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# Investigation into the Development of an Additive Manufacturing Technique for the Production of Fibre Composite Products

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**Abstract**

The advancements in manufacturing technology over recent years have made Additive Manufacturing, a breakthrough technology in the designing and manufacturing field. This paper discusses the possible applications of Additive Manufacturing (AM) techniques for the production of Carbon Fibre (CF) components without the aid of mould or plug used by traditional methods. This paper investigates the available AM designing techniques to experimentally prove the validity of the research to develop a design concept that can be embedded into an AM machine as a 3D Printer. Polylactic acid (PLA) tensile test specimens are produced with CF reinforcement using both traditional moulding and AM techniques. The preliminary mechanical testing of moulded specimens with fibres revealed a tensile strength increase of up to 73% when compared to specimens without fibres and the testing of PLA filaments produced by AM with fibres showed a performance increase of 66% when compared to filaments without fibres.


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*Keywords:* Additive Manufacturing; 3D Printing; Fibre Printing; Composites.

## 1. Introduction

In the world of manufacturing technology, there are occasional breakthroughs that have the potential to transform the industry, empowering existing products to be made faster, cheaper and better, opening up a realm of new possibilities in product development [1]. Additive Manufacturing (AM) is such a technology which is capable of

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manufacturing complex structures directly from a CAD model with less wastage of resources [2]. This paper discusses the possible applications of AM techniques for the production of Carbon Fibre (CF) composites without the aid of mould or plug used by the traditional methods. As the manufacturing industries are considering benefiting from the AM designing techniques, there has been only limited research work done on the possibilities of using fibres as a material in these techniques [1-5].

The research in this area has recently received more attention due to the popularity of user friendly 3D printers, where the users can change the machine's operating mechanisms to suit their specific purpose. Because of the complexity offered in manufacturing by AM technology and the strength to weight ratio offered by fibres such as CF, researches are working on combining these two technologies. At the Zurich Centre of Structure Technologies, researchers are working on laminating the geometrically complex manufactured AM parts with sheets of CF to increase the strength [3]. They used epoxy prepregs to bond the CF sheets, for which additional curing processes are required. Further research is also being carried out to provide efficient co-bonding of epoxy between the AM parts and the CF sheets. The thermoset composites have been in use for many years and are manufactured by traditional methods. However thermoplastic composites have many advantages over thermoset composites [2]. And they can also be altered even after the product is finished as their chemical bonding is completely reversible [4]. For this reason the matrix material preferred is a thermoplastic rather than a thermoset. It is because of these properties, thermoplastics are used in similar researches at Toyohashi University of Technology, which involve sandwiching the 3D printing parts with CF layers in a heated oven [5].

This paper investigates the available AM designing techniques to prove the potential and significance of the research in this area. The main aim of this research is to produce the CF parts at a one-time process using the AM technologies available, similar to building 3D parts from a CAD design in one go. This can be achieved by designing an extruder for a 3D printer which can extrude thermoplastic material and fibres. The printed components will be benchmarked with other AM products by conducting structural tensile tests to analyse their performance under various environmental conditions.

**Nomenclature**

| | |
|---|---|
| AM | Additive Manufacturing |
| 3D | Three dimensional |
| PLA | Polylactic acid |
| ABS | Acrylonitrile butadiene styrene |

## 2. Methodology and Experimental Procedure

Selecting the material for the experimental work is very crucial as it determines the strength of the final parts. The most widely used thermoplastic materials are Polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS). The bonding of these materials is studied at various temperatures as this determines whether resins can be excluded from the work or not. So the behaviour of these materials as binders are studied for the proper selection of the resources required for generating the design concept. The experimental work involves producing Dumb-bell shaped specimens of thermoplastic and thermoplastic with fibres, and these specimens are tested for structural strength analysis. After considering the required criteria such as mechanical properties and the structural behaviour of the materials under various environmental temperature conditions, the working of AM machines used for the deposition of layers and building the parts are studied. Depending on the results obtained by previous studies and observations, a CAD model of the final product is designed using SolidWorks software and is tested for structural tensile and environmental failures. Once the testing of the model is finished, a physical prototype is manufactured and is embedded into the machine for part building. Based on the research done, a decision has to be made whether resins are to be used as binders or not and also whether to develop a single nozzle multi-material extruder system or multi-nozzle system to extrude the materials individually. Once the test specimens are built with carbon fibre by the modified printer, preliminary tests are done on these specimens for structural performance and case studies are developed by benchmarking them with the parts printed by the commercially available industry leading printers.

The designing and building of the parts may be altered depending on the results obtained from the tests, until a satisfactory outcome is achieved.

The reinforcement material selected for this research is CF and the matrix material is PLA. The reason to select these specific materials is that CF exhibited better performance at higher temperatures as observed later in the results section. Also PLA exhibited better bonding and surface finish at higher temperatures when combined with CF. To select the right material for this research the behaviour of these materials is studied at their melting points and beyond using a FLIR T620bx thermal imaging camera. Individual filaments of PLA and ABS are combined together as a layer and are melted in the oven and then cured at atmospheric temperature to observe the viscosity, bonding and surface finish between these filaments. The surface profile is studied under an Alicona Infinite Focus microscope. To test the bonding of the fibres with PLA, the material is melted into standard tensile test dumb-bell specimens by using an aluminum mould, which is made by clamping several dumb-bell punched aluminum plates together. The diameter of PLA and ABS filaments is 1.75 mm, the densities of PLA and ABS are 1.24 and 1.04 g/cm3 and the tensile strengths of PLA and ABS are 50 MPa and 43 MPa respectively and are provided by Robosavvy, London. PLA and ABS filaments, are placed together and the individual filaments and CF strands are deposited in layers alternatively and heated in a Carbolite CWF 1100 oven at 2300C for 5 min until both the thermoplastic layers and fibres are bonded together. For this research continuous CF strands manufactured by Easy Composites Ltd are used and the diameter, density and tensile strength of the fibre are 5 µm, 1.76 g/cm3 and 5 GPa respectively, which are similar to the material used by ken-ichiro Mori et al. [5]. The mould with the PLA filaments and CF layers can be seen in Figure 1 and the melted specimen with CF from the aluminum mould after cooling can be seen in Figure 2. Because of the possibility of proper bonding between melted PLA and CF, use of thermoset resins can be excluded and replaced with PLA as the matrix material for binders.

Fig. 1. Specimen mould in oven

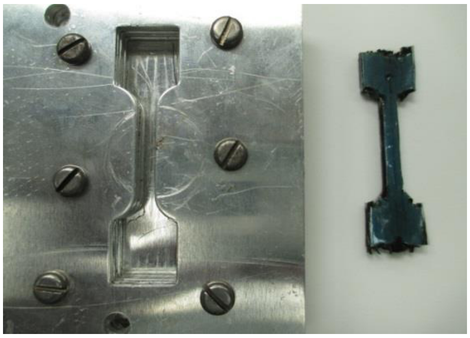

Fig. 2. Tensile specimen with CF layers

The temperature 2300C to be used for the oven to produce these specimens is determined from the normal operating temperature of a MakerBot 3D printer extruder nozzle and also the observations made from the thermal imaging camera. The different types of specimens produced for testing can be seen from table in Table 1.

Table 1. Types of Specimens and their specifications

| Specimen Type | Group Name | Thickness (mm) | Sample ID | No of Fibre Layers | Manufacturing Method |
|---|---|---|---|---|---|
| Dog Bone | Set 1 | 4.6 | Printed PLA | 0 | AM |
| | | | Melted PLA | 0 | Mould |
| | | | Melted PLA+CF | 1 | Mould |
| | Set 2 | 4.8 | Printed PLA | 0 | AM |
| | | | Melted PLA | 0 | Mould |
| | | | Melted PLA+CF | 2 | Mould |

| | | | | | |
|---|---|---|---|---|---|
| Filament Strand | PLA | 0.4 | PLA 1,2,3 | 0 | AM |
| | PLA-CF | 0.4 | PLA-CF 1 | 1 | |
| | | | PLA-CF 2 | 1 | |
| | | | PLA-CF 3 | 2 | |

The 3D printer being used for this research to print the specimens is the FDM based MakerBot Replicator 2 and the most common material available for this printer is PLA. The tensile test specimen printed sample is designed by SolidWorks CAD software and the dimensions used are shown in Figure 3. The printed specimens are tested using Instron 3382 tensile testing machine as can be seen in Figure 4.

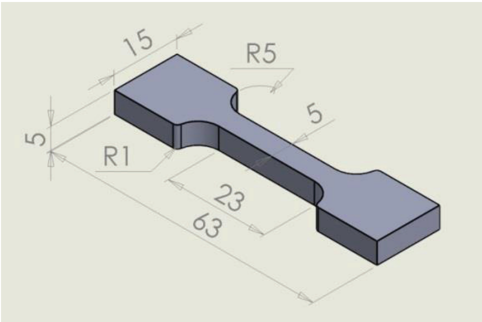


Fig. 3. CAD design of specimen

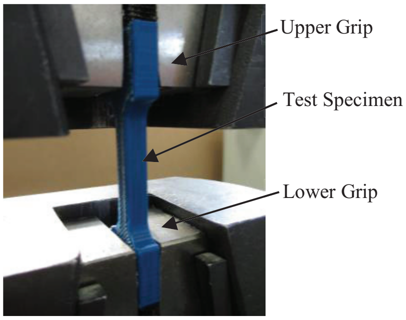


Fig. 4. Tensile testing printed specimen

Since these test specimens are produced by a melting process in an oven and the main objective of this research is to build the PLA-CF parts using the printer, the tensile strength analysis has to be performed on the printed specimens with fibres. So initially to benchmark the performance of the extruded filaments, the fibre is fed through the extruder nozzle of the printer along with the PLA filament and the extruded PLA-CF filaments are initially tested against extruded PLA without fibres before going into the actual PLA-CF specimen printing and part building to establish the potential and reliability of the research.

In this process, Carbon Fibres are fed through the printer nozzle manually and the PLA filament is extruded along with the fibres embedded into it. A part of such PLA-CF filament with two fibre strands can be seen in Figure 5 which is scanned at 200x µm magnification.

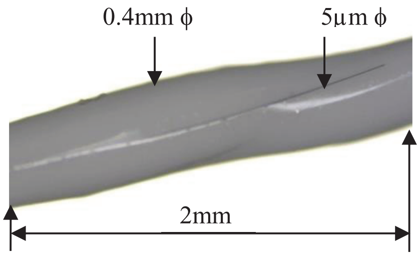


Fig. 5. Extruded PLA filament with CF strands

One set of three of these PLA filaments with 25 mm length are extruded without fibres and another set of three are extruded with fibres and are tested for the strength analysis using the tensile testing machine.

The analysis of tensile strength for all the dog bone specimens is carried out using the Instron 3382 tensile testing machine and all the filaments are tested using Instron E3000 at a crosshead speed of 2.5mm/min for both. The surface structure and finish of these fractured specimens are studied under an Alicona Infinite Focus 3D Scanner microscope.

## 3. Results and Discussion

### *3.1. Viscosity and Curing Time Analysis*

The temperatures of the extruder and the material coming out of the extruder from the printer are studied to estimate the curing time of PLA as it helps in understanding whether two nozzles should be used to lay the PLA and fibre or not. From thermal imaging camera images shown in the Figure 6, it is observed that the extruder temperature and the material coming out of the extruder are of the similar temperatures which are about $210^{0}$C and $186^{0}$C, and it is taking 4 to 5 seconds for the molten PLA to cure and come to the ambient temperature. So if a dual nozzle extruder should be used, the second nozzle should be able to lay the fibre before the curing time of PLA for a proper bonding.

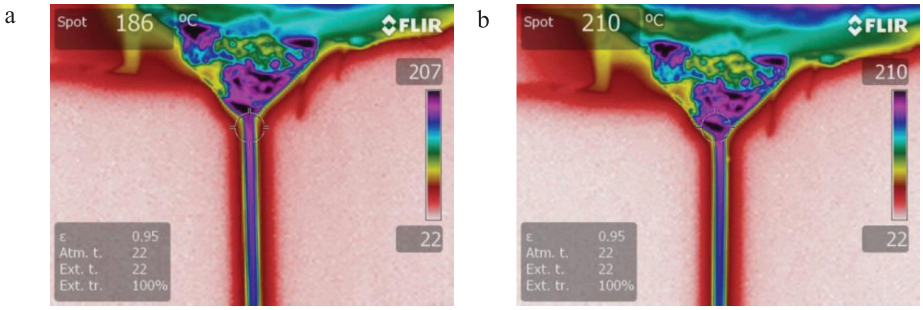


Fig. 6. Temperature spectrum from Thermal Imaging Camera at (a) Filament; (b) Nozzle

From the observations made, if the fibres and the PLA material can be extruded through a single extruder, then the possibility of designing a multi-nozzle system can be eliminated to reduce design complexities.

### *3.2. PLA vs ABS Surface Finish and Bonding*

When the surfaces of the PLA and ABS are observed under the microscope, it can be observed that PLA exhibited better surface finish. This is not a selection criterion for material, but an observed feature characteristic of these materials. The 3D scans of these materials and the profiles of their surface finish can be seen as shown in Figure 7 which are scanned at 200x µm magnification.

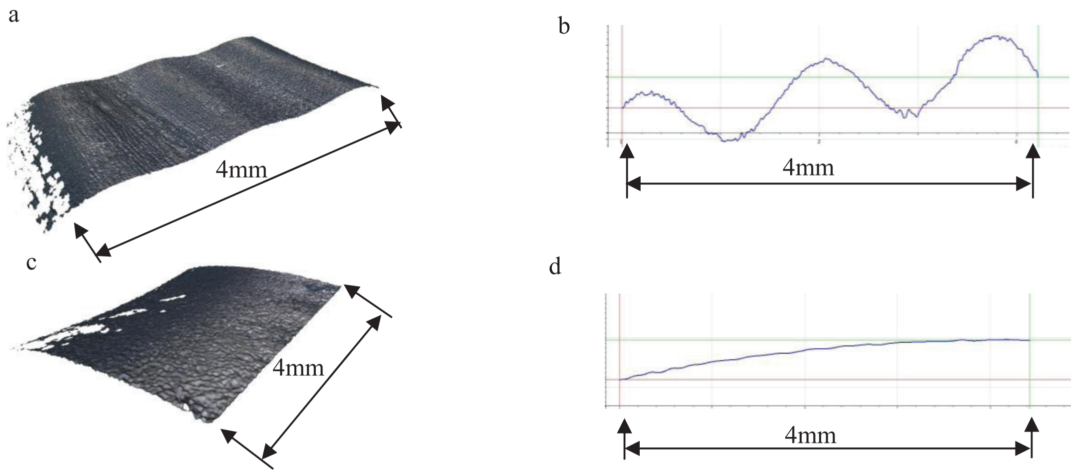


Fig. 7. (a) 3D scan of melted ABS surface; (b) Graph showing surface profile of melted ABS; (c) 3D scan of melted PLA surface; (d) Graph showing surface profile of melted PLA

Since the viscosity of PLA is better at $230^{0}$C temperature, it can bond well with the fibres and so this material can be used to test this assumption. The PLA-CF specimens produced from the melting process are tested for tensile strengths and the fractured sections are observed under the microscope for the analysis of bonding between fibres and melted PLA. The bonding between the melted PLA material and CF can be seen as shown in Figures 8 and 9 which are scanned at 50x and 20x µm magnifications respectively, where the 3D scans revealed a perfect fracture showing that the fibres are not pulled apart from the PLA. The black spots in Figure 8 are the areas of the unavailable data from the microscope.

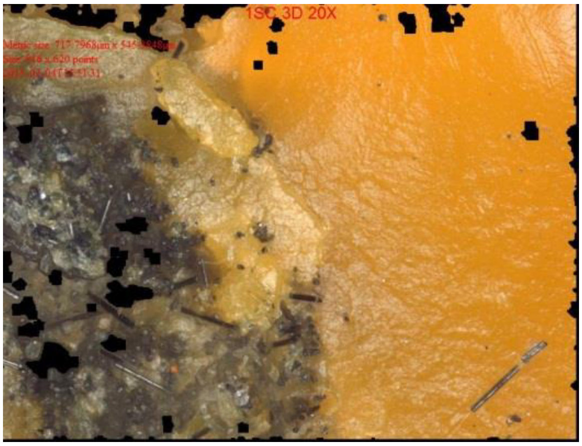

Fig.8. 2D scan of PLA with CF

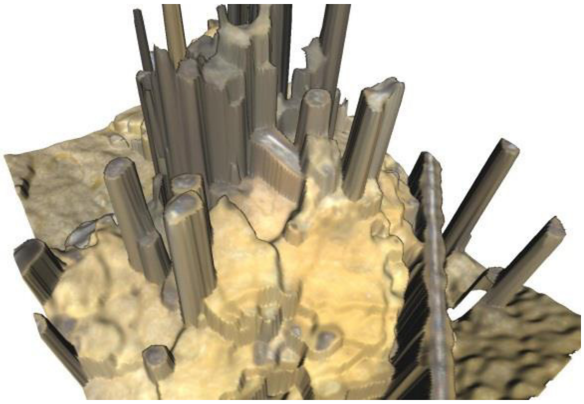

Fig. 9. 3D scan of PLA with CF showing bonding

As it can be observed from these figures, the fibres bonded well with the PLA material and so there is a high possibility that the PLA material can be used as a binder and can serve as the matrix material.

### *3.3. Tensile Strength Analysis of Specimens*

For the first set of testing, the specimens printed and melted with fibres are of 4.6 mm thickness and for the second set of specimens the thickness is increased to 4.8mm because of adding an additional layer of fibres. Also for the first set, one layer of CF is deposited and for the second set of specimens, two layers of CF are deposited. Fractured areas of these specimens after testing can be seen in Figure 10, where they are scanned at 1000x µm magnification.

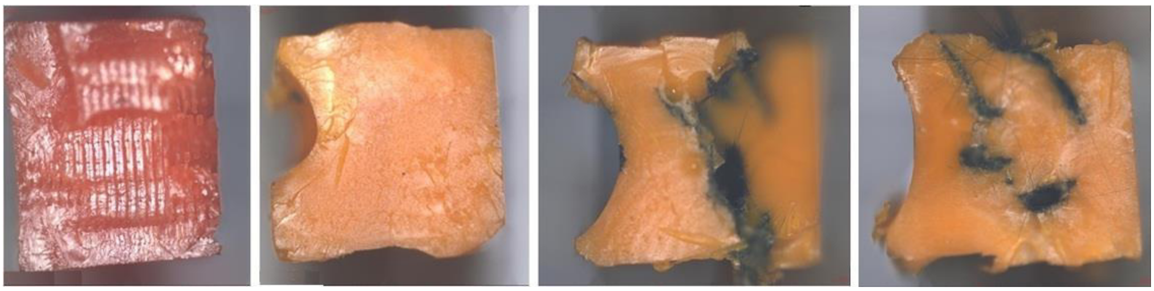

Fig. 10. PLA printed, melted, melted with CF 1 layer and 2 layers

The tensile strength analysis of these specimens can be observed from plotting the graph for Young's Modulus by taking strain on x-axis and stress on y-axis as shown in Figure 14.

From the graph it can be observed that for the first set, the printed specimen's ultimate tensile strength is 42 MPa and the melted specimen also performed similar with a tensile strength of 45 MPa. But when the specimen is embedded with fibres it showed an increase of 38% with the tensile strength of 62 MPa. Also it can be observed from Figure 10 that all the fibres are stacked together at one layer and if these fibres are distributed across the layers, it could have performed even better. So for the next set, care has been taken in the placement of 2 layers of fibres to verify that fibre distribution plays a key role in providing better strength.

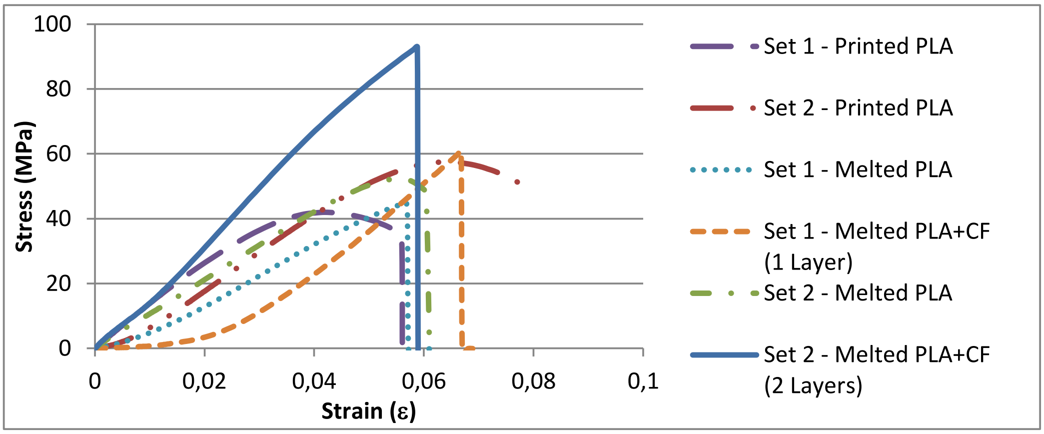


Fig. 11. Graph showing tensile strength comparison of PLA, PLA-CF Specimens

From the graph it can be observed that for the second set, the printed specimen's tensile strength is 58 MPa and the melted is 55 MPa which are close. But when this is compared to specimen with 2 CF layers, its strength is increased to 95 MPa which is 73% higher. This is due to the distribution of fibres and also the concave structure of the surface is reduced as it can be observed from Figure 13. Also it can be observed that the tensile strength of melted specimen with 2 CF layers performed 46.2% better than the specimen with 1 CF layer. So it can be concluded that fibre distribution plays a crucial role in determining the strength of the final PLA-CF product.

### *3.4. Tensile Strength Analysis of Extruded Filaments*

For the tensile strength analysis of the extruded filaments, the results are plotted on the graph for the Young's Modulus by considering strain on x-axis and stress on y-axis as shown in Figure 12.

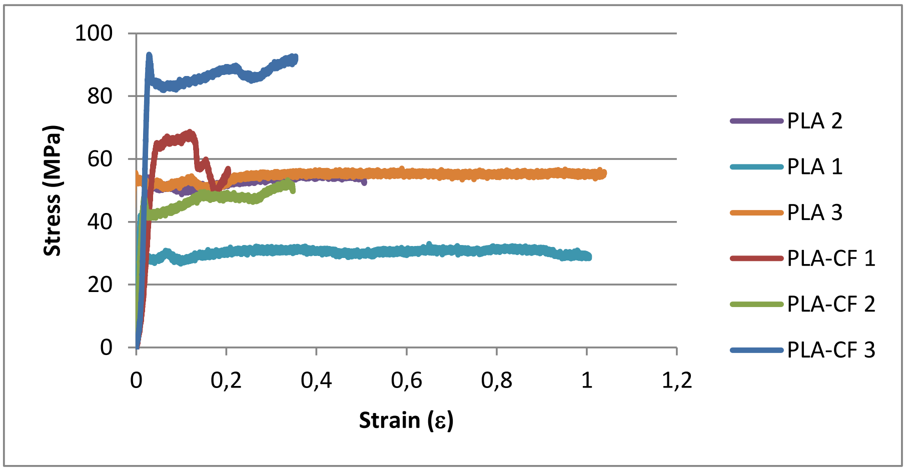


Fig. 12. Graph showing tensile strength comparison of PLA, PLA-CF filaments

The performance of the first set containing three PLA filaments varies between 41 MPa to 56 MPa whereas the second set of three PLA filaments with CF performed with a capability of holding the stresses between 56 MPa to 93 MPa. This is an increment of up to 66% in strength when compared to the filaments without fibres. Even the previous results of the specimens displayed similar results with an increase of 73%. The results of the filament cannot be compared with the specimen as the gauge length for the filament is 15mm as compared to 23mm for the specimen and also the elasticity of the filament is greater to that of the specimen. The difference in the performance of the filaments with fibres is due to the placement of fibres in filaments, as the PLA-CF 3 filament with two fibre strands yielded slightly higher results compared to PLA-CF 1 and PLA-CF 2 filaments which are with one carbon fibre strand.

## 4. Conclusions

From the above obtained results it can be concluded that PLA material can better serve the purpose of this research which is to have a proper bonding between the thermoplastic material and the fibres. The initial tests of the PLA with CF specimens produced by the melting process displayed satisfactory results with an increase of 73% in tensile strength performance. Also the tensile tests conducted on the PLA filaments extruded with CF yielded better results than the filaments without the fibres with a tensile strength increment of 66%, but further tests are to be conducted for the specimens built by the printer rather than just filaments. The results and observations support the potential of this research and suggest there is a need for attention in this area. The implementation of this method practically will provide valuable information for further studies in this field.

The fibres are fed through the extruders manually and as this research aims at designing an extruder which can extrude the fibres without human aid, further research focusses on development of this design of the PLA-CF extruder which can be embedded into the 3D printer.

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