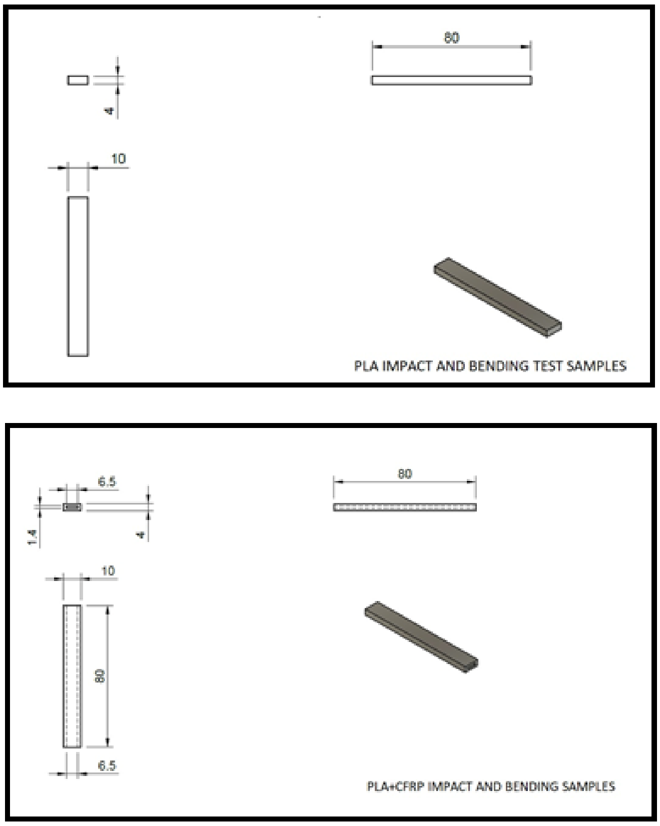

Figure 4: Technical drawing of the impact and bending test specimens

In the next stage, the 3D design (CAD) of the samples was "sliced" in the software called Ultimaker Cura, the parameters were integrated into the printer in a suitable way and converted into Gcode (Figure 5). The files converted into Gcode were transferred to the 3D printer with a USB memory stick.

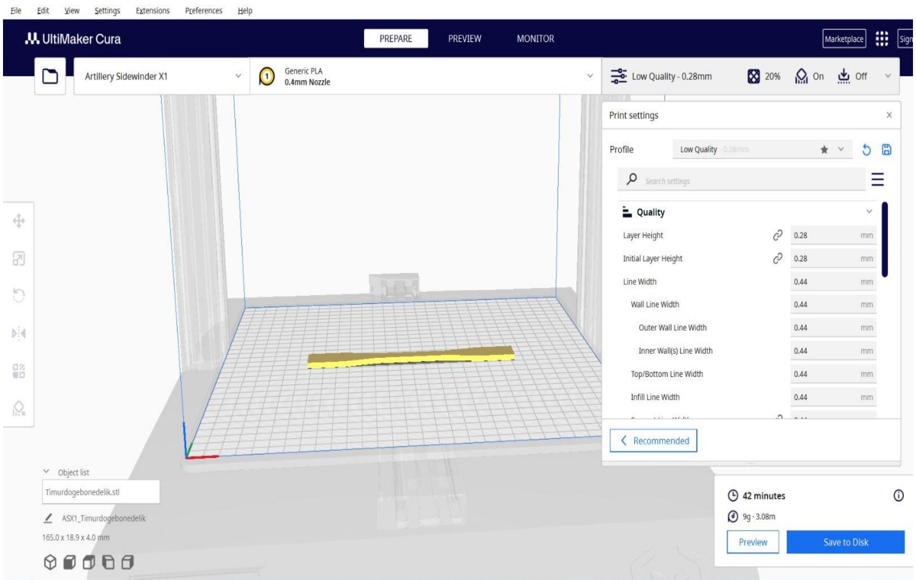

Figure 5: Transfer and adjustment in the Slicing program

After the transfer, the specimens were printed using the 3D printer (Figure 6).

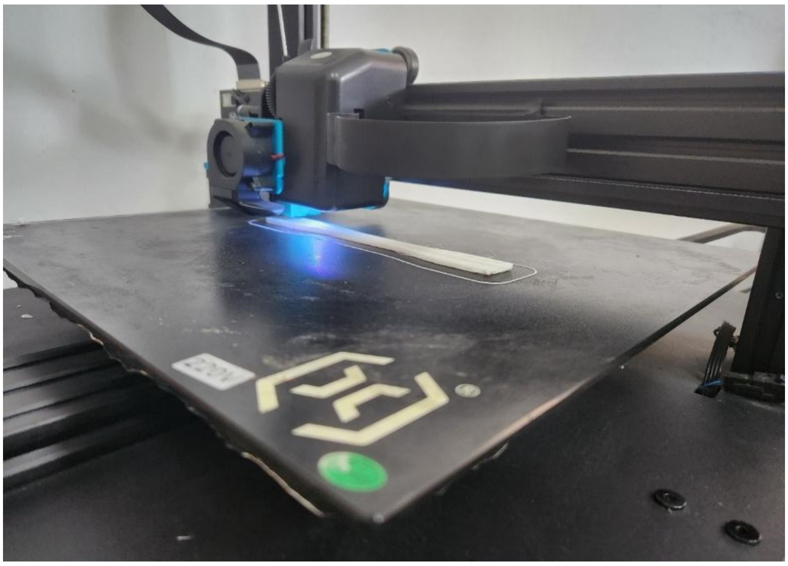

Figure 6: 3D Printing

The samples that finishing printing were slowly removed from the printer platform surface. Then the printer platform surface was cleaned and the process was repeated for the other samples. CFRP plates were placed inside the hollow PLA samples obtained from the 3D printer. Cyanoacrylate adhesive was used to ensure good adhesion between PLA and CFRP (Figure 7).

PLA samples containing CFRP plates were produced as 85% PLA – 15% CFRP. CFRP plates were placed end to end along the length of the PLA samples.

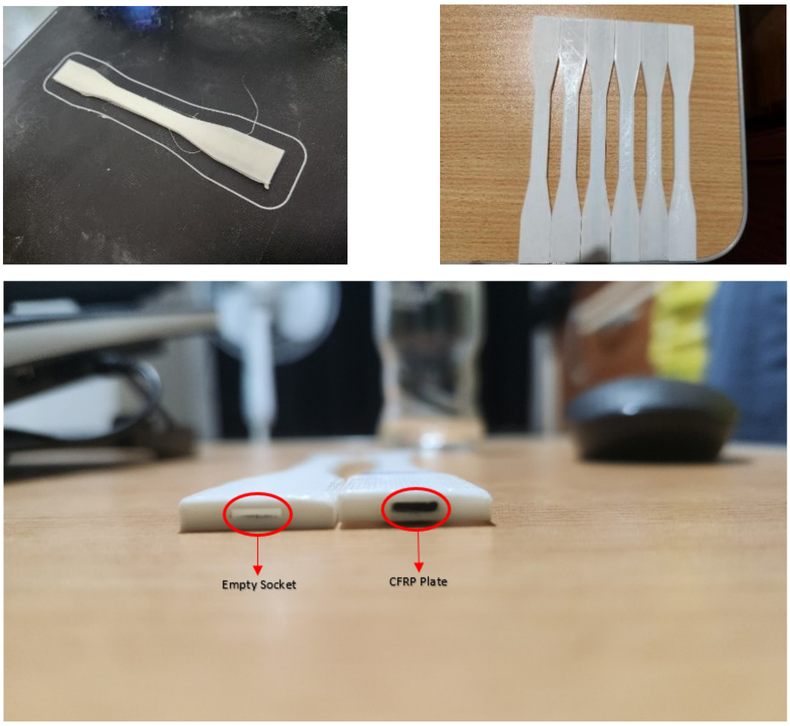

Figure 7: Specimens after printing

3. RESULTS AND DISCUSSION

The comparison between pure PLA and PLA+CFRP in the Izod impact test revealed significant performance differences. The impact strength of the pure PLA specimen was 6.02 kJ/m², whereas the PLA+CFRP composite specimen exhibited an impact strength of 41.85 kJ/m² (Figure 8). This indicates that the impact strength of PLA+CFRP composite material is higher than that of pure PLA, because CFRP reinforcement improved the fracture energy absorption ability of PLA. This improvement is due to the carbon fibre's ability to effectively distribute the impact force and the resulting energy across the PLA matrix. It is well-known that PLA is a brittle material.

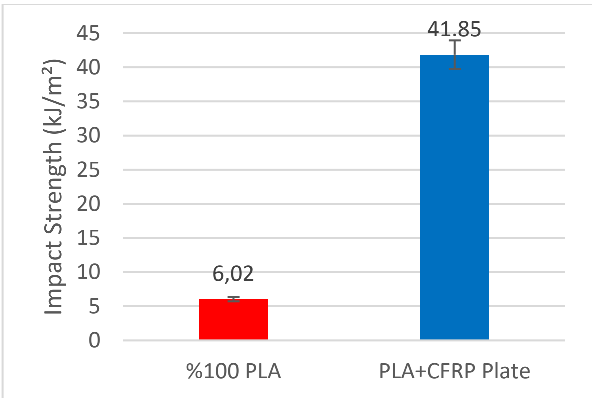

Figure 8: Izod ımpact test results

According to the hardness test results, the Shore hardness value of pure PLA is 62, while the value of the PLA+CFRP composite is 67 (Figure 9). Since CFRP has a harder structure, it increased the hardness of the PLA matrix. This increase in hardness is due to the structural contribution of the carbon fibre, which provides additional support to the PLA matrix.

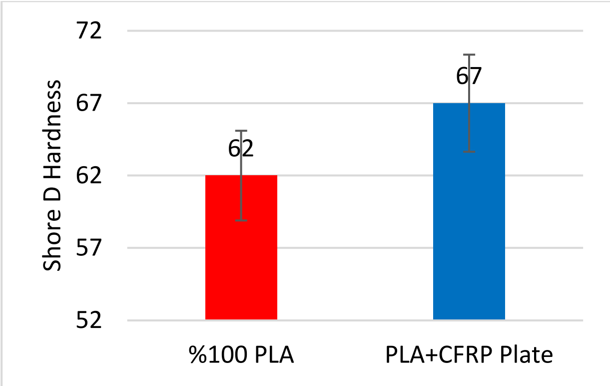

Figure 9: Shore D hardness test results

According to the abrasion test results, the weight loss in the pure PLA sample was 0.13%, while the weight loss in the PLA+CFRP composite was 0.09% (Figure 10). The PLA+CFRP composite sample suffered minimal material loss and exhibited better abrasion resistance. The reinforcement provided by the CFRP prevented rapid surface degradation by resisting the abrasive forces more effectively in the composite sample.

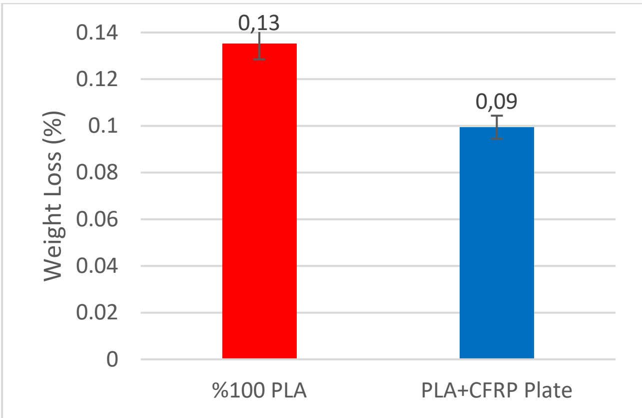

Figure 10: Abrasion test results

The tensile test results revealed a clear difference between the pure PLA and PLA+CFRP samples. While the tensile strength of pure PLA was 20.1 MPa, the tensile strength of the PLA+CFRP composite reached 127.75 MPa (Figure 11). The CFRP reinforcement led to a significant increase in the strength of the pure PLA. In the tensile test, it was observed that only PLA fractured in the PLA+CFRP sample, while the CFRP reinforcement inside did not fracture (Figure 12). This indicates that the adhesion between PLA and CFRP is not very good. If the adhesion were good enough for PLA and CFRP to break together, the tensile strength would have been much higher.

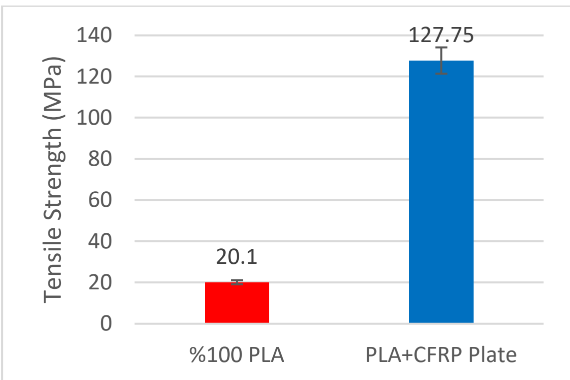

Figure 11: Tensile test results

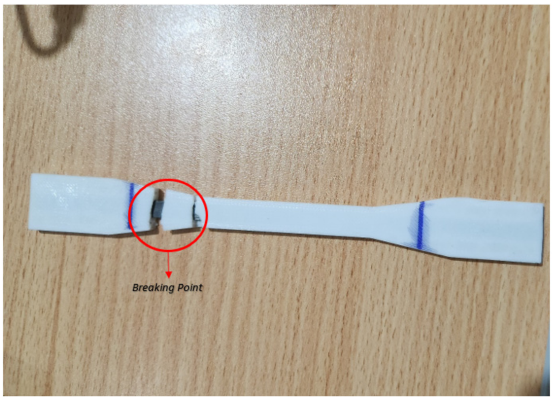

Figure 12: Breaking shape of the sample in tensile test

According to the 3-point bending test results, there was also a significant difference in flexural strength between pure PLA and PLA+CFRP. While the flexural strength of pure PLA was 50.24 MPa, the flexural strength of PLA+CFRP composite increased by more than threefold to 165.25 MPa (Figure 13). An important point observed during this test was that the PLA+CFRP composite sample exhibited brittle behaviour and the two materials were subjected to fracture together under bending. In the tensile test, PLA peeled away from the CFRP plate and fractured, while in the bending test, PLA and CFRP were damaged together. This indicates that the adhesion between PLA and CFRP plate is strong enough to prevent delamination in terms of resistance to bending and that PLA and CFRP can work together under bending stress.

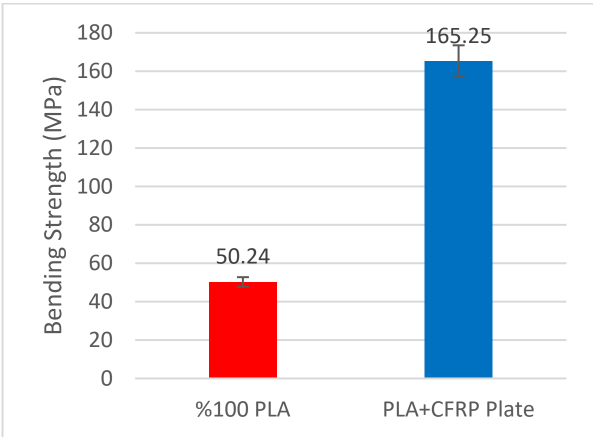

Figure 13: Three-point bending test results

4. CONCLUSION

In this study, the aim was aimed to improve the mechanical properties of PLA produced with a 3D printer by reinforcing it with a carbon fibre reinforced composite (CFRP) plate. The CFRP plates placed inside the PLA samples used in the study provided improvements in mechanical properties. The improved mechanical performance of the PLA+CFRP composite enhances its suitability for challenging mechanical applications. This production method, which increases the tensile, impact, bending and abrasion strengths and hardness of the PLA+CFRP composite sample produced with a 3D printer, can be an effective solution in the production of drone parts where mechanical properties are important and especially in applications requiring lightness and strength.

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