



N A B E E L M A Q S O O D

**RESEARCH AND
DEVELOPMENT
OF ADDITIVELY
MANUFACTURED CARBON
FIBER REINFORCED
SOLID AND CELLULAR
COMPOSITE STRUCTURES**

D O C T O R A L D I S S E R T A T I O N

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KAUNAS UNIVERSITY OF TECHNOLOGY

NABEEL MAQSOOD

RESEARCH AND DEVELOPMENT OF
ADDITIVELY MANUFACTURED CARBON
FIBER REINFORCED SOLID AND CELLULAR
COMPOSITE STRUCTURES

Doctoral dissertation
Technological Sciences, Mechanical Engineering (T 009)

2023, Kaunas

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Scientific Supervisor

Assoc. Prof. Dr. Marius RIMAŠAUSKAS (Kaunas University of Technology, Technological Sciences, Mechanical Engineering, T 009).

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Dissertation Defense Board of Mechanical Engineering Science Field:

Prof. Dr. Paulius GRISKEVIČIUS (Kaunas University of Technology, Technological Sciences, Mechanical Engineering, T 009) – **chairperson**;

Assoc. Prof. Dr. Saulius BASKUTIS (Kaunas University of Technology, Technological Sciences, Mechanical Engineering, T 009);

Prof. Dr. Giedrius JANUŠAS (Kaunas University of Technology, Technological Sciences, Mechanical Engineering, T 009);

Assoc. Prof. Dr. Katarzyna MAJEWSKA (Institute of Fluid-Flow Machinery, Poland, Technological Sciences, Mechanical Engineering, T 009);

Dr. Genrik MORDAS (Vilnius University, Center for Physical Sciences and Technology, Natural Sciences, Physics, N 002).

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Address: K. Donelaičio 73-402, Kaunas, LT-44249, Lithuania

Phone: (+370) 608 28 527; email doktorantura@ktu.lt

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Doktorantūros teisė Kauno technologijos universitetui suteikta kartu su Vytauto Didžiojo universitetu.

Mokslinis vadovas:

doc. dr. Marius RIMAŠAUSKAS (Kauno technologijos universitetas, technologijos mokslai, mechanikos inžinerija, T 009).

Redagavo: anglų kalbos redaktorius dr. Armandas Rumšas (leidykla „Technologija“), lietuvių kalbos redaktorė Aurelija Gražina Rukšaitė (leidykla „Technologija“)

Mechanikos inžinerijos mokslo krypties disertacijos gynimo taryba:

prof. dr. Paulius GRISKEVIČIUS (Kauno technologijos universitetas, technologijos mokslai, mechanikos inžinerija, T 009) – **pirmininkas**;

doc. dr. Saulius BASKUTIS (Kauno technologijos universitetas, technologijos mokslai, mechanikos inžinerija, T 009);

prof. dr. Giedrius JANUŠAS (Kauno technologijos universitetas, technologijos mokslai, mechanikos inžinerija, T 009);

doc. dr. Katarzyna MAJEWSKA (Ševalskio skysčių srautų valdymo institutas, Lenkija, technologijos mokslai, mechanikos inžinerija, T 009);

dr. Genrik MORDAS (Vilniaus universitetas, fizinių ir technologijos mokslų centras, gamtos mokslai, fizika, N 002).

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Adresas: K. Donelaičio g. 73-402, Kaunas, LT-44249, Lietuva

Tel. (+370) 608 28 527; el. paštas doktorantura@ktu.lt

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LIST OF ABBREVIATIONS

AM	Additive Manufacturing;
CAD	Computer-aided design
FDM	Fused deposition modeling
PLA	Polylactic acid
ABS	Acrylonitrile butadiene styrene
PS	Polystyrene
PC	Polycarbonate
PA	Polyamide
CF	Carbon fiber
CCF	Continuous carbon fiber
CCFRPC	Continuous carbon fiber reinforced polymer composite
CCE	Controlled cooling effect
3K	3000 yarn carbon fiber tow
SCF	Short carbon fiber
PVA	Poly vinyl alcohol
V_f	Volume fraction
PPEK	Polyether ether ketone
TPI	Thermoplastic polyimide
FRP	Fiber reinforced polymers
XCT	X ray computed tomography
DCFRPC	Discontinuous carbon fiber-reinforced polymer composites
SLA	Stereolithography
SLS	Selective laser sintering
IJP	Inkjet 3D printing
NPMHE	Non-parametric Modified Histogram Equalization
E.T.	Extrusion temperature
E.W.	Extrusion width
E.M.	Extrusion multiplier
S.I.	Source image
E.D.	Edge detection
C.E.	Contrast enhancement
RoM	Rule of mixture

INTRODUCTION

Relevance of the Thesis

Presently, the manufacturing industries are spreading so significantly that it requires the manufacturing and delivery of products in a huge volume in a limited amount of time while utilizing various types of material for different engineering applications. While the requirements applicable to such manufacturing industries are variable, they still share the need to improve their product quality to make it more precisely with the minimum wastage of the material, and thus make it more sustainable. Such necessities are being fulfilled by converting the conventional production system to a digitalized and computerized controlled system which enables them to reach an extent that can lead to an increase of the production rate with more precision and flexibility in geometrical shapes with a lower amount of wastage.

Additive manufacturing (AM), also referred to as *3D printing* or *rapid prototyping*, is an advanced manufacturing process that constructs a 3D part layer by layer by following the *computer aided design* (CAD) model until the final product has been obtained as opposed to subtractive manufacturing methodologies. This technology is used to manufacture metal, ceramic and plastic parts and composite materials with complex geometries. Compared to the traditional manufacturing technology, the additive manufacturing technology can shorten the design and production cycles, thereby reducing the production costs and improving the corporate competitiveness [1]. AM is emerging as one of the fastest growing and most widely adopted innovations and manufacturing technologies in various engineering industries for rapid production. In recent years, these innovative technologies have advanced to such a level where they can provide end-product production. AM has the manufacturing capabilities and ability to achieve micron-level resolution in 3D printed structures and geometries through flexible material and cost-effective rapid manufacturing. These factors have contributed to the evolution of the AM technology into a multi-billion-dollar industry [1, 2]. For the manufacturing of a product using AM, three main steps are followed:

1. Designing of a 3D CAD model and converting it to a standard file format (.STL).
2. Setting of the parameters of the printing machine for the provided standard file.
3. Starting to build the solid part layer by layer until the part has been completed [3].

AM is extensively used for the fabrication of polymer parts ranging from prototypes to final products [4]. AM of polymers and polymer composites has been applied in a variety of engineering industries, such as aerospace and military for complex lightweight structures, the biomedical field for tissue and organ printing, architectural structural model design, automotive, construction and food machining [3, 5]. The reputation of this technology is significantly enhanced when it is used in the production to manufacture composites, primarily polymer matrix composites.

Fused deposition modeling (FDM), an extrusion-based AM technology, is one of the most widely and commonly techniques to fabricate a structural part with pure polymers and composite materials. The technology is renowned due to its simplicity, ease in usage, the range of materials, less material wastage and economic factors. The thermoplastic matrix, when reinforced with *continuous carbon fiber* (CCF), dramatically increases its mechanical strength and flexibility, thus forming more durable composites. But, on the other hand, the printability, processing and fabrication procedures are the features that are not easy to deal with during the manufacturing process. There are various factors influencing the quality and mechanical performance of the fabricated *CCF reinforced polymer composite* (CCFRPC) structure. Firstly, the process of impregnation of standard CCF plays a vital role in the printability and quality of the fabricated composite specimen. Secondly, the selection of the printing process parameters for the production while using the FDM technology also have an important role which must be analyzed and determined for better mechanical properties.

The relevance of the research emphasized the importance of the AM technology, mainly FDM, in the production of light-weight solid and cellular composite structures using CCF as reinforcement to fulfill the demand of high structural engineering applications using optimized parameters.

Aim of the doctoral thesis

To develop and fabricate continuous carbon fiber reinforced solid and cellular composite structures based on the FDM technology with improved quality and mechanical properties. To achieve this aim, the following objectives were set:

Objectives

1. To fabricate 3D printed thermoplastic polymer composites reinforced with short carbon fiber and impregnated continuous carbon fiber using a modified extrusion head of FDM technology and examine their mechanical performance.
2. To investigate the influence of various printing process parameters (extrusion temperature, extrusion multiplier, and extrusion width) on the mechanical properties of continuous carbon fiber reinforced polymer composite.
3. To develop a methodology and a process for the manufacturing of cellular composite structures reinforced with continuous carbon fiber and to determine its mechanical performance.
4. To study the influence of the controlled cooling effect on the quality and mechanical performance of continuous carbon fiber reinforced polymer composite specimens.
5. To investigate the effect of the layer height and layer orientation on the mechanical performance and quality of the manufactured composite parts by determining the porosity, air voids, and reinforcement contents by using the X-ray computed tomography scan and matrix dissolution method.

Research Methods

The research involves design, experimental, analytical, numerical and theoretical studies to sum up the achieved results. For CAD models, *PTC Pro Engineer Wildfire 5.0* software was used. *Simplify 3D*, *Prusa Slicer* software was used for the preparation and 3D printing of specimens. The universal testing machine *Tinius Olsen H25KT* was used for the experimental determination of mechanical properties. For the morphological fracture interface study, *Nikon Eclipse LV100ND* equipped with a high-resolution camera *DSRi2* and *Delta optical smart digital microscope* were utilized with the software *NIS Elements D* and *Delta Optical SmartAnalysis*, respectively. The void volume content in the 3D printed composite specimens were identified and analyzed by using the X-ray computed tomography (XCT) machine *RayScan 250E*. All the experimental research works were carried out at the Department of Production Engineering, Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Scientific novelty

The doctoral research presents and examines the fabrication of continuous carbon fiber reinforced composite structures 3D printed with the modified extrusion head of a FDM printer. A novel method and process has been introduced to print composite specimens with various cellular structures. Specifically, cellular continuous carbon fiber reinforced composites have been prepared with triangular and grid infill patterns, and reinforcement content has been identified by using the matrix dissolution method. The range of the printing process parameters (extrusion width, extrusion multiplier, layer height, extrusion temperature, and layer orientation) with the controlled cooling effect have been investigated, and their influence on the mechanical properties has been determined.

Practical value of the work

The presented thesis has demonstrated that the impregnation process of CCF with the customized FDM printing head offers the possibility to print light weight functional CCFRPC parts with a complex geometrical design as structural components. The obtained results of the developed technology which includes the impregnation process, the designed printing head with the identification of the optimum printing parameters with an improved part quality allow for the rapid production of CCF composites. The manufactured functional parts are mainly employed in automotive, aerospace and robotics applications. The applications are not limited to automobiles, or automotive and automation parts, but the range could be largely expanded where the strength-to-mass and the stiffness-to-mass ratios are a major priority. Moreover, the results obtained through the characterization and mechanical testing provide a sufficient valuable outcome in order to examine the research work and are beneficial for further improvement in the technological process.

Statements to be defended

1. The manufactured cellular structures are possible to print with the customized designed FDM AM technology with a complex geometry and have the capability to replace solid structures at various instants, while even showing superior mechanical properties at various density levels.
2. The printing process parameters (extrusion width, extrusion multiplier, layer height, extrusion temperature, and layer orientation) exert a great influence on the mechanical performance of 3D printed composite parts.
3. By introducing the controlled cooling effect, the fabricated composite parts can be made with a better quality by the uniform distribution of layers and lines of 3D printed composites and can also improve their properties.

Author's contribution

The experimental and numerical results of the presented research have been published in 6 international journals registered in the *Clarivate Analytics Web of Science database*. Three scientific articles have been published in journals with the impact factor, and 3 scientific articles have been published in journals without the impact factor.

In addition, the research results have also been presented at 5 international conferences: *Advanced Materials and Technologies 2020* (Palanga, Lithuania), *OTEH 2020* (Belgrade, Serbia), *Mechanika-2021* (Kaunas, Lithuania), *POLCOM 2021* (Bucharest, Romania) and *ICIMA 2022* (Coimbatore, India).

The research activities were funded by the project *Additive Manufactured Composite Smart Structures with Embedded Fibre Bragg Grating Sensors*.

Structure of the dissertation

The doctoral thesis consists of the following chapters: an introduction, a literature review, materials and methods, results and discussion, and, finally, conclusions were drawn. They are followed by the list of references and the list of publications. In the literature overview chapter, the knowledge of AM with the basic working principles of FDM are discussed. Further, the full dense solid and cellular carbon fiber (CF) composites reinforced with various materials, their processing, the achieved mechanical properties, and the range of the printing process parameters are presented and discussed in detail. The materials and methods chapter explains the detailed methodology of the printing process, the relevant parameters, the setup of the processing, mechanical testing, the void volume, the carbon fiber content calculations, and the fracture interface study. The results and discussion chapter elaborates on the achievement and explanation of the obtained results. The dissertation comprises of a total of 172 pages, 73 figures, and 22 tables, while the list of references contains 191 sources.

1. LITERATURE REVIEW

1.1. Additive manufacturing

Additive manufacturing (AM), also known as 3D printing or rapid prototyping, got established towards the end of the 1980s. It is an advanced and innovative manufacturing process for creating metallic, ceramic, and plastic materials, as well as their composites, with complicated shape geometries by depositing the material layer by layer to build a 3D-shaped structural part from the designed CAD model in sequential layers [1, 4]. Compared to the conventional manufacturing approaches, the AM technology has shortened the design and production cycles, thereby reducing the production costs as well as time, and improving the corporate competitiveness [6, 7]. Products are made by adding materials while using the AM technology to reduce waste and achieve satisfactory geometrical accuracy [8]. A variety of prototypes and functional parts with complex geometries that were difficult to manufacture by using the 'traditional' methods can now be manufactured by using AM technologies [9].

The technology is now being extensively employed in various engineering industries for the rapid production of parts ranging from prototypes to the final product due to the freedom in design, a flexible shape and geometry, lower time consumption, cost effectiveness, and minimum wastage. Over these factors, the innovative flexible manufacturing technology is now gradually replacing the traditional manufacturing system. Modern industries, such as the aerospace and military, are turning to the AM technology as a fast and cost-effective solution for manufacturing a variety of industrial components because the use of expensive materials, such as titanium, requires waste reduction or recycling efforts that is generated during the fabrication processing [10].

The most essential mechanical properties of AM materials are strength, stiffness, and flexibility. AM offers various benefits over the traditional manufacturing processes, including quick product creation and great customization, complex designs, high levels of automation, and flexibility, and reduction of energy consumption and material waste. It allows multiple parts to be produced from a single component [1, 10]. Due to the development and design improvements, AM technologies have been widely involved in various engineering applications in the areas of automobile industry [11], aerospace [12], biomedical industry [13, 14], food processing [15], construction and architectural fields [16], electronics [17], military [18], robots [19], and fashion [20]. The major issue which limits the wide range application of the AM technology is the limited choice of materials for printing. Thermoplastic materials which include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), polyamide (PA), and polyethylene terephthalate glycol (PETG) are the most commonly used materials [21, 22]. However, this technology is not limited to the thermoplastic materials, but it has also extended its utilization in metallic [23, 24], ceramics [25, 26] and composites [27, 28] materials. AM technologies and their processes are categorized according to the nature of the raw materials available as an input. It could be in various forms that

includes resin, solid filament or powder. 3D printing can be classified into four main categories:

- (i) Photopolymerization – it uses the ultraviolet light to activate the photopolymer polymerization process. Fiber-reinforced polymer composites (FRPC) can be produced by mixing fibers into a resin or by dispersing fibers on the surface of the resin [29].
- (ii) Extrusion – it works on the basis of controlled deposition of the material through a printing nozzle on the printing surface. A major advantage of this technology is the easy material adjustment and control along with the low cost [30].
- (iii) Powder based – it is based on the effect of the thermal energy of powder dispersing. A major limitation is that both the matrix and the reinforcement should be in the powder form [31].
- (iv) Sheet lamination – it works by joining pieces of a material together to form one part. The process involves additive and subtractive processes, adding a piece of some material and cutting it into the desired shape with a laser [32].

Fig. 1.1 elaborates on the classification of 3D printing techniques on the basis of raw materials as the input. Our research focuses on the extrusion-based fused deposition modeling (FDM) AM technique.

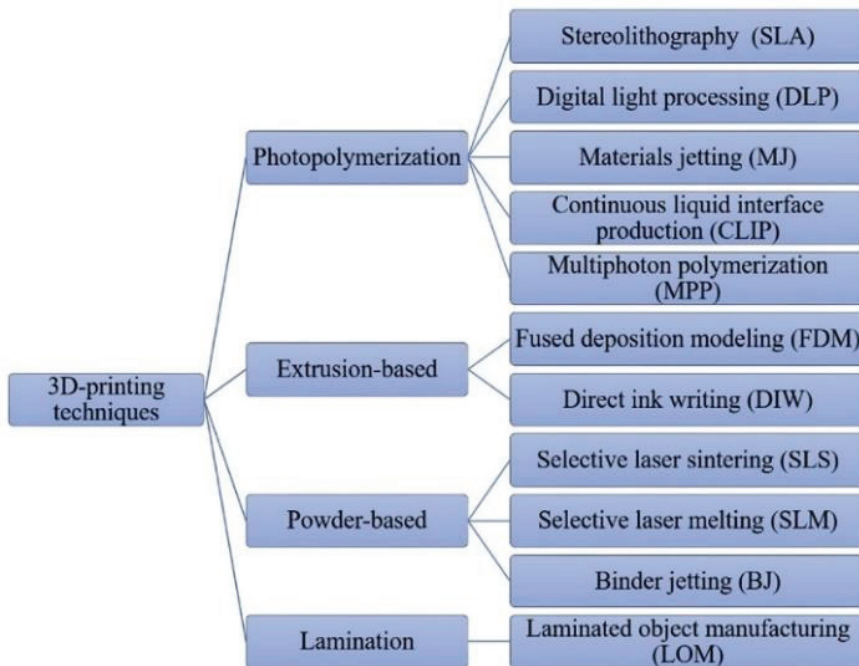


Fig. 1.1 Classification of 3D printing techniques [33]

1.2. Composite materials

Composite materials are a combination of two or more constituents to form a material which gains the properties of each individual constituent to improve its physical, chemical, mechanical and electrical properties. One major constituent which dominates the content and is used as the binding material is called the *matrix*, while the other constituent, by being added, improves the strength and enhances the properties. It is called the *reinforcement*. Essentially, the matrix and the reinforcement combine to form a composite material. Composite materials are widely used as lightweight components in a variety of industries including aerospace, automotive, nuclear, marine, and biomedical. It offers high strength-to-mass and stiffness-to-mass ratios while providing a high mechanical strength and high performance for specific applications. Lightweight composites, including polymer matrix composites (PMCs), are commonly used in a several industries. The efficient production of these composites is a major challenge [34]. Traditionally, fiber-reinforced polymer composites (FRPCs) have been manufactured in a variety of ways, including transfer molding, injection molding, and the pultrusion and filament winding technique [7, 35]. With the advent of the AM technology, most composite materials are made by using these different AM technologies. This is because the 3D printing technology gives designers and engineers ‘design freedom’ to create lightweight materials that can be economically manufactured. Reinforcements can be divided into two broad categories: continuous and discontinuous. The most common reinforcement materials are carbon, glass and kevlar [36, 37].

Composite materials are frequently utilized to create lightweight components and structures because of their exceptional mechanical qualities, structural flexibility, low cost, and remarkable performance. Composite materials are widely used in the aerospace industry for the manufacturing of various aircraft parts. About 50% of the current aircraft structures are made of composite materials [38]. The reinforcement could be in various forms i.e., particles, fibers, flakes or nanoparticles. Mainly continuous and short or discontinuous fibers have been used as reinforcement in the manufacturing of composites. Fig. 1.2 shows the orientation of fibers which could be either continuous or discontinuous. Reinforcements are mainly employed in the polymer industries to enhance the structural strength properties [39] which ensure excellent mechanical properties (a high strength-to-weight ratio) [40].

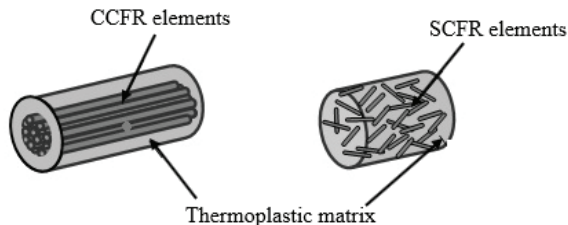


Fig. 1.2 Types of fiber orientations [7]

1.3. AM of polymers and polymer composites

Polymers occupy a significant place in the AM technology and are gaining prominence due to their availability, attractive properties, ease of manufacturing, simple technical printing processes and printing materials [5, 35]. The initially established AM techniques were usually applied to fabricate pure polymer parts [38]. AM techniques used to print polymers include laminated object manufacturing (LOM) from plastic laminations [41], stereolithography (SLA) from a photopolymer liquid [42], FDM from plastic filaments [43], 3D Plotting from liquid [5], selective laser sintering (SLS) and Inkjet 3D printing (IJP) using plastic powders [37, 44]. Unfortunately, pure polymer parts fabricated by these methods attain poor mechanical performance due to lower strength and stiffness values [10, 45], as pure polymers suffer from weak mechanical properties [37, 46].

The process of the printing and technology depends on the availability of the materials for the required form. Almost every form of the polymer can be utilized in 3D printing technologies and get converted to a solid 3D functional part that could be employed in practical value application. The basic working principle depends on the AM technology in use which inherently has some benefits and shortcomings as well.

Table 1.1 summarizes the rapid prototyping methods used for fabricating polymers, their working principle(s), along with the advantages and disadvantages of the technology.

Table 1.1 A summary of AM methods [47]

Technique	State of materials	Polymer materials	Working principle	Advantages	Disadvantages
FDM	Filament	Thermoplastics materials i.e., PC, ABS, PLA, and nylon	Extrusion and deposition	Cheap, good strength, multimaterial capability	Anisotropy, nozzle blockage
IJP	Powder	All polymers in form of powder and binder	drop-on-powder printing	Low cost, multi-material capability	Congestion of binder jet, binder contamination
SLS	Powder	Polycaprolactone (PCL) and polyamide powder	Laser scanning and heat induced sintering	Adequate strength, ease of removal of support powder	High cost, powdery surface
SLA	Liquid photopolymer	Photocurable resin (epoxy or acrylate based resin)	Laser scanning and UV induced curing	High printing resolution	High cost, Material limitation, cytotoxicity
3D Plotting	Liquid or paste	PCL, PLA, hydrogel	Pressurized syringe extrusion, and heat or UV-assisted curing	High printing resolution, soft materials capability	Low mechanical strength, slow process

Polymer materials have distinct mechanical, thermal, electrical, optical, and other functional qualities that make them useful in structural composites, thermal packaging, electrical devices, optoelectronics, biomedical implants, energy storage, filtration, and purification applications [35, 48]. Polymers like PLA, PCL, TPU are mostly used with noncontinuous particles, which helps them to enhance their mechanical, thermal and electrical properties [49]. Semicrystalline polymers (polyamide and polyimide) are usually manufactured by using powder bed fusion [50]. Hydrophilic polymers (PVA and PEG) enhance their adhesion with the addition of hydrophobic particles (carbons or ceramics). Soft polymer materials which are mostly used in medical implantations and human tissue development are also manufactured by using the AM technology [51]. Biological materials, such as PCL, hydrogels and silicone elastomers, have played key roles in applications such as soft robotics [52, 53], flexible electronics [54, 55], and biomedical engineering [56, 57]. Poly(3,4-ethylenedioxythiophene) and polystyrene sulfonate (PEDOT:PSS) are widely used as conducting polymers prepared with 3D printing [58, 59].

Nowadays, the majority of thermoplastic materials in AM are produced by the extrusion-based process, mainly the FDM printing process. Plastics used in FDM can be classified as commodity, engineering, or high-performance. Amorphous polymers (ABS, PS, PVC, PMMA) and semi-crystalline polymers (PP, PE, PEVA) are examples of low-cost commodity plastics for FDM printing [60]. Other engineering polymers which offer mild mechanical strength and temperature resistance that also include amorphous polymers (PC, PVA) and semicrystalline polymers (PLA, PBT, PET, POM, PA, PCL, PLGA) have also been used to manufacture functional parts by using the FDM 3D printing technique [48, 61].

PLA is a bio-based, biodegradable and environmental-friendly polymer derived from a renewable resource having a slow degradation rate, which is useful in some biomedical applications. It is biocompatible with biological fluids and can therefore be used in biomedicine and has no toxic or carcinogenic effects on local tissues [62]. Fig. 1.3 shows the environmentally friendly cycle of the PLA thermoplastic material. Previously, parts from the PLA thermoplastic material were commonly made by using injection molding, blow molding, fiber spinning, and film forming [63, 64]; nowadays, due to the advancement in the digitalized and computerized manufacturing system, the 3D printing technology is being used for making products from thermoplastic materials with complex geometrical structures.

Currently, PLA is one of the most broadly utilized thermoplastics to create an object by using an FDM 3D printer [65, 66]. PLA has been widely used in biomedical, green packaging, and textile applications, and now it is becoming an exceptional polymer used in 3D printing due to its low cost, the ease of processing and good mechanical properties [67, 68]. T. Yao *et al.* [69] fabricated 3D printed PLA with the range of raster angles and layer thicknesses to estimate the tensile strength and fracture analysis. It was determined that the strength level decreases with the increase in the layer thickness, which causes the interlayer fracture. J.M. Chacón *et al.* [70] fabricated PLA structures by using AM while considering the printing parameters, build orientation, layer thickness, and the feed rate effect on the mechanical properties, which resulted in a decrease in ductility with the increase in the layer thickness and

the feed rate. Moreover, the mechanical properties also increase as the layer thickness increases.

Unfortunately, PLA can provide only a limited industrial use due to its low hardness, high brittleness, low melt strength, low thermal stability, and lack of electrical conductivity [60, 71]. Also, the dimensional stability of PLA parts after manufacturing is an issue due to the stresses caused by the changes in the PLA crystallinity and volumetric changes in PLA parts during 3D printing. In general, the poor adhesion between layers is the main cause of the poor mechanical properties of 3D printed PLA parts [66].

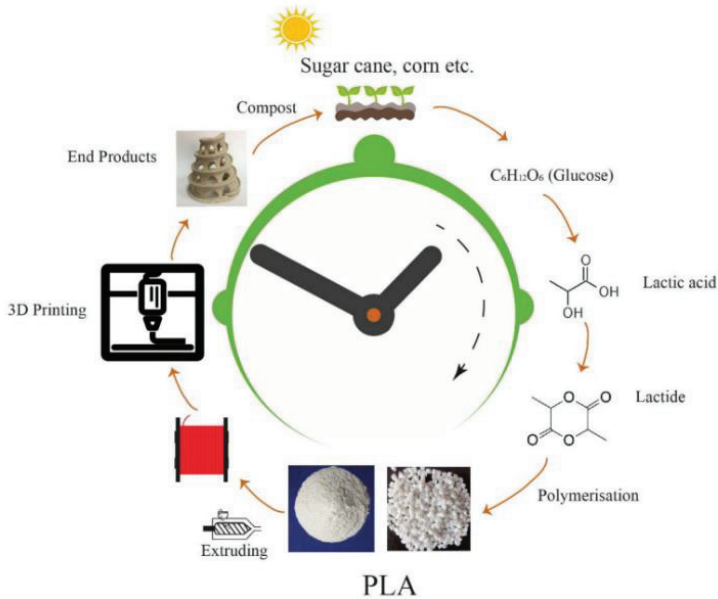


Fig. 1.3 Environmentally friendly PLA life cycle [66]

Several attempts have been made to address the issue of the poor mechanical characteristics in 3D printed pure polymers. These constraints can be circumvented by including polymer reinforcement in the form of particles, fibers, or nanostructures. Adding these reinforcements to the matrix material form FRPC which represents high quality composite materials [5, 27]. There is also a growing demand for polymer-reinforced composites with an improved 3D printing technology, which opens up a whole new range of perspectives regarding the production of composite structures [72].

Recently, 3D printing of polymer composite materials has been receiving great attention. Fiber reinforcement can significantly improve the efficiency and performance of 3D printed parts. The orientation and porosity of composite fibers are key issues in 3D printing these composites [1]. Fiber reinforcement can be utilized with either thermoplastics or thermosets to augment and improve the mechanical characteristics of the products. [73]. *Fiber Reinforced Polymers* (FRPs) provide excellent mechanical properties and allow for significant structural customization.

Reinforcements can also further improve the material properties and functionality, such as electrical and thermal conductivity [74]. FRPC expands its application possibilities due to its excellent mechanical properties and simple manufacturing process. However, it is difficult to incorporate reinforcing fibers into a polymer matrix with sufficient adhesion and control of the fiber orientation.

1.4. Fused deposition modeling

FDM is one of the most extensively as well as commonly utilized and promising techniques among all AM technologies for producing polymer products having complex geometries with desirable mechanical properties offering least wastage, a low cost, and simplicity of the material adjustment [62, 75]. According to ISO/ASTM 52900:2017 Standard, this technology is based on the controlled extrusion of thermoplastic filaments through the printing nozzle. The FDM technology is capable of printing thermoplastic filaments, including PLA, ABS, PC, PA or a combination of any two types of materials due to their low melting temperatures [76, 77]. The FDM technology also has the capability to print FRPC structures with both short and continuous fibers, and it is the perfect alternative for conventional processes for the fabrication of FRPC. The flow step-by-step process of the FDM 3D printer from the CAD design model to a final prototype is explained in Fig. 1.4.

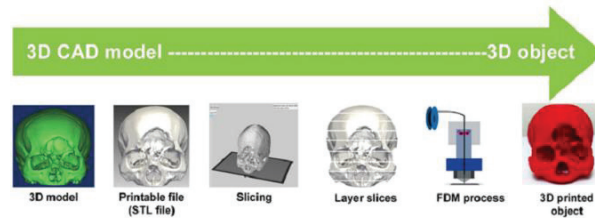


Fig. 1.4 Flow process of FDM [62]

In a typical FDM system, the filament is fed from a spool to the heating head by using the supply pressure generated by a drive gear. Plastic parts can be formed layer-by-layer by applying a filamentary material that is heated to a glass state and extruded through an extrusion nozzle at a constant temperature. The software created toolpath guides the extrusion head to move in the X-Y plane, thus placing the first desired layer on the print base to form the part base. When a layer has been completed, the build platform moves one layer thickness to create the next layer of the filament material. Each individual layer is repeatedly placed over the previous layer in the same way until a part has been completed. In FDM machines with dual extrusion nozzles, a different-colored filament build material or a filament support material can be simultaneously extruded through a second nozzle if desired. After FDM fabrication, the support material can be easily removed at the end of the build process [78, 79]. Fig. 1.5 shows the schematic process of FDM.

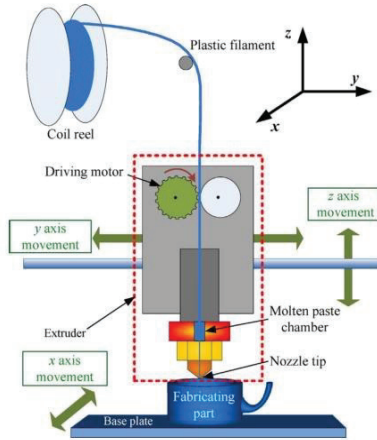


Fig. 1.5 Schematic of FDM process [80]

1.5. Fused deposition modeling of polymer composite materials

Numerous researchers are now turning to FDM to properly examine this process since it offers many advantages over other AM approaches, including cost effectiveness [60, 81, 82]. Due to the lack of the strength and load-bearing capabilities of pure polymer parts made with FDM, the majority of 3D printed polymer items are still unable to be used as functional components [37, 83]. Hence, there is a technique to increase the strength and stiffness to get over the constraints of pure thermoplastic components made by using FDM. Many initiatives have been undertaken to improve the poor mechanical performance of AM components. By incorporating reinforcement particles, fibers, or nanoparticles into polymers to create FRPCs which are characterized by high performance applications and their superior functionality, the AM of polymer matrix composites with enhanced mechanical characteristics has to overcome these restrictions [84, 85]. This has been mainly employed in the polymer industries to enhance the structural strength properties in composites [39, 86]. The reinforcements most commonly used in FRPC include carbon, glass and aramid fibers, which may be either continuous or discontinuous [87, 88]. However, the manufactured composites that have been reinforced with short fibers or particles showed lower mechanical properties compared to composites reinforced with continuous fiber [72, 89]. The potential for engaging continuous FRPC might result in a component with a significantly improved mechanical performance [86]. Also, in comparison to pure 3D-printed thermoplastic constructions, the findings of earlier testing indicate that FRPC created by using the FDM technique ensured a greater mechanical strength [5, 90].

Depending on the kind of the printing filament, FDM 3D printer innovation may be used to manufacture composite structures by using either a short fiber reinforced polymer (SFRP), or a continuous fiber reinforced polymer (CFRP) [5]. Depending on the type of the printing filament in use, the technology has the capacity to print polymers with reinforcement, whether they are continuous or discontinuous. Its

mechanical qualities can often be improved by combining fiber reinforcements with the thermoplastic matrix forming FRPC. Recent studies have demonstrated that CCFRPC structures created by using the FDM technique ensure a greater mechanical strength than the structures printed by using only thermoplastic materials [5, 90].

FDM is a technique with a range of parameters that affect the quality of the product and the properties of the printed part [79, 91]. Therefore, the level of the increase in the mechanical strength of the printed part was affected by the weak bonding between the fiber/matrix layers as well as the existence of the increased levels of porosity within the printed composite structure. Since mechanical performance is critical for practical measures and it is crucial to observe the influence of the process parameters on the mechanical properties, numerous important printing factors, such as the layer thickness, printing orientation, raster angle, air gap, line width, model build temperature, and infill, can be used to regulate the part quality in FDM [92, 93]. Some efforts have been made to study the void formation, poor adhesion of continuous fiber and polymer matrix composites in the course of the printing process [1]. Fig. 1.6 outlines the 3D printing preparation, process parameters, materials, machines and environmental factors affecting composite parts.

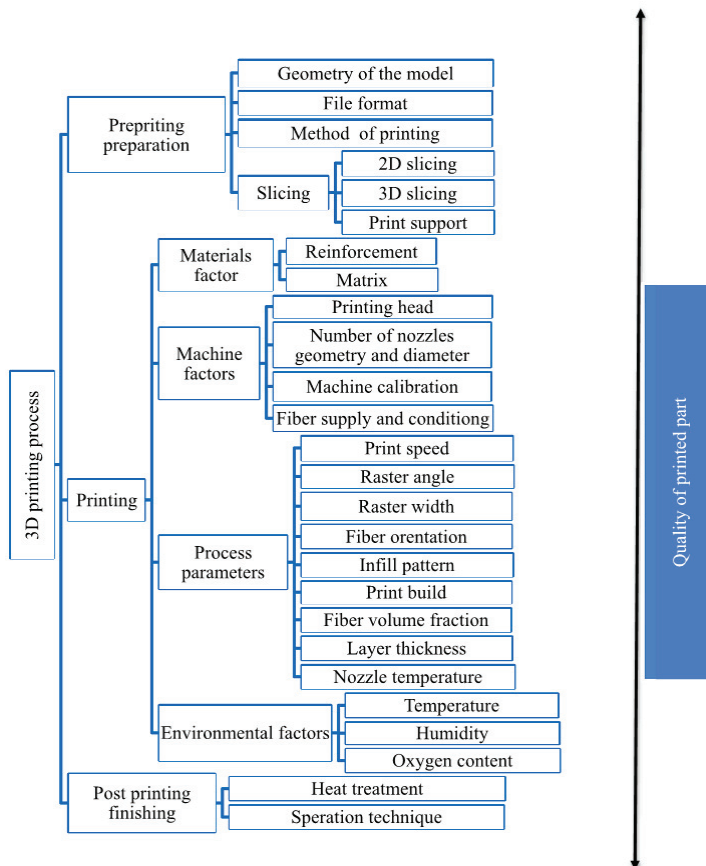


Fig. 1.6 Factors affecting the quality of composites [94]

1.6. Carbon fiber reinforced composites

Carbon fiber is a strong, stiff, lightweight, high temperature tolerance, and low thermal expansion material used in high-performance engineering applications, such as aerospace, automotive and sporting equipment. Carbon fiber has the potential to replace metals [95]. Carbon fiber reinforced polymer composites (CFRPC) provide superior mechanical properties. However, the combination of the reinforcement fibers and the polymer matrix with good consolidation, control of fiber orientation, reinforcement content and low cost manufacturing with the optimum mechanical performance is still a challenging issue [96].

1.6.1. Short fiber reinforced composites

In order to improve the mechanical properties of pure thermoplastic materials, fillers as reinforcement are added to the polymer to enhance its properties, durability and printability. Short fibers are denoted by excellent printing qualities and can be used with the regular printing procedures to increase the stiffness of the components. However, as compared to pure thermoplastics, the modest increase in the mechanical characteristics still limits the increase in strength, as fiber pull out may occur before fiber fracture [97]. Various researchers have been attempting to improve the mechanical performance of 3D printed short fiber reinforced composites by using a number of matrixes and reinforcements while studying various printing parameters, orientations and fiber fractions.

F. Ning *et al.* [38] experimentally studied the processability, microstructure and mechanical performance of SCF (100 μm and 150 μm) reinforced ABS composite parts fabricated by FDM with a range of CF contents. The results found that, by the addition of 5wt% CF content, the maximum tensile and flexural strengths of 42 MPa and 65 MPa, respectively, were achieved, which showed an increase of 11.82%, 16.82%, and 21.86% in the flexural stress, flexural modulus, and flexural toughness, respectively, of the composite specimen compared to the pure plastic specimen. The effect of the raster angle, infill speed, and nozzle temperature have also been examined, and the results show that the specimen produced with a raster of angle [0, 90] offers the maximum tensile strength [98], L. Love *et al.* [95] The impact of the SCFR content on the strength, stiffness, and distortion of 3D printed objects was investigated. Due to the limitations of SCFR reinforcement, the addition of SCFR composite parts resulted in a limited improvement in the mechanical performance of up to 20% [99]. H. Tekinalp *et al.* [89] produced SCFR reinforced ABS composites to investigate their processability and mechanical performance, and managed to achieve a 115% improvement in the tensile strength of the composite part compared to pure ABS. The porosity inside the FDM-printed pieces increased as the short carbon fiber content increased, according to the experimental data. M. Somireddy *et al.* [97] characterized the mechanical properties by studying the influence of the printing direction and the layer thickness by using laminate theories of the 3D fabricated SCF reinforced ABS thermoplastic composites. The results showed that the thin-layered parts are denoted by a higher strength and stiffness in comparison to thick-layered parts, while thick-layered parts perform better in terms of compression and buckling. X. Peng *et al.* [100] prepared SCF reinforced PA6 composites, processed and printed with different

temperatures, printing directions and parameters. The achieved results suggest that printing directions have a great influence on the tensile properties. The maximum strength and modulus of 128 MPa and 3.96 GPa was determined in the specimens printed with 0° layer orientation which showed 33% and 76% higher strength levels than those of 45°/-45° and 90° layer orientation, respectively.

The tensile strength of short fiber reinforced composites depends on the distribution of fiber orientations in the composite [101]. The fiber direction and orientation parallel to the matrix material and the printing direction when subjected to tensile loading, the reinforcement fibers bear maximum loading [102]. L. Sang *et al.* [102] developed short basalt fiber reinforced PLA composites filament by filament extruder and achieved the possibility of printing by using the FDM technology with a different fiber length and weight fraction. The presented results showed that the basalt fiber length of 300 µm with the fiber weight fraction of 10%.wt showed the highest tensile strength of 79.5 MPa, while using the fiber length of 130 µm with the fiber fraction of 20wt% had the highest flexural strength of 131 MPa. Table 1.2 presents the mechanical properties obtained with various short fiber reinforced composites with a ranging fiber fraction.

Table 1.2 Mechanical properties of short fiber reinforced composites [103]

Study	Composite Materials	Fiber fraction (%)	Maximum tensile strength (MPa)	Maximum flexural strength (MPa)
R.T.L. Ferreira <i>et al.</i> [104]	PLA-SCF	15 W	53.7	-
F. Ning <i>et al.</i> [38]	ABS-SCF	5 W	42	65
P. Wang <i>et al.</i> [105]	PEEK-SCF	10 W	84.7	150.8
N. Coughlin <i>et al.</i> [106]	ABS-basalt	25 W	50.58	68.51
W. Zhong <i>et al.</i> [107]	ABS-SGF	13.2 W	58.6	-
M. Somireddy <i>et al.</i> [97]	ABS-SCF	20 W	23.5	-
A. Gupta <i>et al.</i> [108]	PC-SCF	7.5 V	52.68	94.5
W. Ye <i>et al.</i> [109]	TPI-SCF	5 W	31.8	47.4
L. Sang <i>et al.</i> [102]	PLA- basalt fiber	10 W	79.5	128

Note: W: weight fraction; V: volume fraction

In the above reported researches, most of the studies focused on the development, fabrication and characterization of AM of composites with short fiber reinforced composites [5, 79] However, the addition of short fibers to a thermoplastic material slightly increases the strength compared to the pure plastic properties and still limits its usage in the high structural applications. Therefore, it is of great interest to study CCF reinforced composite materials which reflect and offer an even higher strength, durability and flexibility level compared to short fiber reinforced composites [103, 110].

1.6.2. Continuous carbon fiber reinforced composites

CCF reinforcement offers considerable improvement in the mechanical properties compared to discontinuous fibers [1], whereas mixing carbon fibers with polymer increases the strength and stiffness of the part [87]. CCFRPC is a lightweight, strong material, and it can be used in a wide range of engineering applications. The results show that mixing CCF and thermoplastic materials can increase the strength and stiffness of the composites, and it also reduces the distortion of the manufactured composite. Moreover, such composites showed an improved mechanical strength and performance compared to *discontinuous carbon fiber-reinforced polymer composites* (DCFRPC) and non-reinforced polymers [87]. CCFRPC is emerging as an alternative to the traditional metals due to its excellent mechanical properties, recyclability and ability to be used in lightweight structures [94]. AM of CCFRPC has solved these problems by combining the matrix and the reinforcements to achieve a combination with a more functional combination of features that are not achievable by only one constituent [5, 111]. However, this limits the freedom of design, since brittle and durable fibers are not easy to prepare by using 3D printing [74].

The printing of CCF through an FDM machine cannot be made directly, but it needs further modifications in the 3D printer system to make it viable to print. Five major methods have been adapted by the researchers to prepare the composite specimens with CCF by using the FDM technology. The five most commonly used methods are listed below with each technology presented in Fig. 1.7:

1. In-situ Impregnation: The standard CCF tow is impregnated in the heating element just before it passes through the printing nozzle and print on the bed surface [112].
2. Co-Extrusion with towpreg: CCF is processed before the printing process and further fed with the matrix material into the nozzle for printing [65, 99].
3. Towpreg Extrusion: Impregnated CCF is fed into the printing nozzle directly and printed without any matrix material [113].
4. In-situ consolidation: CCF (treated or untreated) and the matrix are fed together to the printing nozzle on the position area where it needs to be printed. An external heat source is used on the printing area to settle down the printing layers and, further, a pressure roller is used to press the deposited layers [112].
5. Inline impregnation: The standard CCF tow is impregnated during the printing process just before it passes through the printing nozzle.

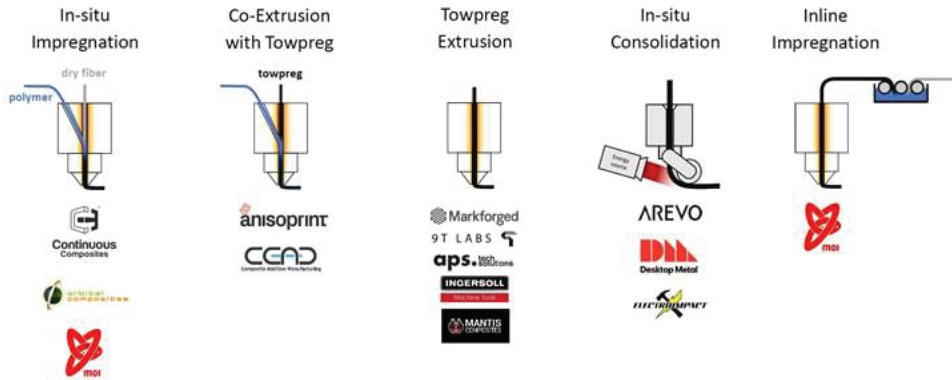


Fig. 1.7 Five major methods to print CCF composite structures with FDM technology [114]

T. Kuncius [115] proposed a novel, modified design of the printing head module of the FDM printer that is capable of printing CCF composite reinforced with a thermoplastic matrix material. Two input channels were designed: one for impregnated CCF, and the other for the thermoplastic filament. Pre-impregnated CCF is fed, and it is allowed to pass directly through the printing nozzle, while the thermoplastic filament passes through the other input to the heating element where it melts and fuses with the impregnated CCF, and together they make a bond by further extruding through the printing nozzle and printing on the built platform. The assembly of the designed printing head also allows easy cleaning of the heating element. Fig. 1.8 shows the prototype of the printing head with two input and one output channels and the final design of the custom printing module.

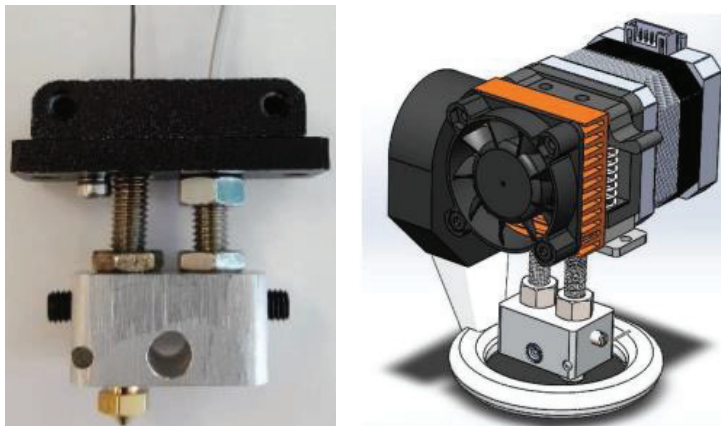


Fig. 1.8 Printing head prototype and custom printing module of FDM process for printing composites [115]

Several researchers have attempted to manufacture composites by using CCF reinforced with thermoplastic matrix by making modifications in preparing impregnated CCF and printing while using optimized printing parameters, infills, orientations and fiber fractions. Most CCFRPC specimens are prepared by using the FDM technique due to the easy production process, a wide availability and the economic factor. Some of the recent progress by various authors in the production of CCF composites is discussed further in the paper.

C. Yang [85] proposed a novel FDM process for CFRPC by using CCF as the reinforcing material and ABS as the matrix material, while the experimental results showed that the flexural strength and the modulus are almost six times higher than the conventional FDM ABS samples, and three times higher than injection molding. The reinforcement content of 10wt% showed the maximum tensile and flexural strengths of 147 MPa and 127 MPa, respectively. J.M. Chacón *et al.* [79] analyzed the characterization and assessment of the effect of the build orientation, layer thickness and fiber volume content on the mechanical properties of 3D printed CCF reinforced with a nylon matrix. The maximum tensile and flexural strength of 436.7 MPa and 423.5 MPa, respectively, was achieved with the fiber volume fraction of 26.38%. The results also showed the importance of the layer height and the fiber fraction on the mechanical performance of the composite. T. Yu *et al.* [87] evaluated the properties and the mechanical performance of using CCF as the reinforcement with the Onyx filament as the matrix. The maximum flexural strength of 270.63 MPa was recorded with the reinforcement fraction of 48.72wt%, and an increase of 40% in the strength level was observed when compared to the composite specimen prepared with SCFRC. A. Dickson *et al.* [37] studied the performance of a nylon filament with CCF reinforced composites by using the FDM technology. The comparison of the results showed that the tensile strength is 6.3 times higher than that of the non-reinforced nylon polymer by obtaining the maximum tensile and flexural strength of 216 MPa and 250.23 MPa, respectively, with 22.5% of the volume fiber fraction. M. Rimašauskas *et al.* [72] calculated the tensile strength of continuous impregnated carbon fiber (1K and 3K) with polymer filaments (PLA, ABS and PC). The experimental results found that the carbon fiber tow impregnated with 10wt% PLA solution showed the highest tensile strength of 165 MPa, while 145 MPa and 154 MPa tensile strength was noted when the CCF reinforcement was printed with the ABS and PC thermoplastic matrix, respectively. M. Heidari-Rarani *et al.* [45] prepared 1K carbon fiber roving and printed with the PLA matrix filament by using a modified extruder design of FDM with the modification in the extruder design and achieved the maximum tensile strength, the tensile modulus, the flexural strength and the modulus of 61.4 MPa, 8.28 GPa, 152.1 MPa and 13.42 GPa, respectively, with a V_f of 28.2%. The tensile and flexural strength showed an increase of up to 36.8% and 109%, respectively, compared to a pure PLA specimen. One study demonstrated a composite formed with the modified CCF tow reinforced with PLA thermoplastic that reached the maximum tensile and flexural strength of 91 MPa and 156 MPa, respectively [65]. T. Kuncius *et al.* [116] studied the effect of the layer height and the line width on the interlayer adhesion and shear strength of the FDM fabricated CCF reinforced PLA composite specimens. The attained results demonstrated the influence and importance

of the printing process parameters on the shear properties. The maximum shear strength of 15.1 MPa was attained with the composite specimen fabricated with the layer height of 0.3 mm. The effect of the layer height, the hatch spacing, the printing temperature and the printing speed of the FDM fabricated CCFRPC on the flexural properties was also listed. The increase of the printing temperature to 240°C showed better properties, while a decrease of the hatch spacing to 0.4 mm and the layer height to 0.3 mm reached the highest flexural strength and modulus to 335 MPa and 30 GPa, respectively, with a V_f of 27% [99]. Table 1.3 presents the mechanical properties obtained with the CCF reinforced composite with ranging fiber fractions.

Table 1.3 Mechanical properties of CCF reinforced composites [74, 94, 110, 117, 118]

Study	Materials	Fiber fraction (%)	Maximum tensile strength (MPa)	Young's modulus (GPa)	Maximum flexural strength (MPa)	Flexural modulus (GPa)
X. Tian <i>et al.</i> [119]	CCF-PLA	8.9 V	256	20.6	263	13.3
M. Heidari-Rarani <i>et al.</i> [45]	CCF-PLA	28.2 V	61.4	8.28	152.1	13.42
T. Yu <i>et al.</i> [87]	CCF-Onyx	48.72 W	-	-	270.63	-
W. Hao <i>et al.</i> [120]	CCF- epoxy resin	-	792.8	161.4	202	143.9
A.N. Dickson <i>et al.</i> [37]	CCF-Nylon	22.5 V	216	7.73	250.23	13.02
X. Tian <i>et al.</i> [99]	CCF-PLA	27 V	-	-	335	30
M. Rimaškauskas <i>et al.</i> [121]	CCF-PLA	11.2 V	183	23.77	-	-
J.M. Chacón <i>et al.</i> [79]	CCF-Nylon	26.38 V	436.7	51.7	423.5	39.2
N. Li <i>et al.</i> [65]	CCF-PLA	34 V	91	-	156	-
L.G. Blok <i>et al.</i> [74]	CCF-Nylon	27 V	726	46.9	363.8	31.2
R. Matsuzaki <i>et al.</i> [122]	CCF/Jute fibers-PLA	6.5 V	185.2	19.5	133	5.93
C. Yang <i>et al.</i> [85]	CCF-ABS	10 W	147	4.185	127	7.72
H. Mei <i>et al.</i> [123]	CCF-Nylon	9.01 V	106	4.27	-	-
G. Chabaud <i>et al.</i> [124]	CCF-PA	35 V	534	60	-	-
G.D. Goh <i>et al.</i> [125]	CCF-Nylon	41 V	600	12.99	430	38.1
J. Justo <i>et al.</i> [126]	CCF-PA (Nylon)	40 V	574.58	25.86	-	-
C. Oztan <i>et al.</i> [127]	CCF-Nylon	14 V	254.8	21.72	-	-
Y. Peng <i>et al.</i> [128]	CCF-PA	47.5 V	515.67	39.20	-	-
F. Ghebretinsae <i>et al.</i> [129]	CCF-Onyx	-	584	26.89	271	16
M. Rimaškauskas <i>et al.</i> [72]	CCF-ABS/PC	25.2 W	145/154	-	-	-

Note: W: weight fraction; V: volume fraction

1.7. Cellular composite structures manufactured by using AM

The cellular structure consists of a chain in which individual cells form a structure. Cellular materials are one of the most promising materials for the future construction of lightweight, efficient, and superior engineering structures where they may be employed as a stand-alone material or in conjunction with other materials as composites [130–132]. Lightweight cellular composites with a high strength-to-weight ratio, high stiffness, high permeability, great impact absorption, and thermal and acoustic insulation are made of a network of interconnected solid struts that make up the edges or faces of the cells [133–135] and exhibit advanced properties, although they are challenging to design and construct [136, 137]. Their response to compression and tensile loadings offers a good insight [138]. The loading orientation affects how cellular structures behave differently. The axial extension or compression of cell walls under out-of-plane loading often results in the deformation of the structure. Cellular structures are stiffer and stronger when loads are applied in an out-of-plane direction. Yet, because they bend under in-plane loads, cellular structures have substantially lower in-plane strength and stiffness [133, 139].

Complex cellular shapes that are challenging or impossible to construct by using conventional manufacturing techniques can be produced by using additive manufacturing. Additive manufacturing can create cellular composites with a precisely regulated cell size, shape, orientation, and volume fraction by carefully layering the material. This degree of control can provide designs that are highly tailored and optimized, thereby improving the performance and minimizing material waste [140, 141]. Cellular composites created by additive manufacturing have several potential uses, including aerospace, automotive, and biological. These materials may be utilized to reduce the vehicle weight and enhance fuel economy, improve aviation component strength-to-weight ratios, and produce complex implantable structures for tissue engineering. 3D printed continuous glass fiber reinforced Nylon cellular structures are manufactured by using various orientations of concentric walls to study the bending behavior, and the maximum flexural strength of 110 MPa has been achieved so far [142]. Z. Hu *et al.* [143] designed and developed ultra-lightweight and high-strength cellular structural composites by using discontinuous fibers. K. Dong *et al.* [131] proposed a novel method of fabricating a cellular structure with the kevlar continuous fiber by using the FDM technology. The cellular composite specimens with diamond infill paths with a varying volume fraction and printing parameters were fabricated to study the tensile properties, and it was noted that the cell length of 40 mm specimen reached the highest tensile strength of 22.11 MPa. Fig 1.9 represents the optical micrographs of cellular structures with square, hexagonal and triangular infill patterns composed of SiC-filled epoxy.

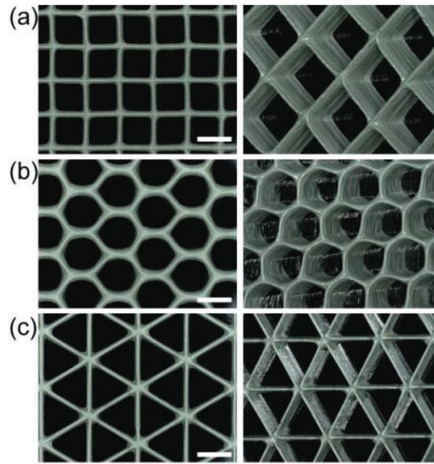


Fig. 1.9 Micrograph of cellular structures with various infills: a) square; b) hexagonal; c) triangular [144]

I. Buj-Corral *et al.* [145] proposed and developed FDM printed porous scaffolds for medical applications by using a specific geometrical plane while considering three variables: the porosity, the pore diameter, and the disparity of the pore diameter of the modeled structures, and the obtained results suggest that an increase of the unit cell and the radius of the columns tends to decrease the porosity and the pore size. C. Huan *et al.* [146] studied the cemented a paste backfill's pore structure, its characteristics and effect on the mechanical performance, and the research results showed that the microstructural integrity has a major impact on the development of the porous structure, which represents their parameters, such as the porosity and the pore area. Complex composite materials with a range of aligned pore architectures have also been produced with various methods [147]. Porous structures have been modeled by using fractal geometry and manufactured by using the 3D printing technology [148].

Lightweight composites can be made by using cellular reinforcing fiber structures that reduce the density of composites, which can significantly reduce the material usage, energy consumption, waste generation, and thus endorses the sustainability of materials [144]. Moreover, despite the weight reduction, 3D-fabricated cellular structures can successfully overcome the poor interlayer properties [93]. The filling ratio plays an important role in the formation of cellular structures [149], and the mechanical properties depend on the process parameters and the infill pattern [77].

3D printing with FDM has been used to fabricate cell lattice structures from various polymeric materials [150]. AM produced several parts from pure PLA for the study of the effect of the wall thickness on the shock absorption [151], print quality and compressive mechanical performance [152], the effect of wall thicknesses on the interlaminar bond strength [153], and the fracture toughness [154]. C. Lubombo and M.A. Huneault [77] investigated the stiffness and strength of cellular PLA parts by using five types of infill patterns at three different infill density levels, and the results

showed that, for the same number of perimeter shells, the strength was increased by up to 82% at the same density simply by using a different type of the infill pattern.

1.8. Influence of printing parameters on mechanical properties

The mechanical performance is greatly influenced by the printing factors including the layer height, the extrusion width, the extrusion multiplier, the printing temperature, the printing speed, and the carbon fiber content [91, 92] as well as the quality of the additively manufactured composite parts [121, 155]. The mechanical performance and the physical look of the finished product are both greatly influenced by the quality of the specimen created by using the AM process [85, 86]. A limited number of studies on the fabrication of composite parts using CCF have been conducted, with the majority of them focusing on enhancing the mechanical performance by using a modified CCF tow with the optimum printing parameters [24, 156]. Some studies have also been conducted to determine the effect of the printing settings on the mechanical performance of composite constructions in order to discover the best solution [89, 157]. Still, the printing parameters also show a dependency on the 3D printing technology and the materials used for fabricating parts. Fig. 1.10 presents the list of parameters that influence the mechanical properties of 3D printed parts.

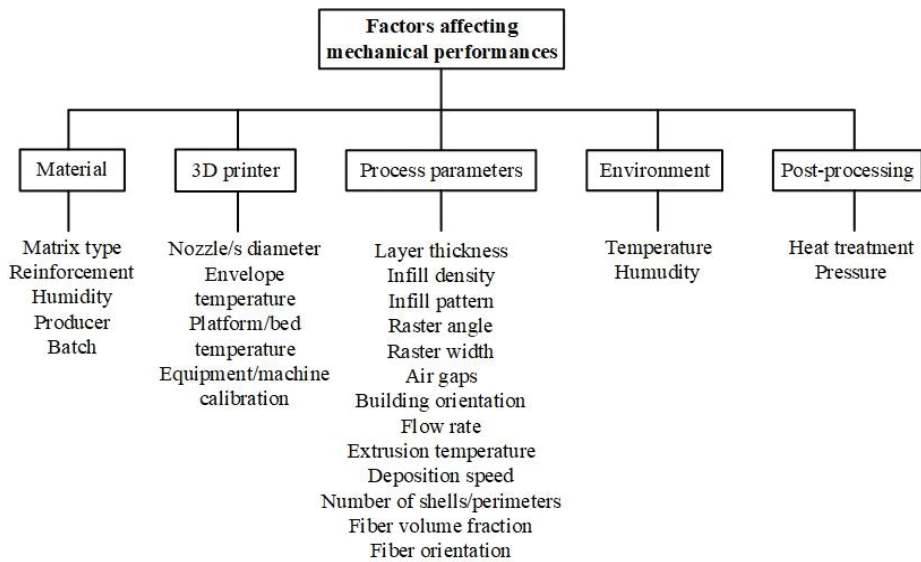


Fig. 1.10 Factors affecting the mechanical properties of 3D printed parts [110]

F. Ning *et al.* [98] studied the FDM process parameters (the raster angle, the infill speed, the nozzle temperature, and the layer thickness) on the composite part fabricated by using the ABS thermoplastic matrix reinforced with chopped carbon fiber. The results demonstrated that the raster angle [0°, 90°], an infill printing speed of 25 mm/s, a temperature of 220°C and a layer thickness of 0.15 mm showed the best results in terms of the tensile strength (32.3 MPa). M. Rimašauskas *et al.* [121] performed an investigation on the quality of 3D printed composite structures based on

the printing parameters (the layer height and the line width) for 1K impregnated CCF to reduce the voids volume of the CCFRPC structures. The experimental results showed that the composite specimen with a layer thickness of 0.3 mm and a line width of 1 mm had the smallest air voids volume inside the specimen by achieving the maximum tensile strength of 183 MPa. Moreover, by reducing the layer thickness and the line width, the tensile strength increases, and a higher amount of carbon fiber leads to superior mechanical performance [92]. Delamination was also observed when the SCF-PLA filament was printed with CCF and underwent bending, and the reason for such behavior was due to the poor quality and the weak interlayer adhesion of the composite specimen [158].

Research of the infill density and the infill pattern of the composite parts fabricated by using the FDM 3D printing technology was performed to study their effect on the mechanical properties and the dynamic mechanical, and thermoelectric properties [91]. M. Moradi *et al.* [157] investigated the effects of the printing parameters including the layer thickness, the infill percentage, and the extruder temperature on the maximum failure load of bronze PLA composites, and the obtained results indicated that maximum failure load of the composite improved with a higher layer thickness. PLA based short carbon and ABS composites filaments were considered with the printing parameters of the layer resolution, the printing orientation, the infill density, the nozzle diameter, the nozzle temperature and the raster angle to study their effect on the electrical conductivity and mechanical properties [159, 160]. The extrusion temperature, the flow rate multiplier and the layer thickness parameters were considered to evaluate the tensile properties of FDM fabricated 17-4PH stainless steel, and the results demonstrated that the flow rate multiplier had the strongest effect on the tensile properties [161]. K. Chen *et al.* [162] evaluated the optimum printing parameters (the nozzle diameter, the layer thickness, the printing speed and temperature) of 3D-printed continuous glass fiber reinforced PLA composites on the mechanical properties and the microstructure by achieving the maximum tensile strength of 241 MPa with a 45wt% reinforcement content. The printing speed and the layer thickness effect parameters on the quality of 3D printed composite cement-based materials were presented [155]. H. Dou *et al.* [92] performed experimentation on the tensile properties of 3D Printed 1K CCF-reinforced PLA composites by considering the printing parameters of the layer height, the extrusion width, the printing temperature, and the printing speed. The results demonstrated that, upon decreasing the layer height, the extrusion width and the printing speed with a higher printing temperature will help to achieve better mechanical properties. The optimum printing parameters reach a maximum tensile strength and tensile stiffness of 226.60 MPa and 22.38 GPa, respectively.

Numerous research has been found when discussing the quality of the composite parts, mainly CCFRPC parts printed by using the FDM technique [38, 74]. The quality and mechanical performance have a mutual connection that forces the final product to perform better in terms of both constraints.

1.9. Pre-impregnation of CCF before 3D printing

One of the major problems and issues faced in the AM of CCF composites is the adhesion and bonding between the matrix and the reinforcement as well as the layers of the composite specimen and the quality of the printed final structure. It greatly depends on how the CCF is treated and prepared for the printing. The issue of the bonding is relevant to both SCF and CCF composites. The standard CCF tow consists of several thousand fibers which are often difficult to feed into the printing head for the printing process, and there is also the issue with adhesion. However, this problem can be reduced by using the proper treatment of CCF before the printing process, which can result in better adhesion and bonding between the matrix and the reinforcement. Most researchers treated CCF before the printing process and impregnated it to bind the fibers together by using various chemical solutions for better printability and adhesion. A solution prepared for the impregnation of CCF depends on the compatibility with the matrix material and the printing conditions. The impregnation of carbon fiber with a thin layer of epoxy resin does not withstand printing temperatures above 250°C; thus it is preferable or recommended only for printability at a low temperature as epoxy degrades instantly. Researchers have modified and impregnated CCF by using various solutions.

M. Heidari-Rarani *et al.* [45] treated the surface modification of 1K CCF with PVA solution before the printing process. N. Li *et al.* [65] modified the carbon fiber with methylene chloride (CH_2CL_2) and PLA particles (8% by mass) solution for better adhesion bonding with the PLA matrix. Fig. 1.11 shows the procedure followed by the author of this thesis for the surface modification of carbon fiber.

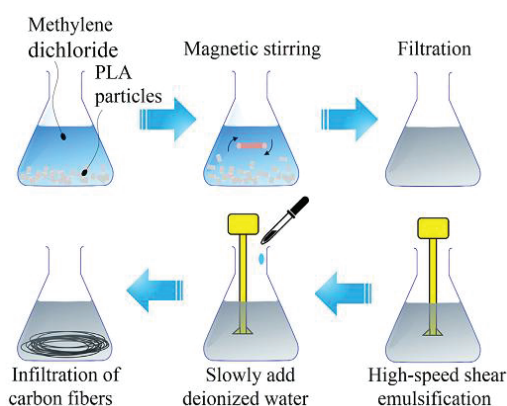


Fig. 1.11 Procedure for surface modification of carbon fibers [65]

M. Rimašauskas *et al.* [72] developed a novel method for the impregnation of the standard CCF tow for better quality printability and adhesion bonding with improved mechanical properties. 1K and 3K carbon fiber tows were impregnated with three different types of polymer materials (PLA, PC, ABS) with the solvent methylene chloride solution of various concentrations (8–10% by mass). The standard carbon fiber tow was inserted from one end and passed through the resin prepared with a

range of concentration of a chemical solution, further, it went to a hot air chamber where it dried instantly, and fibers bonded in a single thin wired chain, and finally they rolled on the spool at the other end of the device. The result showed that the concentration of the solution had a high impact on the quality of carbon fiber impregnation. An increase of the concentration of the solution allowed decreasing the amount of air voids in impregnated carbon fiber. The schematic design used is illustrated in Fig. 1.12.

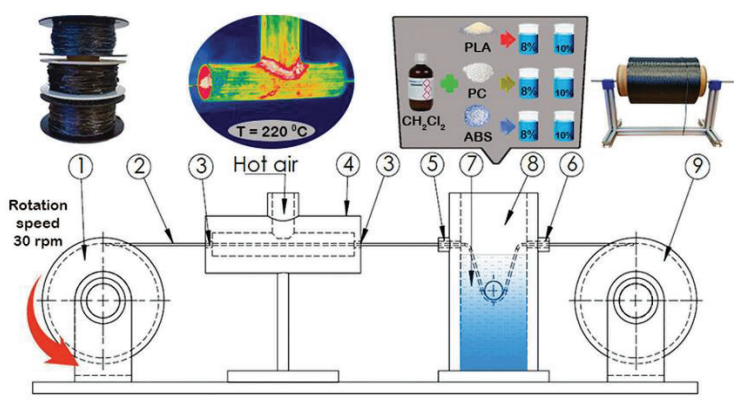


Fig. 1.12 Schematic design process for CCF impregnation [72]

The impregnated CCF further printed with thermoplastic matrix material to study its mechanical performance. The obtained results demonstrated that the use of 3K carbon fiber tow yielded better tensile strength compared to the 1K carbon fiber tow impregnated with the same amount of plastic. This tendency is strong in PLA and PC impregnated with 3K carbon fiber. The impregnation solution prepared with PLA 10% presented the best results among all the prepared solutions.

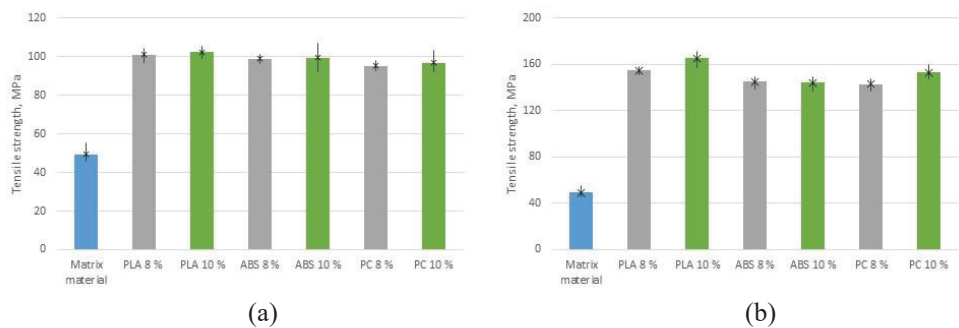


Fig. 1.13 Results of tensile strength of CCF reinforced composites: a) 1K carbon fiber; b) 3K carbon fiber [72]

The maximum tensile strength reached 165 MPa with the PLA solution. The results also indicated that the tensile force increased with a higher solution concentration. Fig. 1.13 presented the tensile test results achieved of CCF composites

using various materials. The same impregnation method shall be used for the present research in the dissertation.

1.10. Chapter conclusions

High mechanical performance composite materials have had their utilization significantly increased in extreme structural engineering applications mostly in aviation and automobile industries. The demand for such composites has rapidly increased with their enhanced mechanical properties. Most of the structures involved a complex geometrical shape which needed to be fabricated more swiftly in less time with the minimum wastage of material and under economic considerations. These factors have been encouraging scientists to develop innovative rapid production of composites with improved mechanical properties by using AM technologies.

CCF, due to its light weight, high stiffness, strength and durability is now being used as the reinforcement with the thermoplastic matrix to give a remarkable mechanical strength-to-mass ratio which withstands higher loads and temperatures. For the rapid production of such CCFRPC structures, the FDM AM technology is being employed for the manufacturing with the aim of enhanced mechanical properties. The mechanical strength of composite structures greatly depends on the impregnation process of CCF and how it is treated; it also depends on the printing process parameters of the FDM 3D printer which controls the fabrication process, the adhesion between the matrix and the reinforcement, the interlaminar bonding between the layers and the quality of the specimen as well as the V_f of the product. It is obvious that, by introducing the reinforcement, the strength was increased by 8 times compared to pure thermoplastic properties. The printability with the aim of a lightweight structure, enhanced mechanical properties, superior printing quality with a controlled V_f value is still a challenging task. Moreover, the fabrication of a cellular lightweight structure is mainly achieved with short fiber materials or with a pure thermoplastic material using various infill patterns and infill density levels. No study has been provided so far with the fabrication of cellular structure using CCF composites as it is difficult to print the infill pattern with complex geometrical shapes with CCF. Therefore, it is of great interest to explore the study of the development of the cellular structure with various infills and density levels, its response to mechanical loading and comparison with the dense solid structure. The linkage between the printing process parameters, the quality of the printed part and the porosity of the composite specimen with altering printing parameters are also important factors to consider.

In this dissertation, firstly, we emphasize the characterization of the mechanical properties of the printing of impregnated CCF with pure thermoplastic and SCF filament by using standard printing parameters. Secondly, the fabrication of cellular CCFRPC parts with various infill patterns and density levels shall be presented, and the properties shall be tested. Thirdly, the influence of the controlled cooling effect, the printing process parameters and V_f on the mechanical properties and the quality of the composite structure, as well as the fracture interface study mechanism after mechanical testing shall be discussed and reported in detail.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

Composites shall be printed with impregnated CCF by using a modified extrusion head of an FDM 3D printer. The research work presented in this thesis basically comprises three main parts of the CCF life cycle. The flow chart of the step-by-step experimental work performed in this dissertation is illustrated in Fig. 2.1.

1. Preparation of materials: Firstly, the standard CCF was impregnated for the printing process to achieve superior quality and adhesion results.
2. Printing of composite specimens: Composite specimens (solid and cellular) were fabricated by using a customized printing head of an FDM printer. The fabrication process was carried out with various printing process parameters to find suitable optimized parameters.
3. Testing: After the successful fabrication process, the composite specimens underwent mechanical testing for the determination of the main mechanical properties, dissolution and XCT scan test for the CCF content and air void detection, along with microscopic analysis for the fracture interface study.

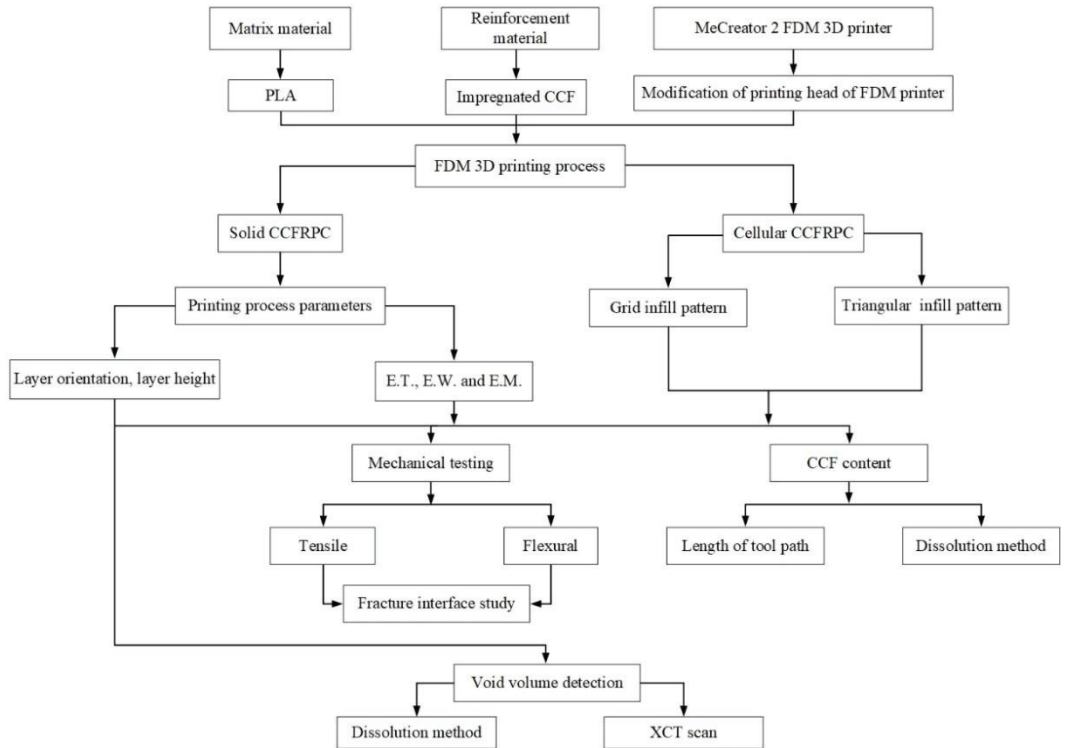


Fig. 2.1 Flow chart of the experimental work

2.1. Materials for additive manufacturing of composite structures

2.1.1. Matrix materials

There are various thermoplastic materials which are presently being used as matrix materials for 3D printing with CCF composites while using the FDM technology. The most commonly used thermoplastic materials are PLA, ABS, PETG, PC and Nylon. The printability of such materials depends on their properties. Currently, PLA is the most commonly used thermoplastic material used for 3D printing of solid structures. The PLA material is derived from natural resources and is widely utilized due to its availability and compatibility. This thermoplastic material was chosen due to its easy printing conditions, a low printing temperature, easy adjustment for printing, great adhesion, recyclability, and adequate mechanical properties. As PLA is a biodegradable material and is mostly used in the development of biomedical applications, therefore, it is evident that it is nontoxic and non-harmful, and that it does not emit any harmful particles during the printing, and, if gets clogged during printing, it is easy to clean and replace.

In the present study, two types of matrix materials have been used. Firstly, the PLA thermoplastic filament of 1.75 mm diameter from *PolyLite PLA (Polymaker)* was used with CCF. The thermoplastic filament has a printing temperature range between 190 °C – 230 °C, a printing speed of 40 mm/s – 60 mm/s, and a bed temperature range between 25 °C – 60 °C. Other main properties of the PolyLite PLA filament are provided in Table 2.1.

Table 2.1 Properties of PolyLite PLA [163]

Density	Tensile strength	Young's modulus	Flexural strength	Glass transition temperature
1.24 g/cm ³	46.6 ± 0.9 MPa	2.6 ± 0.33 GPa	85.1 ± 2.9 MPa	61°C

Secondly, the *ColorFabb XT-CF20* filament of 1.75 mm diameter was used as the matrix material. XT-CF20 is a composite filament made from PLA with chopped carbon fibers constituting 20%. The recommended printing temperature of XT-CF20 is 240 °C – 260 °C with a print speed of 40 – 70 mm/s and a bed temperature of 60°C – 70 °C. Other properties of the ColorFabb XT-CF20 filament are provided in Table 2.2.

Table 2.2 Properties of ColorFabb XT-CF20 [164]

Density	Tensile strength	Tensile elongation	Flexural strength	Flexural modulus
1.35 g/cm ³	76 MPa	7.5 %	110 MPa	6.2 GPa

2.1.2 Reinforcement material

Carbon fiber is a lightweight, strong and stiff material usually used as reinforcement in various composite materials to provide ultra-high strength. Carbon

fiber weighs about 40% less than aluminum, 70% less than steel, and even less than glass fiber. It can be used in high temperature applications due to its negative coefficient of thermal expansion. CCF in 3D printing can be printed up to 300 °C or even more, but it largely depends on the matrix material.

For the experimental study of the reinforcement in composite manufacturing, standard non-woven 3K CCF tow *T300B-3000* by *Toray* (Lacq, France) was used for the experimental research. The T300 CCF tow is a light weight and high-performance carbon fiber tow made of polyacrylonitrile with 3000 fibers in a tow with a diameter of 7 µm each. The main characteristics and properties of T300B-3000 CCF as stated in the producer's datasheet are provided in Table 2.3.

Table 2.3 Main characteristics of T300B-3000 [165]

Carbon Fiber Tow	Density	Tensile strength	Young's modulus	Elongation, %
T300B-3000	1.76 g/cm ³	3530 MPa	230 GPa	1.5

2.2. Impregnation process for CCF

Before the printing of the composite specimens, for superior printing quality, interlayer adhesion and mechanical performance, nonwoven standard 3K CCF tow was impregnated with a solution of PLA pellets (*3D850* biopolymer, *NatureWorks*) and solvent methylene chloride (CH₂Cl₂) by *Eurochemicals* with the ratio concentration of 90g/10g, respectively. The magnetic *LBXH01* mini stirrer at 600 rpm was used to thoroughly dissolve the PLA pellets. For the production and processing of impregnated CCF, the same method was followed as described previously by the author of [72] with some modifications in the process. The nozzle diameters for each part were modified for the impregnation process. The standard non-impregnated fiber was passed through one end thus passing through the prepared solution towards the heating chamber where it was dried at 220 °C and mounted towards the other end where the impregnated spool was rolled. Previous results revealed that impregnation exerts great influence on the mechanical properties and increases the concentration of the impregnation solution, which leads to a superior printing quality and mechanical properties of the composite specimens [72].

2.3. Modification of extrusion printing head of FDM printer¹

Originally, the designed extrusion printing head of the FDM 3D printer had the ability to print with pure thermoplastic materials. The same modified and custom made extrusion printing head was used previously by the author of [115], which enabled the FDM printer to print with CCF composites. The extrusion head of the FDM 3D printer was modified with an integrated heating element which allows it to print two materials at a time. Two input channels were introduced, one for the thermoplastic filament and the other for the impregnated CCF. The impregnated CCF

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was inserted directly to the printing nozzle through the extrusion head passing through the PTFE tube providing the path to the nozzle, while the thermoplastic filament passed through the drive wheel pushed to the extrusion head. After going through the printing head, the polymer melts in the mixing zone where it bonds with the CCF that has been impregnated to create a composite. Molten polymer is used to feed the CCF tow, and it is continuously forced into the printing nozzle. By using the printing nozzle, the PLA material reinforced with carbon fiber is extruded onto a borosilicate glass printing bed which is mounted on an aluminum plate. The schematic view of 3D printing of the FDM process, equipment and the overall printing process are presented in Fig. 2.2.

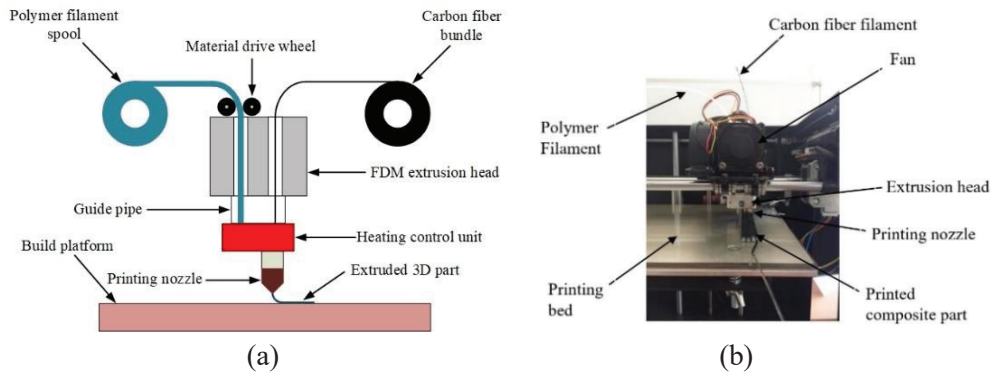


Fig. 2.2 FDM 3D printer: a) schematic view; b) equipment used for printing process

2.4. Printing and process parameters of composite manufacturing²

For the modeling of the specimen's geometry, *PTC Pro-engineer Wildfire 5.0* software was used, then the CAD model was exported as an STL file from the software and imported to the 3D printing software for the printing process preparation. For the fabrication of composites, a *MeCreator 2 (Geeetech)* 3D printer with the modified version of the printing head was used for the production of PLA and PLA-SCF specimens reinforced with CCF, while a *Prusa i3 MK3S 3D FDM* printer was used to print pure PLA and PLA-SCF specimens. These printers were selected because of their simplicity and ease of use. The FDM 3D printer equipment used for the experimental work for the fabrication of composites and the part with a unidirectional raster angle is presented in Fig. 2.3. *Simplify 3D* and *Prusa slicer* software was used to deal with the fabrication process and the selection of the printing parameters. At this stage, the basic printing process parameters were selected according to the recommendation of the materials supplier; the composite specimens were also attempted to print with the basic parameters to evaluate the printing process.

The standard filament feeding mechanism is used to feed filaments with a diameter of 1.75 mm to the printing head in order to print specimens with CCF, PLA

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and PLA-SCF. The filaments in the printing head received heat up to 210°C for PLA and 250°C for PLA-SCF.

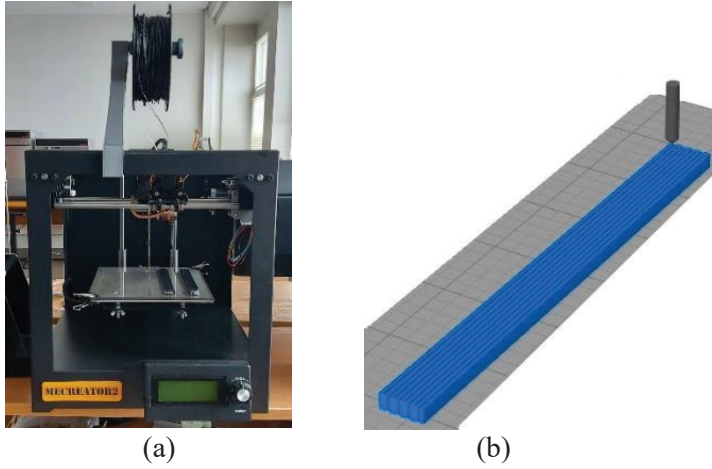


Fig. 2.3 FDM 3D printer: a) MeCreator 2 used for the fabrication of composites; b) part with unidirectional raster angle 0°

In this investigation, unidirectional 0° rectangular flat specimens with isotropic fiber patterns were chosen to print on. Bronze nozzles with a 1.5 mm diameter were utilized to fabricate CCF specimens while using the MeCreator 3D printer. With a basic Prusa i3 MK3S 3D printer with a 0.4 mm nozzle diameter, the same procedure was used to manufacture PLA and PLA-SCF specimens.

Table 2.4 Parameters of 3D printing

Parameters	3D Printer types			
	MeCreator 2		Prusa i3 MK3S	
	PLA-CCF	PLA-SCF-CCF	PLA	PLA-SCF
Nozzle diameter	1.5 mm	1.5 mm	0.4 mm	0.4 mm
Extrusion multiplier	0.5	0.5	1	1
Extrusion width	1.5 mm	1.5 mm	0.45 mm	0.45 mm
Layer height	0.5 mm	0.5 mm	0.2 mm	0.2 mm
Printing speed	3.0 mm/s	3.0 mm/s	25 mm/s	25 mm/s
First layer speed	1.20 mm/s	1.20 mm/s	20 mm/s	20 mm/s
Extruder temperature	210 °C	250 °C	210 °C	250 °C
Bed temperature	90 °C	90 °C	60 °C	75 °C
Fan speed	60%	60%	30%	30%
Internal/External fill pattern	Rectilinear	Rectilinear	Rectilinear	Rectilinear
Infill percentage	100%	100%	100%	100%

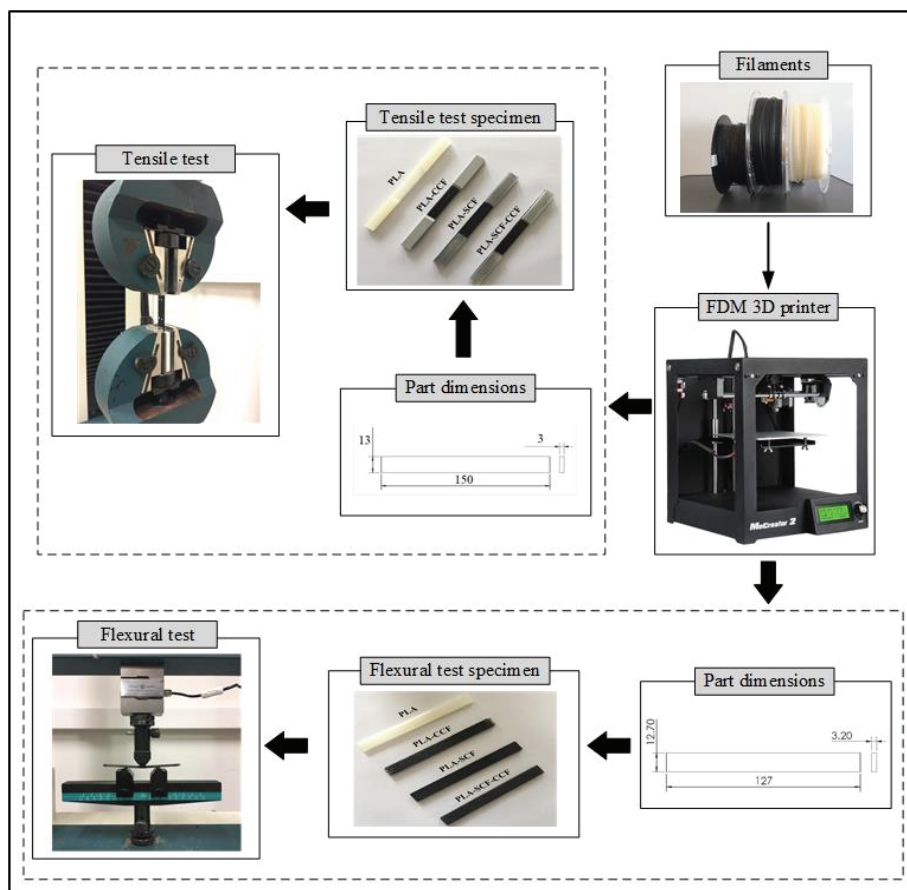


Fig. 2.4 Sample fabrication and testing process for the experiment

All the printing parameters for the fabrication of PLA, PLA-SCF, and PLA and PLA-SCF filament reinforced with CCF are presented in Table 2.4. The differences in the extrusion multiplier (E.M.), extrusion width (E.W.), layer height, printing speed, extrusion and bed temperature were selected according to the 3D printer technology and the manufacturer's recommendations. All the specimens were chosen to print with the 100% infill rectilinear pattern. The sample fabrication and testing procedure for the experimental work is illustrated in Fig. 2.4.

2.5. Investigation of the influence of printing parameters on mechanical properties

This investigation aims to characterize the evaluation of optimized printing parameters of the modified FDM printer to achieve the best possible mechanical properties of the manufactured CCFRPC structure. In this analysis, three printing parameters i.e., the extrusion temperature, the extrusion multiplier (E.M.), and the extrusion width (E.W.) were considered. At this stage, the layer height of 0.5 mm, the printing speed of 3 mm/s and the bed surface temperature of 90° were kept constant

throughout the experimental research. Firstly, the composite specimens were fabricated by using the ranges of the extrusion temperature of (200°C – 230°C) with the printing parameters of E.W. -1.5 mm and E.M. -0.5. The ranges of the extrusion temperature were selected according to the thermoplastic matrix material that was chosen. The range of the printing process parameters used for fabricating the composite specimens is presented in Table 2.5.

Table 2.5 FDM process parameters

Extrusion temperature (E.T.) °C	Extrusion width (E.W.) mm	Extrusion multiplier (E.M.)
230	1.2	0.5, 0.7, 0.9
230	1.3	0.5
230	1.4	0.5
230	1.5	0.5, 0.8
200, 210, 220, 230	1.5	0.5

2.6. Additive manufacturing of cellular composite structures³

For the manufacturing of cellular composite structures using CCF, two different types of infill patterns (grid and triangular) at three different infill densities (20%, 40%, and 60%) of specimens were selected with one perimeter shell to print for the experiment. The outer perimeter shell represents the layer that was deposited at the outer surface of the specimen prior to filling the inner part. Two different infill schemes were used to fill the inner portion. There were two top and two bottom unidirectional 0° layers that covered the infill patterns. For a triangular design pattern, the internal infill angle offsets were 60°, -60°, whereas they were 45°, -45° for a grid pattern. Due to the complexity of the printing layers, the Simplify 3D-defined path, the experience of different offset angles in response to the mechanical properties, and the printer compatibility to the print parts with such structures, 45° and -45°, were chosen for the grid pattern and 60° and -60° for the triangular pattern. Fig. 2.5 depicts the infill patterns or the structure of specimens created by using 3D printing and one perimeter shell for the grid and triangle infills at three different infill density levels.

Fig. 2.5 (a–f) depicts the structures of two different infill patterns, grid and triangular, produced at three infill density levels (20%, 40%, and 60%) with one perimeter shell with two top and two bottom unidirectional 0° layers covering the inner cellular structure. By adding more unit cells to the cellular structure while maintaining the same wall thickness, the specimen geometries length of the cell walls shrank when the infill percentage was raised. It was noticed that after the printing of cellular composites, uneven material distributions were seen that overlap the layers between the infill structures. This resulted from Simplify 3D's infill printing paths

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and the important component of the anisotropy of the cellular structures [166]. The triangular structure which has a nodal connectivity equals to 3 is known to be isotropic in the plane, while the grid structure has a nodal connectivity which equals to 4 and is known to be anisotropic [77, 167]. The printing parameters for the production of 3D printed cellular composite specimens for the grid and triangular infill pattern are presented in Table 2.6. The presently mentioned infill patterns were considered due to the self-generated defined path by Simplify 3D and the possibility to print with the modified extrusion head of the FDM printer. The complexity of the structure is defined by the infill pattern used to fabricate the cellular structure.

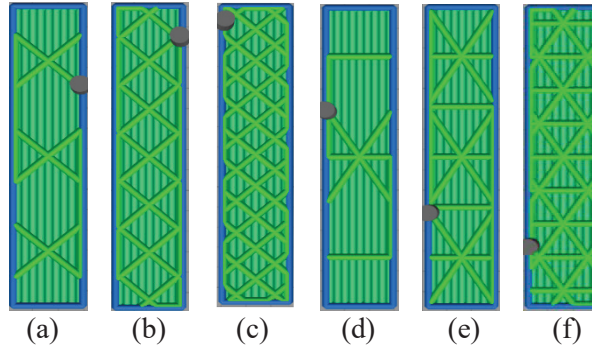


Fig. 2.5 Infill patterns of full-length 3D printed specimens fabricated with 1 perimeter shell with grid infill pattern at: a) 20%; b) 40%; c) 60% infill densities level and triangular infill pattern at d) 20%; e) 40%; f) 60% infill densities level

Table 2.6 Printing parameters for fabricating cellular composite structures

Nozzle diameter	1.5 mm
Extrusion multiplier	0.4
Extrusion width	1.5 mm
Layer height	0.5 mm
Top solid layers	2
Bottom solid layers	2
Outline/Perimeter shells	1
Printing speed	3.0 mm/s
First layer speed	1.20 mm/s
Extruder temperature	210°C
Bed temperature	90°C
Internal infill angle offsets (Grid)	45°, -45°
Internal infill angle offsets (Triangular)	60°, -60°
Infills	20%, 40%, 60%

The samples fabrication process of cellular structures, the testing procedures and the fracture analysis for the 3D printed composites for the experiment are presented in Fig. 2.6.

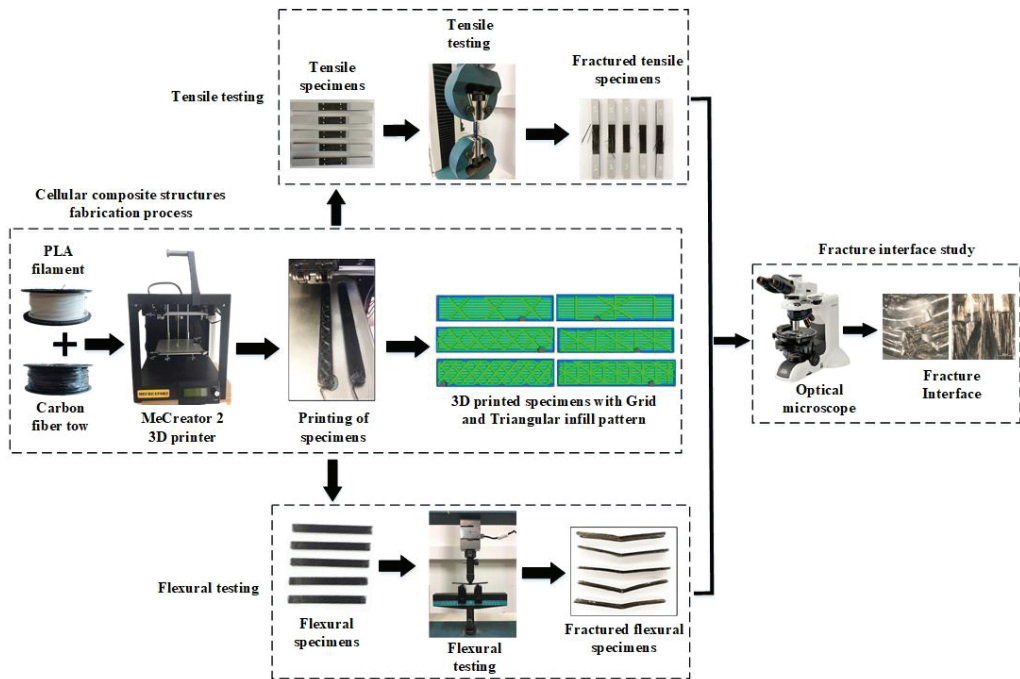


Fig. 2.6 Fabrication, testing process and fracture analysis of cellular composite specimens for the experiment

2.7. Development of controlled cooling effect for 3D printing⁴

The major modification performed during the experiment was the introduction of the controlled air flow cooling through a pressurized regulator. The reason for such a modification is to ensure the high quality and fine fabrication of CCFRPC structures. The copper tube of a 3 mm inner diameter was inserted outside and attached near the printing nozzle so that it would enable the extruded composite to be uniformly printed on the built surface. Fig. 2.7 shows the schematic view of the modified designed MeCreator 2 3D printer used for fabricating the composite structure. The flow rate of the compressed air cooling was controlled through the digital pressure regulator valve. The composite specimens were fabricated with and without cooling to compare the quality achieved in both cases. The cooling was controlled under the range of the air flow rates of 30 l/min, 40 l/min, 50 l/min, and 55 l/min and kept constant till the part had been fabricated completely.

The copper cooling tube was kept 9 mm away from the printing nozzle. The point direction of the copper tube was directly towards the bed surface and pointed towards the composite extruding through the printing nozzle which guides the extruded material and solidifies it as it lies on borosilicate glass and ensures that the

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composite is placed on it instantly in the course of the curve being made for another line. Additional cooling solidifies within the projected path and does not drag or displace the printing path.

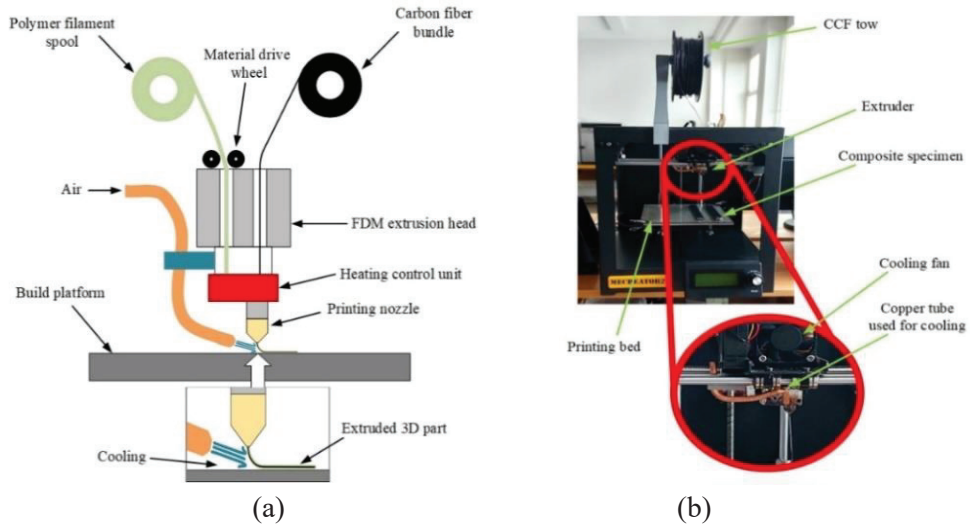


Fig. 2.7 FDM 3D printer: a) schematic view of the designed structure; b) machine used for fabricating a composite structure with a cooling tube

To study the influence of CCE on the mechanical properties of the composite specimens, three groups were selected i.e., E.W. -1.2 mm E.M. -0.5, E.W. -1.2 mm E.M. -0.7, and E.W. -1.3 mm E.M. -0.5. Tensile and flexural properties of the above mentioned groups were studied, and the obtained results were thoroughly compared to those of the composite specimens which were printed without CCE to determine in what direction the properties can be improved. It will also provide the validation of the relationship of the quality of the specimen with the mechanical properties and how they affect each other and link to each other. For the experimental research, 0° unidirectional composite specimens were printed with a rectilinear 100% infill pattern. The airflow rate of 40 l/min was used for the manufacturing of all the three groups because it showed the best results in terms of the quality of the printed composite.

2.8. Influence of the layer height and layer orientation on mechanical properties

This experimental work was performed to investigate the effect of the layer height and the layer orientation on the mechanical properties, the air void volume and the reinforcement content of additively manufactured CCFRPC structures. Although it is clear that the mechanical properties of 3D printed parts deteriorate with increasing voids [168], it is not yet clear how the printing process parameters and voids affect the quality of 3D printed composite parts and the mechanical condition function. The

lower layer height and the line width between the printed layers shows the minimal porosity and superior adhesion properties [121].

For this study, four groups were selected with the layer height of (0.4 mm and 0.5 mm) and the layer orientation of (0° and $0^\circ - 90^\circ$) as listed in Table 2.7. Various printing parameters were selected to evaluate the effect of the layer height and the layer orientation on the mechanical properties and the effect of the void volume [169, 170]. The line width of the composite specimen was kept 1 mm with the E.M. of 0.7 and the printing speed of 3 mm/s. The nozzle or the extrusion temperature and the bed temperature were set to 230°C and 90°C , respectively. These printing parameters were kept constant throughout the experimentation. All the composite specimens were fabricated with 100% infill unidirectional structure. The layer orientation direction of the composite layers is presented in Fig. 2.8.

Table 2.7 Printing process parameters for the experimentation

Specimen's	Line width (mm)	Layer height (mm)	Layer orientation
Group 1	1	0.5	0°
Group 2	1	0.4	0°
Group 3	1	0.5	0° - 90°
Group 4	1	0.4	0° - 90°

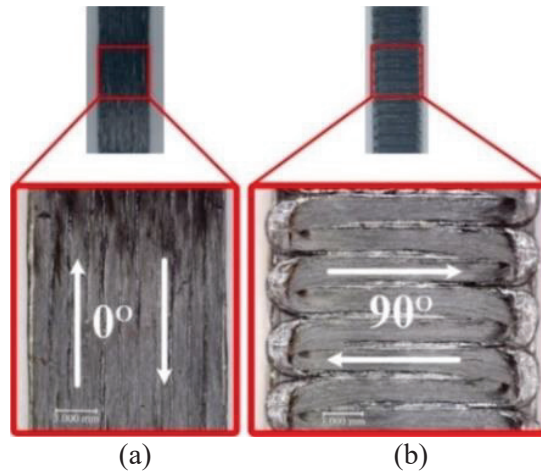


Fig. 2.8 Composite specimens printed with: a) 0° ; b) $0^\circ - 90^\circ$ layer orientations

2.9. Tensile and flexural testing procedure

Mechanical (tensile and flexural) tests were conducted to examine and determine the properties of 3D fabricated composite specimens. The effects on the tensile properties (the tensile strength and Young's modulus) and the flexural properties (the flexural strength and flexural modulus) of composite specimens were experimentally investigated and analyzed. Since there are no standard test methods defined for determining the tensile and flexural properties of CFRPC parts fabricated

using the FDM technology [79], in this experimental testing of composites manufactured by using the AM technology, ASTM D3039 Standard [171] was used to conduct the tensile test, whereas ASTM D790 Standard [172] was used for the flexural test. All the testing was performed at room temperature. According to the above-mentioned standards, to indicate repeatability and obtain the average value, at least five samples for each property were printed to analyze the mechanical performance of the targeted properties.

For the tensile test, a dual column universal testing machine *H25KT* (*Tinius Olsen*, UK) having a capacity of 25 kN was used to conduct the test. For the solid composite specimens, the rectangular cross-section shape having dimensions of 150×13×3 mm was fabricated. 3D printed PLA tabs were applied at each end of the specimen while using glue for a better grip. Tabs were printed of the dimensions of 50×14×2 mm with the bevel angle of 30°. For the 3D printed cellular composite, the specimens were fabricated by using the rectangular cross-section shape with the dimensions of 150×14×4.2 mm. The increase in the thickness and width was caused by the additional upper and lower solid layers, and the unit perimeter shell, respectively. In order to measure the elastic strain, four points were marked at 16 mm from the center on the specimens. The test was employed between two grips (one fixed and the other one movable) to hold the specimens with the standard head displacement rate of 2 mm/min. The test was carried out until the fracture of the specimen where the graph had decreased dramatically.

Fig. 2.9 shows the mechanical testing equipment setup for the tensile and flexural test. The tensile strength and the modulus of elasticity were calculated by using the following formulas:

$$\sigma_{tu} = \frac{P_{max}}{A} \quad (1)$$

where:

σ_{tu} – ultimate tensile strength (MPa);

P_{max} – maximum load before failure (N);

A – average cross-sectional area (mm²).

$$E = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \quad (2)$$

where:

E – modulus of elasticity (GPa);

σ_1 – stress at a strain point of 0.10%;

σ_2 – stress at a strain point of 0.30%;

ϵ_1 – strain point 1;

ϵ_2 – strain point 2.

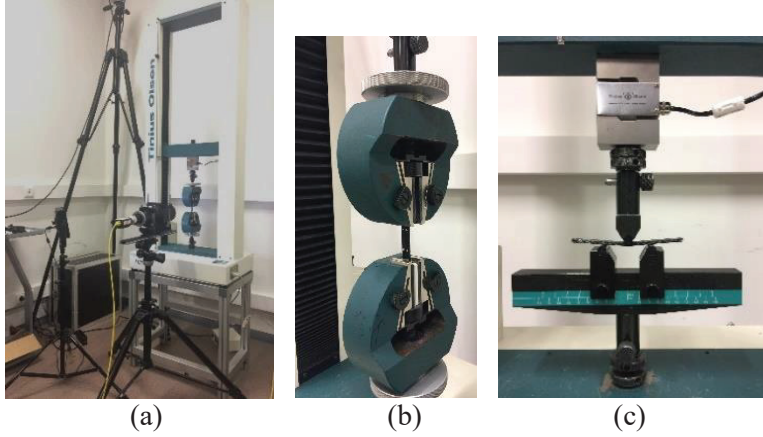


Fig. 2.9 Experimental setup: a) Tinius Olsen mechanical testing equipment for: b) the tensile test; c) the flexural test

According to ASTM D790 Standard for flexural testing, rectangle-shaped specimens were fabricated with the dimensions of 123×12.7×3.2 mm. A three-point bending set-up (two supports and one midway load nose each of a 10mm diameter) was used for the flexural test while using a Tinius Olsen H25KT universal testing machine. The test was performed by using the rate of the crosshead motion of 1.35 mm/min with the span support length of 51.2 mm. Data acquisition software *Tinius Olsen Horizon* was used to collect the force (N) and displacement (mm) relationships. The three-point flexural bending test was performed till the fracture of the composite specimen where the force graph started its decline.

The flexural strain, flexural stress and flexural modulus of elasticity were calculated by using Equation 3, Equation 4 and Equation 5, respectively.

$$\epsilon_f = \frac{6Dd}{L^2} \quad (3)$$

where:

ϵ_f – strain at the outer surface (mm/mm);

D – maximum deflection at the center of the specimen (mm);

L – span length (mm);

d – thickness of the specimen (mm).

$$\sigma_f = \frac{3PL}{2bd^2} \quad (4)$$

where:

σ_f – flexural strength (MPa);

P – applied bending load (N);

L – span length (mm);

b – width (mm);

d – thickness of the specimen (mm).

$$E_f = \frac{(\sigma_{f2} - \sigma_{f1})}{(\epsilon_{f2} - \epsilon_{f1})} \quad (5)$$

where:

E_f – flexural chord modulus;

σ_{f2} and σ_{f1} – flexural stresses at the predefined points on the load deflection curve;

ϵ_{f2} and ϵ_{f1} – flexural strain values at the predetermined points on the load deflection curve.

2.10. Estimation of carbon fiber content in composites⁵

The reinforcement content in a composite has a significant role in terms of the production and defining the mechanical properties as a varying reinforcement content changes the mechanical properties. The constant impregnated CCF was provided with the same spool throughout the experimental work, while the PLA matrix was varied in different ratios to observe the composite behavior in response to mechanical loads. The ratio of the matrix and reinforcement directly affected the quality of production as well as the mechanical response as varying reinforcement causes the printing parameters to be changed to acquire a better printing result. To study the influence of the reinforcement content on the mechanical properties, it was decided to calculate and estimate the carbon fiber content in the composite fabricated by using FDM.

The carbon fiber content in a unidirectional 0° composite specimen was estimated by using the tool length path in which the approximate content is calculated by knowing the number of the layer and the lines of the 3D printed specimen and its mass. Meanwhile, in the cellular fabricated composite and the composite prepared with a different layer orientation, it was difficult to calculate the reinforcement content by using the tool length path as the layer offset angles were different in each case. Therefore, in order to calculate the fiber content in a cellular structure and a composite with 0° – 90° layer orientation, the dissolution method was used in which the matrix of the composite was fully dissolved, and the remaining fiber was weighted and calculated as the weight ratio.

The length of the specimen's tool path was used to compute the approximate carbon fiber content in the matrix. As a result, the weight ratio of the carbon fiber to the composite specimen can be used to calculate the carbon fiber content [99].

In order to estimate the carbon fiber reinforcement content in cellular and 0° – 90° layer orientation CCFRPC parts, the *ASTM D 3171 Standard Test Methods for Constituent Content of Composite Materials* [173] procedure was followed. Method-I was followed to calculate the reinforcement content in which the matrix of the composite specimens was physically removed by digestion in the solution, thus leaving the essentially unaffected reinforcement behind to compute the matrix or the fiber content. Three samples from each group were examined in order to avoid repeatability and to ascertain the average amount of the reinforcement which was

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present in the composite parts. The reinforcement content measurement procedure using the dissolution method is presented in Fig. 2.10.

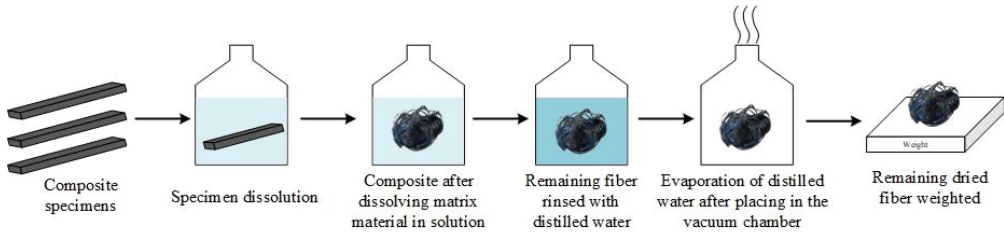


Fig. 2.10 Reinforcement content measurement procedure using the dissolution method

As no specified geometry is defined for the specimen to estimate the reinforcement content by the standard, the dimensions should be known before the dissolution to calculate the amount. For cellular composite parts with the grid and triangular infill pattern, the specimens having dimensions 120×12×3 mm were used. While for the layer orientation of 0° – 90° and with a layer height of 0.4 mm and 0.5 mm, the composite specimens were fabricated of the dimensions of 35×10×10 mm.

After the fabrication process, the composite specimens were placed in a beaker and filled with the solution covering the sample with the liquid. The solution was changed after every 48 hours until the thermoplastic matrix had been fully dissolved to obtain the unaffected carbon fiber to be examined. Later, it was rinsed with distilled water and placed in the oven until the reinforcement fibers had fully dried to be weighed. Fig. 2.11 shows the carbon fiber content method where the composite is dissolved in a beaker and placed in a vacuum oven.

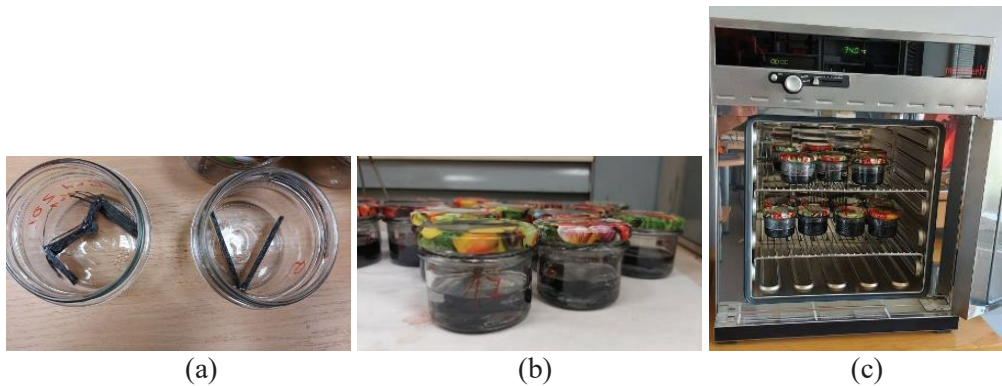


Fig. 2.11 Carbon fiber reinforcement content measurement: a) placing composite specimens in beakers; b) dissolving in the solution; c) placing in the vacuum oven

Finally, the unaffected carbon fiber was weighed, and the content of the reinforcement was calculated by using the following Expression 6:

$$W_r = (M_f / M_i) \times 100 \quad (6)$$

where:

W_r – weight percentage of reinforcement;

M_i – initial mass of the specimen, g;

M_f – final mass of the specimen after digestion or combustion, g.

2.11. Detection of the air void volume content in composite

The presence of air void volume in 3D printed composites is one of the major issues affecting the mechanical performance of the designed structure that converted to a solid functional component. Usually, during the simulation process and numerical modeling, the composite is considered as a void-free structure that will perform its highest mechanical performance. This is one of the key differences calculated in the modeled part compared to the 3D generated component. Moreover, it significantly influences the mechanical properties and its functionality. Therefore, it was decided to calculate the void volume in the composite fabricated with the layer height of 0.4 mm and 0.5 mm and the layer orientation of $0^\circ - 90^\circ$. The influence of the printing parameter and the layer orientation on the void volume of the composite was calculated by using *X-ray computed tomography* (XCT) and the dissolution method. The results obtained by both methods were experimentally examined and compared.

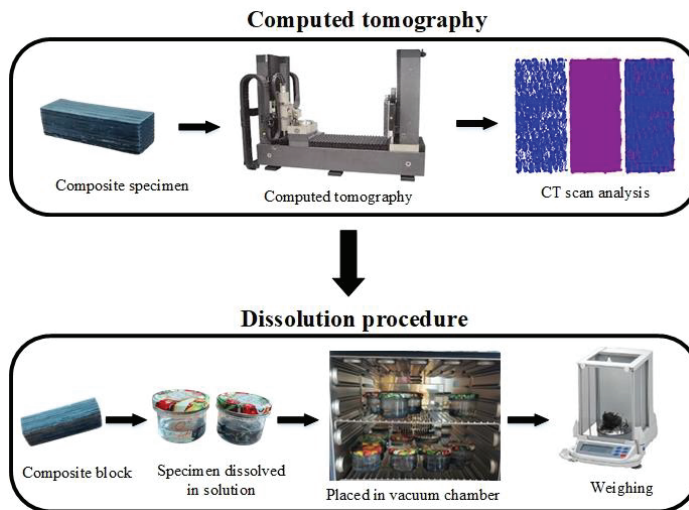


Fig. 2.12 Air void volume detection by using XCT scan and dissolution procedure

X-ray computed tomography scans were performed with a *RayScan 250E* X-ray computed tomography scanner (*RayScan Technologies GmbH*, Germany). The RayScan 250E is a 3D computed tomography system with two X-ray sources, a 10–230 kV X-ray source in the microfocus mode (focal length 3–250 μm) and a 10–230 kV X-ray source and kV for the macro focus mode (focus 0.4mm). The X-ray source and the X-ray detector can move up and down depending on the size of the object to be inspected. The effective area of the X-ray detector is $410 \times 410 \text{ mm}^2$ with 2048×2048 pixels. It works in the microfocus mode while using a 10–230 kV X-ray

source with a voltage of 100 kV, a current of 200 μ A, and an exposure time of 2000 ms. 1800 projections were measured with a resolution of 11 μ m. The data was averaged five times.

The dissolution method compared to CT was used to validate the void content measurement. ASTM D3171 Standard was used to examine the carbon fiber content and the porosity of composite samples. Here, the matrix of the composite sample was dissolved in the solution to physically remove it and count the amount of the matrix or fibers without significantly damaging the reinforcement. The composite specimens were printed as a set of rectangular cross section specimens measuring 120x10x10 mm and divided into three equal parts with an average size of 35x10x10 mm. Composite samples were pre-treated prior to the experimentation. The surface roughness was reduced by grinding the sample to reduce the measurement error and minimize its impact on the total void volume [121].

From each set of groups, three samples were tested to determine the reinforcement and the void content according to the standard. We continued changing the solution and checking after every 48 hrs until the composite matrix had been completely dissolved. The remaining carbon fiber was rinsed with distilled water and dried in a vacuum oven at 100 °C for 3 hours. Finally, a *GR-200* physical balance (accuracy $\pm$ 0.1 mg) was used to measure the CCF content and weight. The manufacturer specified the density of the thermoplastic matrix and the CCF reinforcement. The reinforcement and void volumes were calculated according to the equations specified in the standard.

$$V_r = \left(\frac{M_f}{M_i} \right) \times 100 \times \rho_c / \rho_r \quad (7)$$

$$V_v = 100 - (V_r + V_m) \quad (8)$$

where:

V_r – volume percentage (reinforcement content);

ρ_r – density of the reinforcement, g/mL;

ρ_c – density of the composite, g/mL;

V_v – void volume;

V_m – volume percentage (matrix content).

2.12. Fracture interface analysis

2.12.1. Microscopic analysis

The fracture interfaces of the 3D printed CCFRPC samples were observed after mechanical testing by using an *Eclipse LV100ND* optical microscope (*Nikon*, Japan) equipped with a high-resolution color camera (*Nikon DS-Ri2*). The data was prepared and processed at 5x magnification by using imaging software (*NIS Elements 4.5.1.00*) at 5x magnification on the fractured area of the composite sample examined for the

study between the polymer matrix and the individual printed layers and the fracture in carbon fiber. From the five specimens tested for fracture interfaces, those specimens were selected that best represented or characterized the behavior of materials in mechanical testing. Fig. 2.13 shows the *Eclipse LV100ND* optical microscope equipment used for the experimental work.

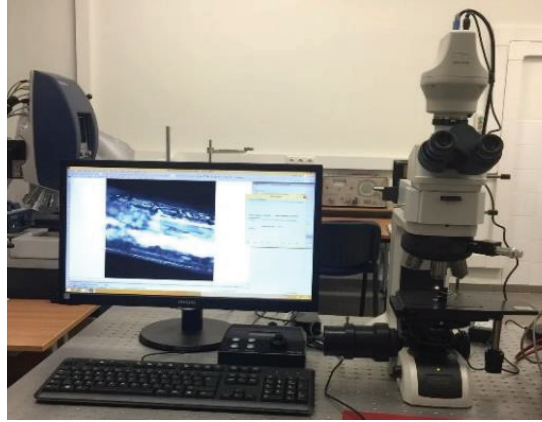


Fig. 2.13 *Eclipse LV100ND* optical microscope

2.12.2. Image processing study⁶

Fracture interface analysis was also performed on the composite specimens by using image processing. Firstly, micrograph images were captured and observed by using a microscope (*Delta Optical Smart*) at the fractured region after mechanical testing to study the failure mode and the response of the deposited layers and their detachment and ruptured fibers in the matrix during mechanical loading. The microscope-obtained micrograph of the ruptured region further underwent the image processing technique so that to enhance the quality of the source image for detailed study and analysis. The source images were improved by using contrast enhancement and edge detection to specify the region, especially to observe in the case of cellular structure composites.

This image processing technique is used to enhance low-contrast images. Histogram smoothing seems to be an effective way to improve the image contrast. In this sense, *Non-parametric Modified Histogram Equalization* (NPMHE) [174, 175] is used to improve the image contrast and preserve the low brightness of the source image A_i .

$$X_i \rightarrow \hat{X}_i \quad (9)$$

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NPMHE is employed to fracture interface images to obtain an improved image $\hat{X}_i$. Contrast enhancement centrally improves the intensity distribution and enhances the image details.

After contrast enhancement, the images were then rectified by using the *Spatial stimulus sketch model* (SSGSM) edge detection technique [176, 177] which is based on object representation by detecting luminance irregularities [178]. Edge detection improves the performance of high-contrast images. This method obtains focus information from the two active plane maps by highlighting the focus intensity and the image edges and computing the unknown area in the coarse resolution map. The weights of the local stimuli are intentionally adjusted by determining the local changes in perceived brightness at each location. The brightness of the contrast enhanced image $\hat{X}_i$ is perceived in Eq. (10) as:

$$E_i = z \log_{10}(\hat{X}_i) \quad (10)$$

where $\hat{X}_i$ represents the contrast enhanced image and z denotes the scaling factor. Gradients indicate strong changes in the image intensity.

It is a measure of the spatial distance to the measured variation of local pixels. This amplitude is mathematically computed as the mesh difference in the identified brightness in r and s directions as:

$$B_i = \text{gradient} [\mathfrak{G}_j^r, \mathfrak{G}_j^s] \quad (11)$$

$$\zeta_j^r = \mathfrak{G}_j^r(e^{-|\mathfrak{G}_j^r|}); \zeta_j^s = \mathfrak{G}_j^s(e^{-|\mathfrak{G}_j^s|}) \quad (12)$$

where intensity variations (B_i) on the r and s axes were denoted by ζ_j^r and ζ_j^s respectively. These variations are computed in Eq. (11) and Eq. (12) by employing the corresponding gradients $\mathfrak{G}_j^r, \mathfrak{G}_j^s$.

The local stimuli (L_i) are calculated with Eq. (13) as:

$$L_i = \sqrt{(\zeta_j^r)^2 + (\zeta_j^s)^2} \quad (13)$$

2.13. Analytical approach to estimate the elastic modulus of the composite

The maximum possible elastic modulus of the composite before manufacturing could be predicted and estimated by using analytical approaches. In this study, two types of analytical methods i.e., the Halpin-Tsai model and the rule of mixture (RoM) were utilized to predict the modulus and compare to the results achieved with experimental and numerical simulation.

2.13.1. Halpin-Tsai Model

The Halpin-Tsai model is a mathematical model for predicting the composite material's elasticity based on the geometry and orientation of the filler as well as the elastic properties of the filler and the matrix. The mechanical characteristics of composite materials can be predicted by using the Halpin-Tsai model in a certain direction, usually in the direction of the fibers. Based on the characteristics of the

matrix and the reinforcing materials as well as their volume fractions, the model can be used to determine the elastic modulus of the composite material. By modifying the volume percentage and the aspect ratio of the fibers, the model can be utilized to optimize the properties of composite materials [179, 180]. This can help to achieve the desired mechanical properties of the composite material. However, it is important to note that the Halpin-Tsai model holds assumptions that fibers are perfectly aligned and that the deformation of the matrix and reinforcement materials is uniform. Only a unidirectional 0° 3D printed composite with 100% infill specimens has been considered with varying E.W. to predict the modulus by using this model. The volume fraction of the fiber is already known, and the elastic modulus of the matrix and the fiber is provided by the manufacturer. By knowing these factors, the elastic modulus of the composite using the Halpin-Tsai model could be predicted by using the following Equation 14.

$$\frac{E_C}{E_m} = \left(\frac{1 + \xi \eta V_f}{1 + \eta V_f} \right) \quad (14)$$

$$\eta = \frac{E_f - E_m}{E_f - \xi E_m} \quad (15)$$

$$\xi = \frac{2l}{d} \quad (16)$$

where ξ = reinforcing efficiency which depends on the fiber orientation, distribution and arrangement and the loads conditions.

2.13.2. Rule of mixture (RoM)

RoM is a mathematical model used to predict the effective properties of a composite material by combining the properties of its constituent materials. RoM predicts the effective properties of the composite material based on the volume fraction and the properties of the constituent materials. The effective properties of the composite material can be calculated by adding together the contributions of the constituent materials weighted by their respective volume fractions. RoM is capable of estimating the maximum possible mechanical performance of the constituent parts of a mixture, given the total composite strength and the fiber V_f %. Prior to the manufacturing of a composite, the ideal mechanical property (the elastic modulus of the composite) is estimated [179, 181]. The elastic modulus is assessed by using RoM for the composite under the following assumptions:

1. All the fibers are uniformly distributed in the matrix.
2. They are perfectly bonded with each other i.e., there is no interface issue.
3. The composite is void and stress-free.
4. The fiber and the matrix behave with linear elasticity.

A.N. Dickson *et al.* [37] calculated the mechanical performance of the constituent parts of a mixture of CCF with a nylon matrix by using this rule. The theoretical elastic modulus of the composite could be assessed based on the properties of the carbon fiber reinforcement and a polymer matrix [181, 182].

The modulus values of PLA and PLA-SCF (which are used as matrixes) obtained from tensile tests are 3.09 GPa and 4.79 GPa, respectively. The fiber fraction in the printed composite part was measured as a weight fraction. Thereby, it was calculated as the volume fraction V_f by using Equation 17 by knowing the density of the fiber and the matrix and the weight fraction of the fiber.

$$V_f \% = \left[\frac{1}{1 + \frac{\rho_f (1 - W_f)}{\rho_m W_f}} \right] \quad (17)$$

where:

V_f – volume fractions of the carbon fiber;

W_f – weight fraction of the carbon fiber;

ρ_f – density of CCF (1.76 g/cm³);

ρ_m – density of the PLA matrix (1.24 g/cm³).

In this study, the elastic modulus for the structure of the prepared composite parts of CCF reinforced with PLA and PLA-SCF with the longitudinal printing direction was estimated by using Equation 19.

$$E_c = E_f V_f + E_m V_m \quad (18)$$

$$E_c = E_f V_f + E_m (1 - V_f) \quad (19)$$

where:

E_c – elastic modulus of composite;

V_f – volume fraction of fiber;

E_m – elastic modulus of PLA matrix (2.6 GPa);

E_f – elastic modulus of CCF (230 GPa).

2.14. Chapter conclusions

Following the planned research, firstly, the impregnation of CCF was performed with the aim to print with the modified extrusion head of the FDM technology, which enables CCF reinforced with the polymer matrix to print. Secondly, by using the standard printing parameters and conditions, composites were fabricated to examine their printability and the manufactured specimens. CCF was printed with a pure PLA matrix and a PLA-SCF matrix to study its performance and compatibility. After the successful fabrication of a solid structure, the influence of the printing process parameters (E.T., E.M., E.W., and the layer height) and the layer orientation (0° and

0° – 90°) on the mechanical properties were investigated. Later, cellular CCFRPCs were fabricated by using a grid and a triangular infill pattern at three different infill density levels (20%, 40%, and 60%). The mechanical performance of the manufactured structure was compared thoroughly. The tensile properties (the tensile strength and Young's modulus) and the flexural properties (the flexural strength and flexural modulus) were calculated and studied for each set of the groups of composites to make a comparison of the difference. Based on the experiment of tensile and flexural tests, the fracture interface of 3D printed samples was studied to explore the deformation and fracture process. An optical microscope and an image processing technique were used to discover such an interfacial deformation process. The carbon fiber content in the cellular composite was estimated by using the dissolution method by fully dissolving the matrix material. The void volume of the composite specimen printed with a layer height of (0.4 mm and 0.5 mm) and a layer orientation of (0° and 0° – 90°) were determined by using the X-ray CT scan and the dissolution method to validate the results.

3. RESULTS AND DISCUSSIONS

3.1. Observation of prepared impregnated carbon fiber¹

Following the CCF impregnation procedure, an optical microscope was used to visualize the impregnated carbon fiber. Optical micrographs of the cross-section of the impregnated CCF are displayed in Fig. 3.1 (a). When seen in cross-section, PLA and carbon fiber are plainly visible along with some air voids. Carbon fiber tow has an asymmetrical geometric cross section. The irregular shape is caused due to the cutting procedure of carbon fiber due to the added pressure. The matrix material deforms and changes the geometry during cutting from circular to elliptical. The smooth and even distribution of the plastic over the carbon fiber strand is depicted in the full-length micrograph view in Fig. 3.1 (b). The concentration of the solution greatly influences the quality of the carbon fiber tow. The amount of air voids in the impregnated carbon fiber tow can be reduced by increasing the concentration of the plastic solution [72]. Additionally, it is possible to view how the matrix material adheres to the carbon fiber. According to research on the mechanical characteristics of carbon fiber impregnated with various solution concentrations and their effects, carbon fiber impregnated with a 10% weight solution yields the best results [72].

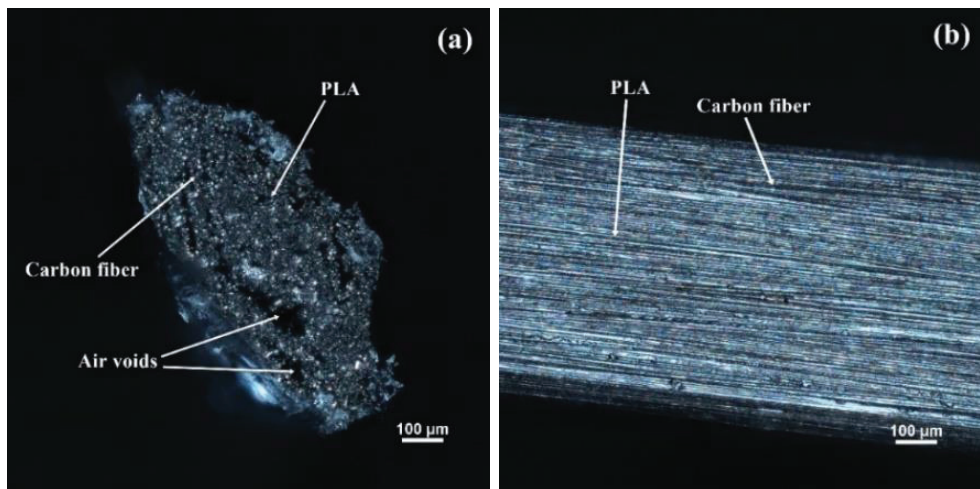


Fig. 3.1 Optical micrographs of impregnated CCF: a) cross-section; b) full-length

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3.2. Observation of 3D printed solid and cellular composite specimens^{2, 3}

The FDM 3D printing technique was used to create CCFRPC specimens. Initially, 210° C E.T. was used to extrude the matrix filament for all the specimens, based on the producer's recommended temperature. E.W. of 1.5 mm and a layer height of 0.5 mm were kept constant throughout the printing process.

Following the creation process, the morphology of the printed layers was studied by using a microscope-derived micrograph on 3D printed CCFRPC specimens. A micrograph of the layers and lines that were deposited is shown in Fig. 3.2. The illustration shows some void spaces that were left behind after printing the composite part's layers. The printed layers also exhibit irregularities. This is typically brought on by uneven printing and extrusion processes. Sometimes, the semi-melted matrix extruded unevenly through the printing nozzle during the extrusion process, which would result in creating these spaces. The matrix material serves as a link and an adhesive between the layers. In contrast to the layers, the lines printed on the composite portion displayed more equal distribution.

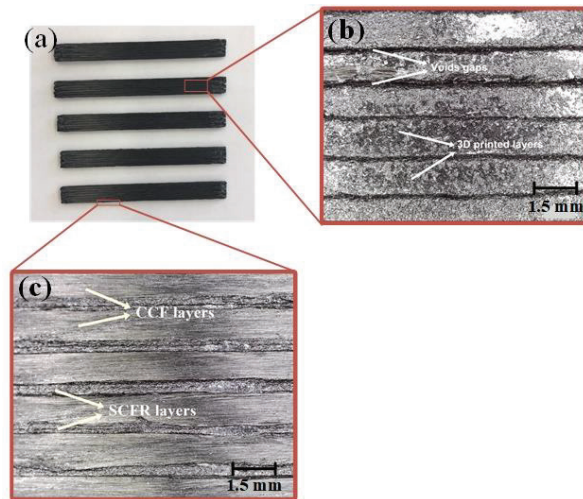


Fig. 3.2 Microscope micrograph of: a) 3D printed composite; b) deposited layers; c) deposited lines

A microscope was used to analyze the inside pattern of CCFRPC cellular structures, as shown in Fig. 3.3. According to the observation, the nodal connection of the triangle infill specimen is equal to 3, thus making it isotropic in the plane,

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whereas the nodal connectivity of the grid infill structure is equal to 4, thus making it anisotropic in the plane. As a comparison to the triangle infill pattern, the grid infill structure demonstrated a more compact and dense structure for each infill density level by taking up more space within the perimeter shell and consuming more mass. The content of the reinforcement and mechanical characteristics are greatly influenced by the infill pattern.

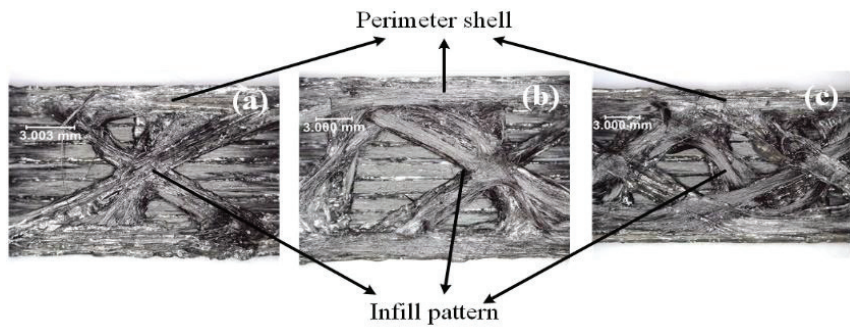


Fig. 3.3 Micrographs of composite structures produced with grid infill density levels: a) 20%; b) 40%; c) 60%

The printing time exerts influence on the infill pattern and the density levels (Fig. 3.4). The triangular infill pattern consumes more time for printing the composite part compared to the grid infill pattern.

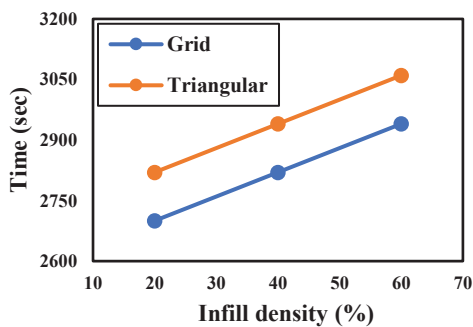


Fig. 3.4 Printing time for fabricating composite parts for all infill density levels

When comparing the printing time, the grid pattern with 40% and 60% infill density took the same time when compared to the triangular pattern of 20% and 40% infill density, respectively. Such differences in the printing time are caused by the different infill structure which was created inside the perimeter shell. The complexity of the structure also affects the duration of printing.

All the average dimensions of 3D printed specimens used to perform mechanical testing are provided in Table 3.1. While the dimensions of 3D printed cellular specimens for both grid and triangular infill patterns are provided in Table 3.2 and Table 3.3, respectively.

Table 3.1 Dimensions of 3D printed specimens

Material	Tensile testing				Flexural testing			
	Length, mm	Width, mm	Thickness, mm	Mass, g	Length, mm	Width, mm	Thickness, mm	Mass, g
PLA	149.68 $\pm$ 0.08	13.07 $\pm$ 0.05	3.01 $\pm$ 0.04	6.80 $\pm$ 0.02	122.80 $\pm$ 0.06	12.95 $\pm$ 0.14	3.03 $\pm$ 0.08	5.56 $\pm$ 0.01
PLA-CCF	149.53 $\pm$ 0.34	12.05 $\pm$ 0.07	3.19 $\pm$ 0.02	5.58 $\pm$ 0.03	121.83 $\pm$ 0.06	12 $\pm$ 0.11	3.72 $\pm$ 0.06	5.17 $\pm$ 0.04
PLA-SCF	149.9 $\pm$ 0.07	13.04 $\pm$ 0.03	3.03 $\pm$ 0.04	6.95 $\pm$ 0.02	122.95 $\pm$ 0.03	12.96 $\pm$ 0.02	3.21 $\pm$ 0.02	5.91 $\pm$ 0.02
PLA-SCF-CCF	150.63 $\pm$ 0.23	11.91 $\pm$ 0.14	3.25 $\pm$ 0.11	5.73 $\pm$ 0.08	120 $\pm$ 0.92	11.97 $\pm$ 0.01	3.72 $\pm$ 0.05	5.14 $\pm$ 0.04

Table 3.2 Dimensions of 3D printed specimens for grid infill

Infill	Tensile specimens				Flexural specimens			
	Length, mm	Width, mm	Thickness, mm	Mass, g	Length, mm	Width, mm	Thickness, mm	Mass, g
20%	150.68 $\pm$ 0.47	13.87 $\pm$ 0.13	4.20 $\pm$ 0.05	6.16 $\pm$ 0.02	123.33 $\pm$ 0.74	12.73 $\pm$ 0.08	3.31 $\pm$ 0.08	3.96 $\pm$ 0.04
40%	149.86 $\pm$ 0.39	14.01 $\pm$ 0.08	4.27 $\pm$ 0.06	6.69 $\pm$ 0.07	123.25 $\pm$ 0.27	12.83 $\pm$ 0.04	3.27 $\pm$ 0.03	4.19 $\pm$ 0.0587
60%	149.64 $\pm$ 0.62	13.98 $\pm$ 0.03	4.25 $\pm$ 0.06	7.16 $\pm$ 0.09	122.83 $\pm$ 0.03	12.77 $\pm$ 0.07	3.23 $\pm$ 0.02	4.38 $\pm$ 0.03

Table 3.3 Dimensions of 3D printed specimens for triangular infill

Infill	Tensile specimens				Flexural specimens			
	Length, mm	Width, mm	Thickness, mm	Mass, g	Length, mm	Width, mm	Thickness, mm	Mass, g
20%	150.44 $\pm$ 0.30	13.95 $\pm$ 0.17	4.21 $\pm$ 0.06	5.55 $\pm$ 0.03	122.73 $\pm$ 0.53	12.67 $\pm$ 0.14	3.22 $\pm$ 0.01	3.60 $\pm$ 0.04
40%	149.41 $\pm$ 0.81	13.85 $\pm$ 0.038	4.23 $\pm$ 0.02	6.10 $\pm$ 0.03	123.22 $\pm$ 0.24	12.63 $\pm$ 0.08	3.25 $\pm$ 0.03	3.78 $\pm$ 0.02
60%	149.70 $\pm$ 0.70	13.92 $\pm$ 0.11	4.23 $\pm$ 0.02	6.71 $\pm$ 0.28	122.87 $\pm$ 0.71	12.80 $\pm$ 0.10	3.25 $\pm$ 0.02	4.2 $\pm$ 0.32

3.3. Observation of quality of composites printed without CCE⁴

To clearly compare the printing quality, CCFRPC specimens were created by utilizing both FDM printing processes with and without the air flow cooling effect controlled by the pressure control valve regulator. In order to observe how the layers and lines were distributed and arranged on the surface of the bed, the initial layer of the specimen was printed without CCE. Micrographs taken with a microscope were used to observe the first layer of each specimen group. The micrographs of the composite lines from the first layer produced without CCE are displayed in Fig. 3.5. It is clear from the figure that the composite lines are distributed unevenly. The printing of the composite lines experienced a number of issues.

The excess thermoplastic was extruded with the CCF embedded within it. Due to the thermoplastic failing to solidify at the designated location during the printing process, carbon fiber was dragged back, and it did not stick to the plastic at that position, which caused and highlighted the poor quality impediment which required plastic to be removed or cut once the printing had been finished. Another issue was that the thermoplastic itself did not extrude properly as it bonded to the bed surface and dragged away from the end of the composite lines, thereby leaving gaps between them and lowering the quality. On the other hand, if it does not drag the carbon fiber away from it, excess plastic will be extruded beyond the CCF because when the specimen's layer is returning, the carbon fiber sticks away from the returning position due to the drag force caused by the thermoplastic's failure to instantly solidify on the built platform.

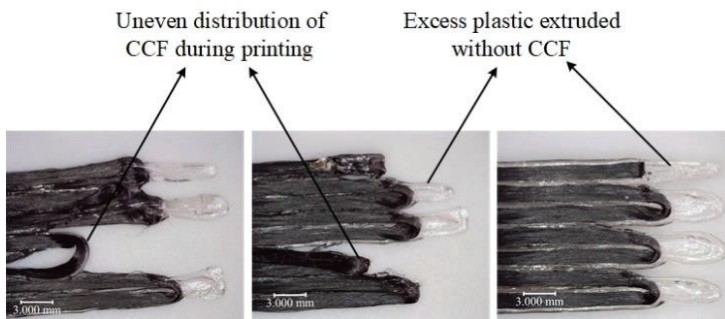


Fig. 3.5 Micrographs of composite lines printed without CCE

3.4. Observation of quality of composites printed with CCE

Secondly, the first layer of the composite specimen was used to print under CCE at various air flow rates (30 l/min, 40 l/min, 50 l/min, and 55 l/min), and a microscope-derived micrograph was used to assess the dispersion of the lines, as presented in Fig. 3.6. The findings showed that while the distribution of the lines on the 3D printed composite specimen was more uniform when the flow rate was maintained at 30 l/min,

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the low cooling still caused excess plastic to be extruded during the returning and the start of the new line. When the flow rate was slightly raised to 40 l/min, more consistency was seen in the distributed lines, and CCF was completely covered with the thermoplastic matrix when starting a new line, thus preventing the carbon fiber from being dragged. Additionally, more regularity with a low void area was also attained in this situation. In order to rapidly solidify the thermoplastic matrix on the constructed platform with a uniform distribution and to prevent CCF from pulling back within the matrix, the cooling effect enables the composite lines used in printing to do so. Similar results were seen with the slightly irregular thermoplastic extrusion and gaps between the lines when the air flow rate was increased to 50 l/min. Inconsistencies in printing lines were observed when the flow rate was increased to 55 l/min because too much cooling was being provided. More cooling accelerated the matrix's solidification, created abrupt edges and dislocated the composite distribution along it, which resulted in producing a worse specimen and a worse quality matrix. The composite part printed at the 40 l/min flow rate demonstrated a finer quality with the uniform dispersion of the layers when compared to the various air flow rate ranges.

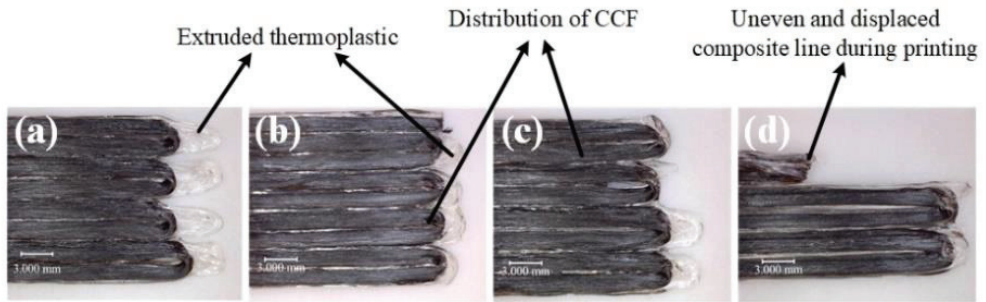


Fig. 3.6 Micrographs of the composite lines printed with CCE at the air flow rate of: a) 30 l/min; b) 40 l/min; c) 50 l/min; d) 55 l/min

Fig. 3.7 represents the micrographs taken under the microscope of the composite layers that were printed by using various E.W. and E.M. With inadequate extruded thermoplastic and weak interfacial bonding, the composite layer with an E.W. of 1.5 mm and an E.M. of 0.5 displayed the greatest gaps between the lines. The same behavior is still evident when E.M. was increased to 0.8 while maintaining the same E.W. with a minor reduction in the spaces between the printed lines. As the printing continues, E.W. decreases, the gaps get smaller, and the bonding gets better. When E.W. decreased to 1.3 mm and 1.2 mm, a finer and more desirable quality was attained by reducing the smallest gaps between the lines and increasing the CCF reinforcement, which improved adhesion and interfacial bonding [128]. Excess plastic was extruded during fabrication in the case of specimens with an E.W. of 1.2 mm and an E.M. of 0.9. The quality of the specimen degrades as new layers are added at the boundary and on the surface, even though the additional thermoplastic matrix minimizes breaches. The specimen that had an ideal CCFRPC structural quality, with an E.W. and E.M. of 1.2 mm and 0.7 mm, was produced additively.

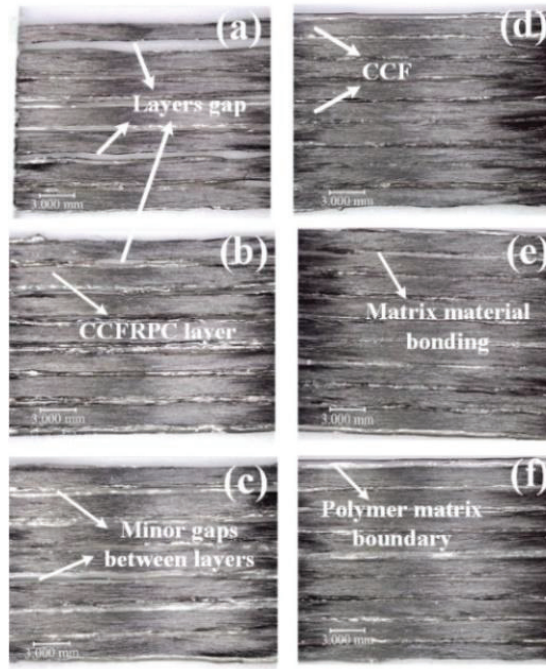


Fig. 3.7 Microscope-derived micrographs of composite layers printed with E.W. (mm), E.M. of: a) 1.5, 0.5; b) 1.5, 0.8; c) 1.4, 0.5; d) 1.3, 0.5; e) 1.2, 0.7; f) 1.2, 0.9

3.5. Analysis of cellular structure infill pattern and density⁵

Fig. 3.8 (a & b) shows the manufactured composite specimens for tensile and flexural testing as a mass function of the infill percentage for the grid and triangular infill patterns. The obtained graph revealed that, with an increase in the infill density, the mass of each specimen grows. The infill layers grow more densely and cover the majority of the area inside the structure's shell, thus increasing the mass, while the perimeter shell, the bottom solid layer, and the top solid layer remain constant for each specimen throughout the experiment. By comparing the two infill patterns, it can be seen that the grid structure takes up more space inside the perimeter shell for each infill density compared to the triangular infill pattern, which results in a more compact and denser structure, therefore, it exhibits more mass for both the tensile and the flexural test specimens.

Due to the changes in the geometry's structural makeup, different infill patterns display distinct masses despite having the same infill densities. The mechanical characteristics of the composite parts are significantly influenced by the interior structure of the 3D printed specimen. Simplify 3D was used to create and choose the

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unit cells for the density levels, infill patterns, and the distribution of the line orientation.

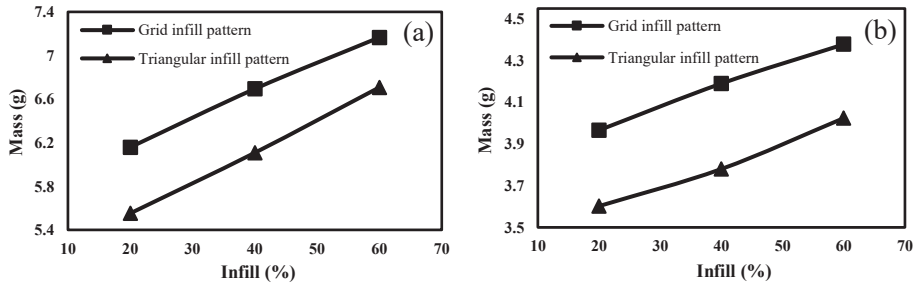


Fig. 3.8 Cellular specimens fabricated by using AM with grid and triangular infill pattern mass as a function of infill percentage for: a) tensile; b) flexural tests

The internal geometric structure of the composite part was represented by a grid and a triangular infill pattern that was used to produce cellular composite specimens at three different infill density levels (20%, 40%, and 60%). One perimeter shell and two bottom and two top unidirectional layers were used to cover the infill structure. By adding more unit cells to the cellular structure, the specimen's internal structure grows while the exterior wall layer stays the same as the infill density is increased. During the printing process, an irregular layer distribution was seen. This is caused due to the infill paths produced by Simplify 3D, which is a crucial aspect of anisotropy [166]. The nodal connectivity of the grid infill structure is equivalent to 4, which is known to be anisotropic [77, 167].

3.6. Mechanical properties of 3D printed composite structures⁶

Mechanical testing was conducted to study the behavior response of tensile properties (the tensile strength and Young's modulus) and flexural properties (the flexural strength and flexural modulus). Firstly, four groups of composite specimens (PLA, PLA-CCF, PLA-SCF, PLA-SCF-CCF) were fabricated to observe and compare their properties in terms of mechanical performance.

3.6.1. Tensile test response of CFRPC

The tensile test was performed to compare the tensile properties of the printed specimens for each group. Fig. 3.9 shows a ruptured sample after performing the tensile test. The typical tensile stress-strain curves of the best representing curve from each group are presented in Fig. 3.10. The resulting curves are selected from the test representing the average tensile stress results. From the stress-strain curve, it can be seen that PLA-CCF reaches the highest peak value of tensile stress, followed by PLA-SCF-CCF, PLA-SCF, and PLA. The tensile properties of each group (the tensile strength and Young's modulus) are shown in Fig. 3.11. Bar graphs were used to

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present the data of tensile properties. The mean values in the bar plots were used to illustrate the trends of each printed specimen with a range of their result effects on the tensile properties.

The *Grip-at-Tab-Top* (GAT) failure mode was visible in the specimens printed with PLA-SCF, in accordance with ASTM D3039. Meanwhile, the *Lateral-at Tab-Top* (LAT) failure mode is visible in the specimens printed with PLA-CCF and PLA-SCF-CCF (Fig. 3.9). Under identical testing conditions, the gripping pressure, the specimen geometry, and the tab material influence the tensile strength of the specimens [183], and distinct failure modes can also be seen, like in the instance where specimens printed with CCF demonstrated a comparable manner of failure. The results of tensile testing to determine tensile characteristics are displayed in Table 3.4.

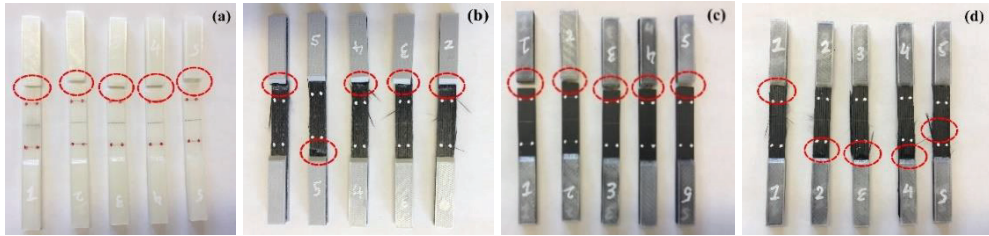


Fig. 3.9 Fractured modes of specimens after performing tensile testing of: a) PLA; b) PLA-CCF; c) PLA-SCF; d) PLA-SCF-CCF

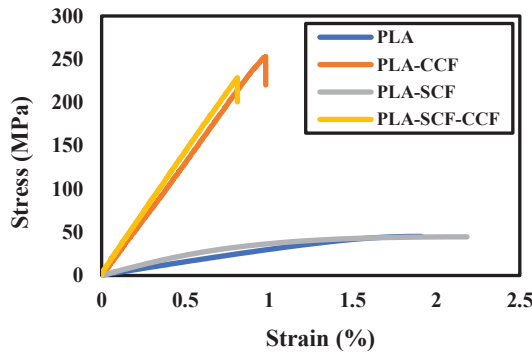


Fig. 3.10 Stress-strain curves obtained from tensile test

The tensile strength of the 3D printed composite of each group is presented in Fig. 3.11(a). PLA-SCF achieves the smallest average tensile strength value of 43.75 MPa, as can be observed from the bar graph plot. The tensile strength of PLA is 43.83 MPa (almost the same as that of PLA-SCF). The average tensile strength value of PLA-SCF-CCF is 227.56 MPa. The PLA-CCF group achieved the highest mean maximum of 245.40 MPa. The strongest tensile strength was shown by the PLA printed with impregnated CCF, which is about 6 times stronger than PLA and PLA-SCF and even stronger than the PLA-SCF printed with CCF. The tensile strength was increased by 460% compared to pure PLA and PLA-SCF specimens and by 7.84% compared to PLA-SCF-CCF specimens.

Pure PLA demonstrated similar strength results as those reported by the manufacturer, but PLA-SCF showed a lower strength than that reported by the manufacturer. This is due to the different selection of the printing parameters and also because of the weak interfacial bonding between the layers. The manufacturer of *XT-CF20* provided the strength for the molded prototypes. When compared to the earlier result [45], PLA-CCF exhibits a 299.67% improvement in terms of the tensile strength.

Fig. 3.11(b) displays the computed Young's modulus. The trend in the data is changing, with the PLA-SCF-CCF having the highest mean Young's modulus value of 27.93 GPa, followed by PLA-CCF, PLA-SCF, and PLA which have average Young's modulus values of 25.94 GPa, 4.79 GPa, and 3.09 GPa, respectively. The findings suggest that an increase of the matrix's fiber content will enhance the Young's modulus value. A similar trend can also be observed [38], which increases the Young's modulus value up to a certain level of the content of fibers in the matrix.

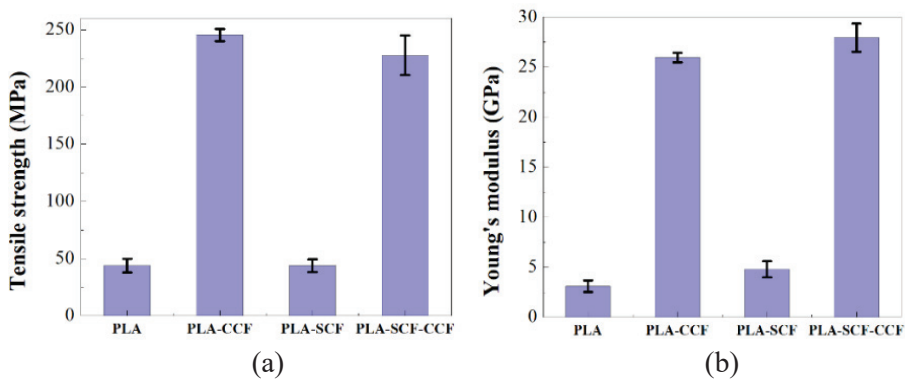


Fig. 3.11 Results of tensile properties of 3D printed samples: a) Tensile strength; b) Young's modulus

Table 3.4 Results of measured mechanical properties

Specimens	Tensile properties		Flexural properties	
	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
PLA	43.83 ± 2.39	3.09 ± 0.05	83.18 ± 3.22	3.067 ± 0.29
PLA-CCF	245.40 ± 0.14	25.94 ± 0.47	168.88 ± 5.17	10.63 ± 0.59
PLA-SCF	43.75 ± 0.39	4.79 ± 0.08	76.33 ± 1.21	4.52 ± 0.11
PLA-SCF-CCF	227.56 ± 0.13	27.93 ± 1.40	116.75 ± 13.3	10.85 ± 1.51

3.6.2. Flexural test response of CFRPC

The fractured test samples are displayed in Fig. 3.12 after performing the flexural test. According to ASTM D790 Standard, the highest strain in the outer region of the specimen breaking must fall within the 5% strain limit in order for the flexural test to be valid. None of the specimens in this investigation broke above the 5% strain limit. Fig. 3.13 shows the typical flexural stress-strain curves for all the specimens for each group. The graphs show the curve that represents the average flexural strength results for each group. According to the stress-strain curve, the PLA printed with CCF exhibits the highest level of stress, followed by PLA-SCF-CCF, PLA and PLA-SCF, respectively. Fig. 3.14 compares the flexural properties (the flexural strength and flexural modulus) of each group of CFRPCs. The findings of the values of the flexural properties determined from flexural testing are displayed in Table 3.4. The carbon fiber content reduces as the layer thickness increases, thus reducing the CFRPC's flexural strength [99]. Due to inadequate interfacial bonding between the layers of the specimen, which might result in such variations [184], PLA-SCF-CCF displayed an abrupt breakage and drop in the stress value in the stress-strain curve as well as large standard deviation values in both situations (the flexural strength and flexural modulus).

When the PLA, PLA-CCF, and PLA-SCF specimens undergo bending during flexural testing, a fracture occurs at the applied load (Fig. 3.12 a, b & c). In the case of PLA-SCF printed with CCF, when undergoing bending, delamination occurs rather than breaking toward the sides of the applied load in the center, and the layers of the fiber split and produce gaps between the printed layers (Fig. 3.12 d).

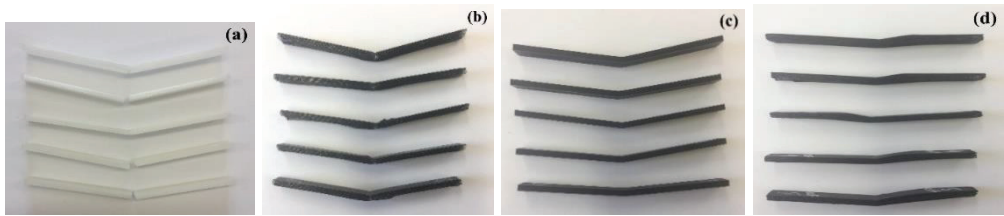


Fig. 3.12 Flexural test fractured samples of: a) PLA; b) PLA-CCF; c) PLA-SCF; d) PLA-SCF-CCF

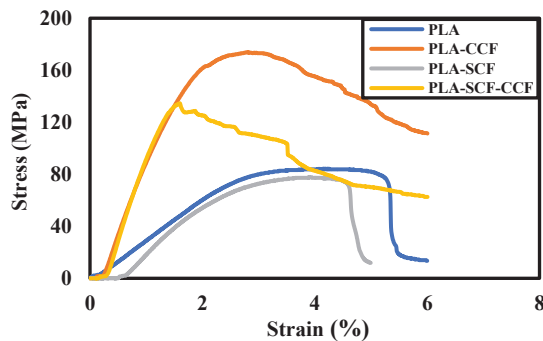


Fig. 3.13 Typical flexural stress-strain curves obtained from flexural test

The flexural strength of each group's 3D printed specimens is illustrated in Fig. 3.14 (a). PLA-CCF has the highest mean flexural strength value of 168.88 MPa, as seen by the bar graph plot. The average flexural strength of PLA-SCF printed by using CCF is 116.75 MPa. The average flexural strength of PLA and PLA-SCF is 83.18 MPa and 76.33 MPa, respectively. When compared to PLA-SCF, pure PLA, and PLA-SCF-CCF specimens, PLA printed with CCF had the greatest flexural strength increasing by 121%, 103%, and 44.6%, respectively. The trend also shows that the flexural strength rises by increasing the content of CCF in the composite [87]. Since that higher flexural stress is anticipated for high excellent fiber composites, the lower flexural strength in comparison to the tensile strength is mainly due to the difference in the length of the testing specimen according to the standard testing method; it was also suggested that there may be issues with the quality of the printed specimens [185].

The flexural modulus results for each set of groups are displayed in Fig. 3.14 (b). The PLA-SCF printed with CCF has the greatest mean flexural modulus value, 10.85 GPa, and a similar trend can be seen in the results of the tensile test. In terms of the flexural modulus, PLA-CCF, PLA-SCF, and pure PLA exhibit the average values of 10.63 GPa, 4.52 GPa, and 3.06 GPa, respectively. The flexural modulus results also showed that the composite's flexural modulus will increase with an increase in the amount of reinforcing fibers in the matrix [38].

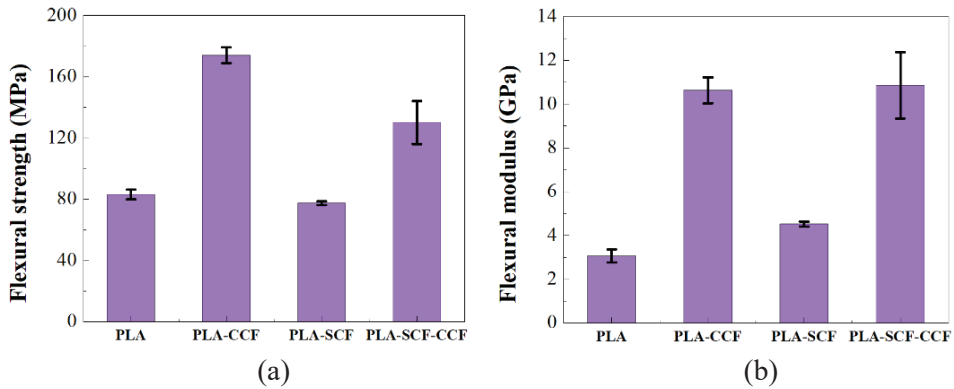


Fig. 3.14 Results of flexural properties of 3D printed samples: a) flexural strength; b) flexural modulus

3.7. Influence of printing process parameters on mechanical properties⁷

3.7.1. Effect of extrusion temperature (E.T.)

Firstly, composite specimens were fabricated by using the ranges of extrusion temperatures (200°C – 230°C) with the printing parameters of E.W.-1.5 mm and

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E.M.-0.5, and their effect on the tensile and flexural properties was investigated. The extrusion temperature range was selected based on the thermoplastic matrix material.

According to the findings (presented in Table 3.5), E.T. significantly influences the tensile properties. The tensile strength increases as E.T. rises [92], as seen by the tensile stress-strain curve (Fig. 3.15 a). When the temperature rises from 220°C to 230°C, the tensile stress slightly rises. Figure 3.16 (a & b) presents the tensile properties (the tensile strength and Young’s modulus, respectively). The high E.T. demonstrated the highest tensile properties, according to the results shown in the bar graph. The lowest tensile strength and Young’s modulus values of 160.2 MPa and 21.65 GPa, respectively, were observed when the specimens were fabricated by using E.T. of 200 °C, while the maximum tensile strength and Young’s modulus of 218.19 MPa and 28.56 GPa, respectively, were achieved when composite specimens were fabricated by using the extrusion temperature of 230°C. In contrast, increasing E.T. from 200°C to 230°C resulted in a 36.2% increase in the tensile strength.

Table 3.5 Results of measured mechanical properties

Specimen's Temperature	Tensile Properties		Flexural Properties	
	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
200°C	160.2 ± 10.31	21.65 ± 2.26	122.23 ± 12.42	9.86 ± 1.23
210°C	193.84 ± 12.35	25.62 ± 1.56	146.70 ± 13.45	11.94 ± 1.15
220°C	211.36 ± 9.23	27.46 ± 1.10	162.36 ± 13.10	13.11 ± 1.40
230°C	218.19 ± 11.26	28.56 ± 2.16	172.27 ± 10.46	13.71 ± 1.44

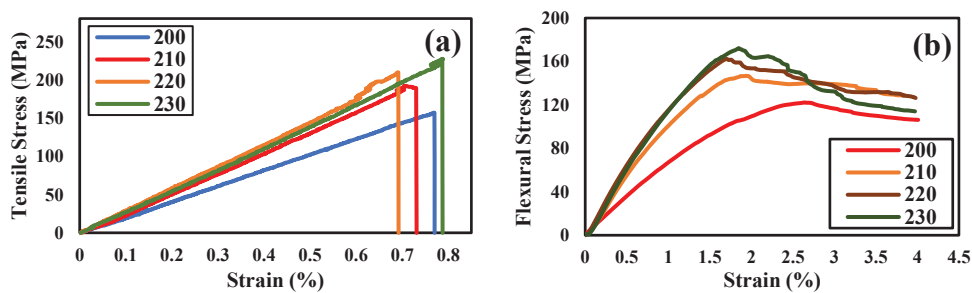


Fig. 3.15 Stress-strain curves obtained with the range of temperatures (°C) from: a) tensile test; b) flexural test

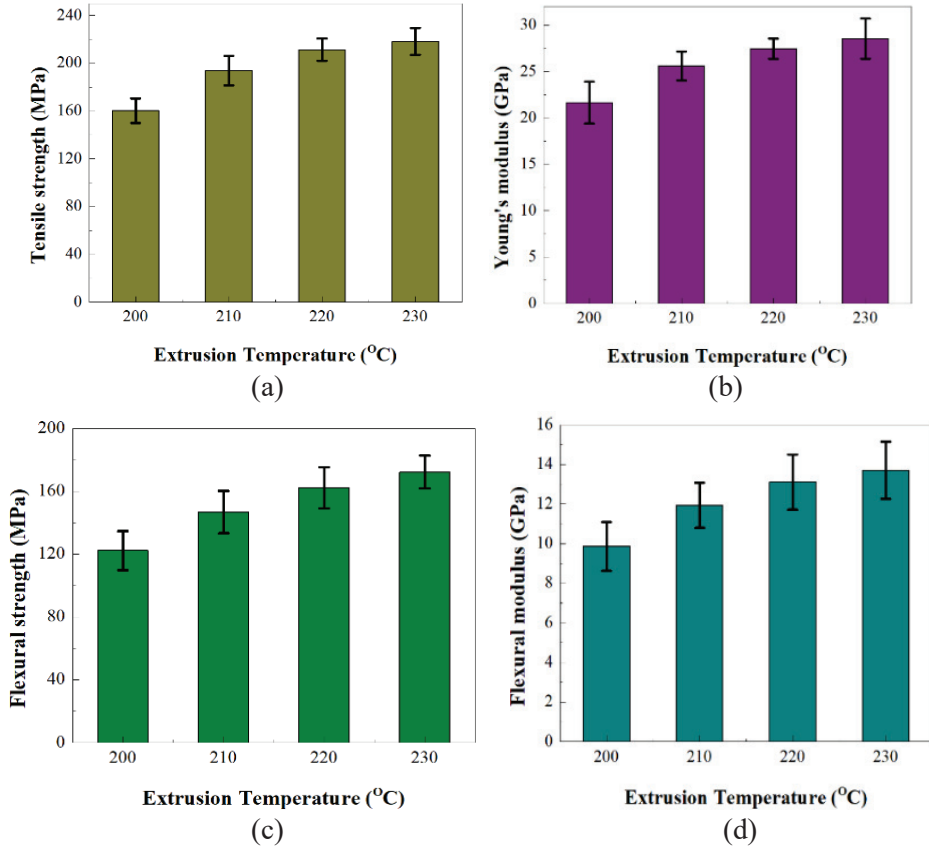


Fig. 3.16 Results obtained with the range of temperatures of: a) tensile strength; b) Young's modulus; c) flexural strength; d) flexural modulus

The flexural test also exhibits a similar pattern of behavior. Increasing E.T. causes the flexural strength and the modulus to increase. The behavior of E.T., which exhibits a rise with respect to temperature, can be investigated from the flexural stress-strain curves (Fig. 3.15 b). The flexural properties (the flexural strength and flexural modulus) of the CCFRPC specimen as determined by the flexural test are shown in Fig. 3.16 (c & d). From the obtained results, the specimen with an E.T. of 230°C had the highest flexural strength and modulus values measuring 172.27 MPa and 13.71 GPa, respectively. The strength level significantly increased as E.T. rose from 200°C to 210°C, and moderately continued with the rising E.T. When examining the influence of E.T. on the strength level, it was found that raising E.T. from 200°C to 230°C resulted in a 41% increase in the flexural strength. Table 3.4 displays the results of the measured mechanical properties.

3.7.2. Effect of extrusion multiplier (E.M.)

E.M. was crucial in defining the mechanical properties of the composite structure created by FDM 3D printing. In order to define and analyze the comparisons

made within each group, the E.M. value of 0.5 was kept constant for each E.W., although it changed for E.W. of 1.2 mm and 1.5 mm.

The E.M. behaved differently with each E.W. The stress-strain curves from the tensile test for each group are displayed in Fig. 3.17. The maximum tensile stress was visible with an E.M. of 0.7 and an E.W. of 1.2 mm. Meanwhile, the stress level lowers as E.M. increases to 0.9. The additional thermoplastic matrix extruded, which reduced the amount of CCF in the composite, and caused this drop in the tensile strength and Young's modulus. The quality of the composite specimen, as seen under microscope, which indicates its poor quality due to the excess matrix material, may also be used to validate the result. A similar behavior was also observed when the specimen was made with an E.W. of 1.5 mm and an E.M. of 0.8 mm, which showed lower tensile stress levels than an E.M. of -0.5. The results of the tensile properties (the tensile strength and Young's modulus) showing the effects of E.W. and E.M. are presented in Fig. 3.19 (a & b), respectively.

According to the results, the composite specimens made with an E.W. of 1.2 mm and an E.M. of 0.7 demonstrated the highest tensile strength of 251.62 MPa, while the composite part made with an E.W. of 1.3 mm and an E.M. of 0.5 demonstrated the highest Young's modulus of 30.36 GPa. The CCFRPC specimen printed by using E.W. -1.5 mm, E.M. -0.8 and E.W. -1.2 mm, E.M. -0.9, resulted in the lowest tensile strength of 213.19 MPa and Young's modulus of 24.83 GPa, respectively. The findings also showed that increasing the E.M. boosts the tensile strength up to a certain point, and, afterwards, a decline is observed [38, 99].

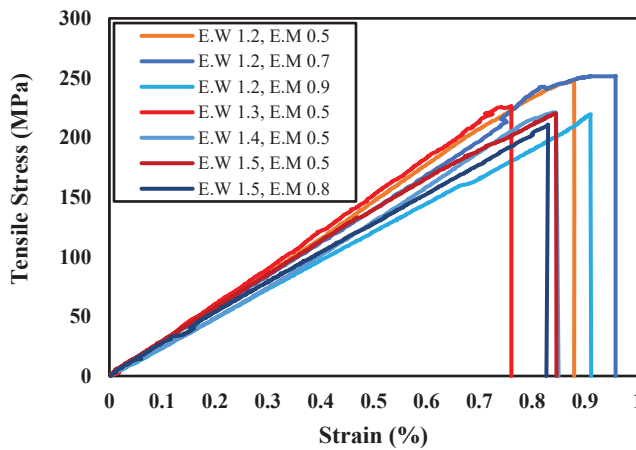


Fig. 3.17 Stress-strain curves obtained from tensile test

Table 3.6 Tensile and flexural properties obtained from the experiment

Specimen's Extrusion width (E.W.) mm	Specimen's Extrusion multiplier (E.M.)	Tensile Properties		Flexural Properties	
		Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
1.2	0.5	246.76 $\pm$ 8.63	28.90 $\pm$ 1.64	193.26 $\pm$ 7.89	14.37 $\pm$ 1.20
1.2	0.7	251.62 $\pm$ 9.63	27.59 $\pm$ 2.61	197.81 $\pm$ 11.05	12.15 $\pm$ 1.60
1.2	0.9	219.62 $\pm$ 15.65	24.83 $\pm$ 0.84	173.86 $\pm$ 6.83	8.94 $\pm$ 0.78
1.3	0.5	226.49 $\pm$ 11.64	30.36 $\pm$ 3.36	183.02 $\pm$ 4.96	15.07 $\pm$ 0.60
1.4	0.5	221.01 $\pm$ 12.52	25.43 $\pm$ 0.91	177.67 $\pm$ 5.30	3.75 $\pm$ 1.34
1.5	0.5	220.48 $\pm$ 10.54	27.92 $\pm$ 1.56	170.72 $\pm$ 6.73	8.47 $\pm$ 1.12
1.5	0.8	213.19 $\pm$ 8.53	25.54 $\pm$ 1.22	148.17 $\pm$ 5.67	10.44 $\pm$ 0.81

In the flexural bending test experiments, a similar behavior can also be observed. According to Fig. 3.18, the group of composite specimens printed with the printing parameters of E.W. -1.2 mm and E.M. -0.7 reached the highest level of the flexural stress. With the printing parameters of E.W. -1.2 mm and E.M. -0.5, nearly the same stress level was attained. According to the calculations made by using the E.W. group of 1.2 mm and 1.5 mm, increasing the amount of thermoplastic above a specific limit tends to reduce the level of the flexural stress. In both situations, the stress curve declines as it surpasses the amount of the matrix in the composite. The flexural properties (the flexural strength and flexural modulus) obtained from the flexural test are shown in Fig. 3.19 (c & d), respectively. From the graph, it can be assessed that the highest flexural strength level of 197.81 MPa and the flexural modulus of 15.07 GPa were reached with the printing parameters of E.W.-1.2 mm, E.M.-0.7 and E.W.-1.3 mm, E.M.-0.5, respectively. Meanwhile, the CCFRPC specimen printed with the printing parameters of E.W. -1.5 mm, E.M. -0.8 and E.W. -1.4 mm, E.M. -0.5, respectively, reached the minimum flexural strength of 148.17 MPa and the flexural modulus of 3.75 GPa. The mechanical characteristics sourced from the tensile and flexural tests are shown in Table 3.6.

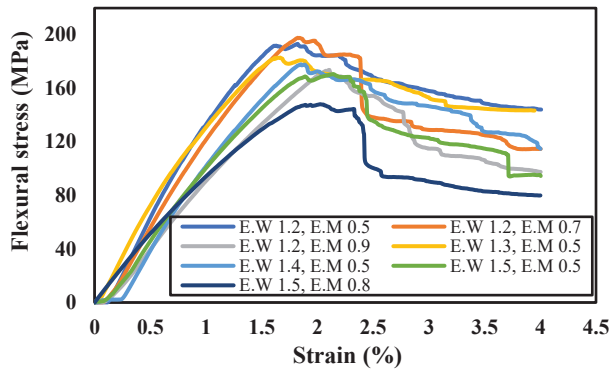


Fig. 3.18 Stress-strain curves obtained from the 3-point bending test

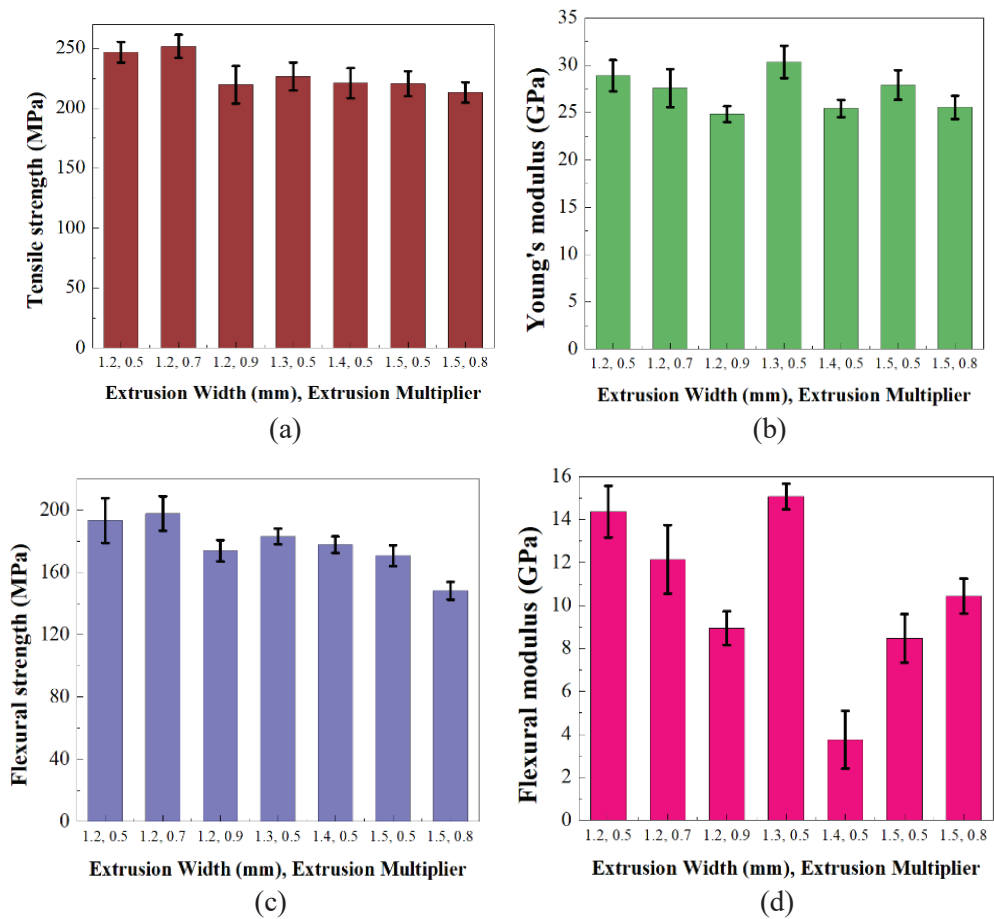


Fig. 3.19 Results obtained with the effect of E.W. and E.M. on: a) tensile strength; b) Young's modulus; c) flexural strength; d) flexural modulus

3.7.3. Effect of the extrusion width (E.W.)

To compare the groups of 3D printed CCFRPC specimens, composite specimens were made by using four groups of E.W. (1.2 mm, 1.3 mm, 1.4 mm, and 1.5 mm) fabricated while using an E.M. of 0.5. The impact of E.W. on the tensile and flexural strength is depicted in Fig. 3.20 (a & b). The findings showed that E.W. had a significant impact on the strength levels. The specimen with an E.W. of 1.5 mm displayed a tensile strength level that was nearly identical to that of an E.W. of 1.4 mm. The tensile strength tends to rise when E.W. is reduced to 1.3 mm, and a considerable increase in strength is shown when E.W. is reduced to 1.2 mm. Similar results were also seen for the flexural strength which gradually rises with the falling E.W. and reaches the highest value in the composite specimen with an E.W. of 1.2 mm. By decreasing the E.W., the distance between the neighbour lines of the composite layers becomes closer, hence making a more compact and denser structure with the minimum void volume and porosity by increasing the content of CCF in the composite part, which leads to an increase in the strength levels [91, 92].

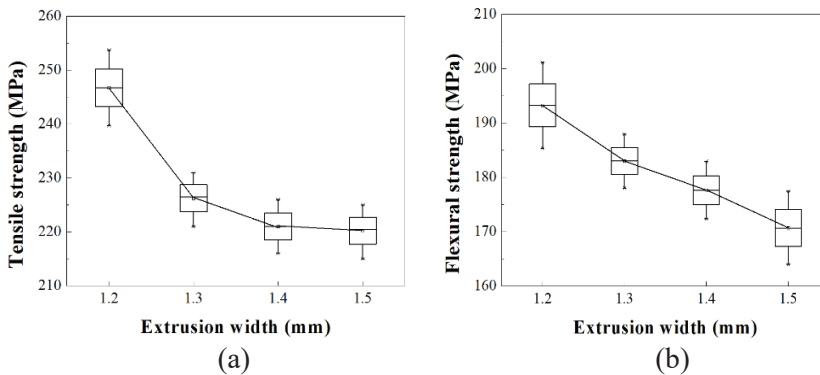


Fig. 3.20 Effect of the E.W. on: a) tensile strength; b) flexural strength

3.8. Mechanical response of 3D printed cellular CCFRPC⁸

A cellular CCFRPC structure was fabricated by using the FDM 3D printing technology with the modified extrusion head that was able to print and generate a complex structure. The cellular structure was fabricated by using two types of infill patterns (grid and triangular) printed at three different infill density levels (20%, 40%, and 60%). The infill path generated by *Simplify 3D* was used to fabricate the structure. The composite specimens were manufactured by using two bottom and two top unidirectional 0° layers with one perimeter shell.

3.8.1. Grid infill pattern

The purpose of the tensile test was to examine the tensile properties of specimens printed at various infill densities. The typical tensile stress-strain curves

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for each infill density are shown in Fig. 3.21 (a). According to the curves, the specimen printed with a 60% grid infill density achieves the maximum stress level, followed by the infill densities of 40% and 20% which exhibit nearly identical stress points.

According to ASTM D3039 [171], when specimens undergo a tensile test up to the rupture point, the *delamination-gage-middle* (DGM) and *grip-at-tab-top* (GAT) failure modes are observed. Under identical test settings, the gripping pressure, the specimen geometry, and the tab material all have an impact on the tensile strength of the specimens, which results in various failure mechanisms [183]. The average tensile strength and Young’s modulus are presented as a function of the mass for each individual specimen level in Fig. 3.21 (b & c). The results revealed an increase in the strength and modulus values with increasing the mass and infill percentage. Even though the same printing and testing conditions were used for each specimen, the variances in the mass and strength of each specimen with the same infill may be the result of the printing process not being uniform. For the infill density levels of 20% and 40%, the tensile strength as a function of the mass exhibited nearly identical behavior, while the infill density level of 60% caused a considerable increase in the tensile strength. In the case of Young’s modulus, it showed a slight change and an increase in the value with high differences in the individual specimen level when the infill density increases from 20% to 60%. Table 3.7 shows the results of the tensile properties measured from the tensile test.

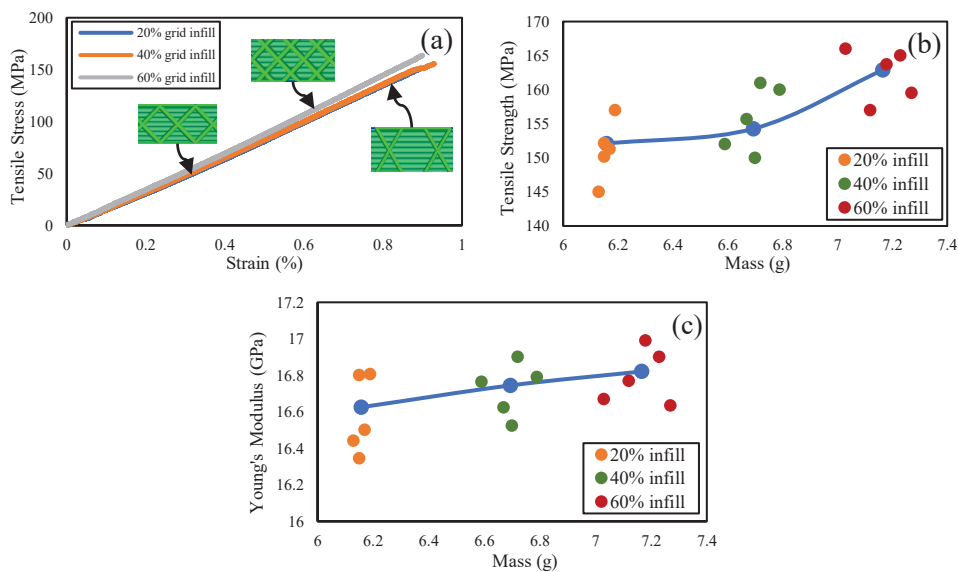


Fig. 3.21 Grid infill pattern data for the tensile test: a) stress-strain curves; b) strength as a function of mass; c) Young’s modulus as a function of mass

Table 3.7 Results of tensile properties

Specimens	Tensile Properties			
	Grid infill pattern		Triangular infill pattern	
	Tensile strength (MPa)	Young's modulus (GPa)	Tensile strength (MPa)	Young's modulus (GPa)
20%	152.1 $\pm$ 8.27	16.62 $\pm$ 0.61	131.15 $\pm$ 8.80	20.33 $\pm$ 0.46
40%	154.28 $\pm$ 7.26	16.74 $\pm$ 0.46	140.75 $\pm$ 7.32	20.58 $\pm$ 0.42
60%	162.9 $\pm$ 8.14	16.82 $\pm$ 0.58	152.62 $\pm$ 9.58	20.78 $\pm$ 0.52

Fig. 3.22 displays the tensile characteristics for each infill density, including the tensile strength and Young's modulus. The data of the tensile properties was expressed by using bar graph plots. From the bar graph plot in Fig. 3.22 (a), it can be seen that the specimen with a 60% infill density achieves the highest mean tensile strength value of 162.9 MPa, while 40% and 20% percent grid infill has mean strength values of 154.28 MPa and 152.1 MPa, respectively, and shows an increase in the strength value with an increase in the infill density. When compared to 20% and 40% infill densities, the tensile strength for the grid infill pattern with a 60% infill density increased to 7% and 5.6%, respectively.

Fig 3.22 (b) illustrates how infill densities affect Young's modulus. With an increase in the specimen's infill density, Young's modulus marginally rises. The average Young's modulus reaches 16.62 GPa at 20% infill density. Young's modulus grew to 16.74 GPa at 40% infill density and reached its highest value of 16.82 GPa at 60% infill density when the infill density continued to be raised. According to the findings, the specimen's infill density can be increased while still raising the Young's modulus value.

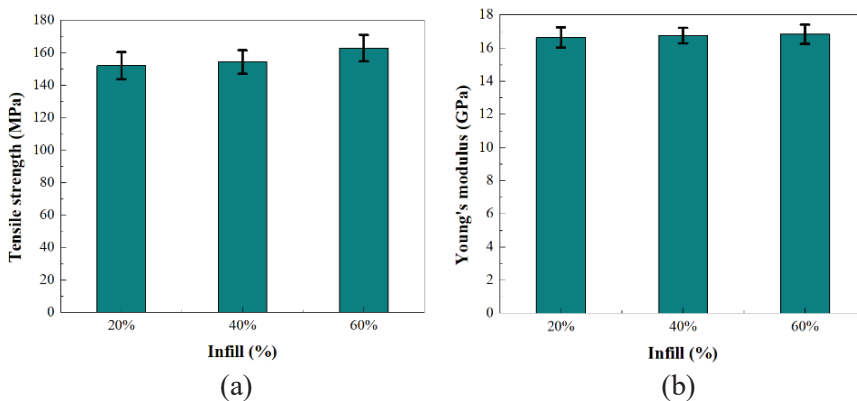


Fig. 3.22 Tensile properties of 3D printed grid infill pattern composite: a) tensile strength; b) Young's modulus

To examine the flexural characteristics of the specimens produced at various infill densities, a flexural test was conducted. Fig. 3.23 (a) demonstrates a typical flexural stress-strain curve for the specimens printed by using a grid infill pattern at three different infill densities levels. The specimen printed with a 60% infill density level exhibits the maximum level of flexural stress, according to the stress-strain curve, whereas the specimen printed with a 20% infill density level exhibits the lowest level of the flexural stress.

Fig. 3.23 (b & c) illustrates the average flexural stress and the flexural modulus as a function of mass for each specimen level produced at three different infill percentages. The outcome demonstrated that, when the mass increased, the strength and modulus values increased as well. With an increase in the infill density level and specimen masses, there is a noticeable increase in the flexural stress and the modulus. The graphs show the average curves with each individual 3D printed specimen infill level.

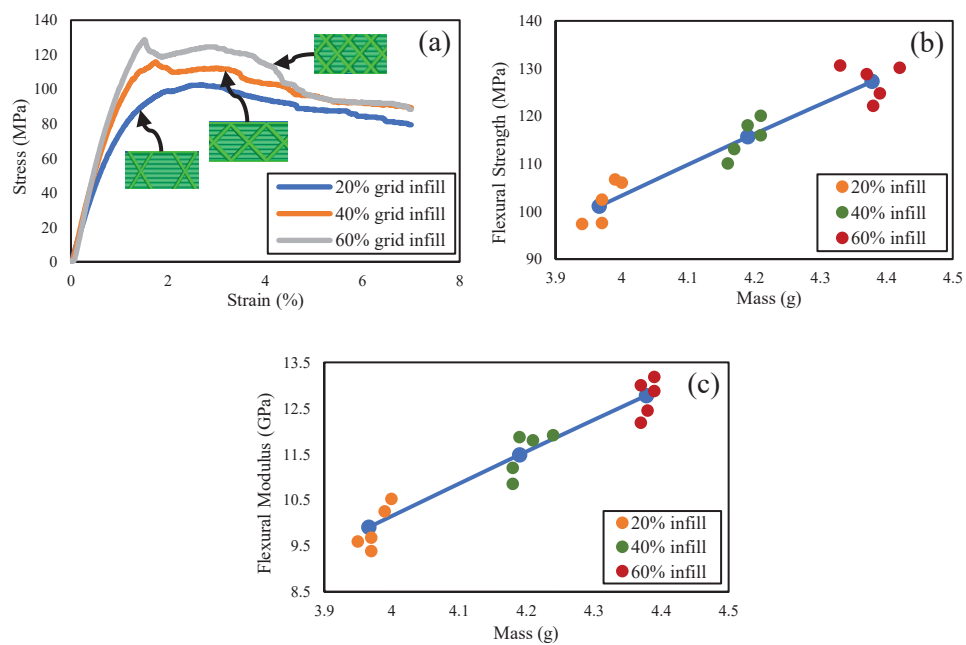


Fig. 3.23 Grid infill pattern data for flexural: a) stress-strain curves; b) strength as a function of mass; c) modulus as a function of mass

Table 3.8 shows the results of the flexural properties obtained from the flexural test. Bar graphs were used to demonstrate the comparison of the flexural properties (the flexural strength and the flexural modulus) in terms of the CCFRPC specimens printed at three different infill density levels as shown in Fig. 3.24.

The bar graph plot (Fig. 3.24 a) illustrates how the flexural strength value rises as the infill density level increases. The specimen with the highest mean flexural strength value of 127.82 MPa was obtained with 60% infill density. The average

flexural strength value for the specimens printed with 40% and 20% infill densities were 115.6 MPa and 101.1 MPa, respectively. In comparison to 40% and 20% infill, the flexural strength of the grid infill pattern with 60% infill increased by 10% and 25%, respectively. The results of the flexural modulus are shown in Fig. 3.24 (b). The specimen printed with 60% infill had the highest mean flexural modulus value of 12.77 GPa, whereas the specimens printed with 40% and 20% infill had average flexural modulus values of 11.49 GPa and 9.91 GPa, respectively. According to the data, the composite printed specimen's flexural modulus value will grow as the infill density level is raised.

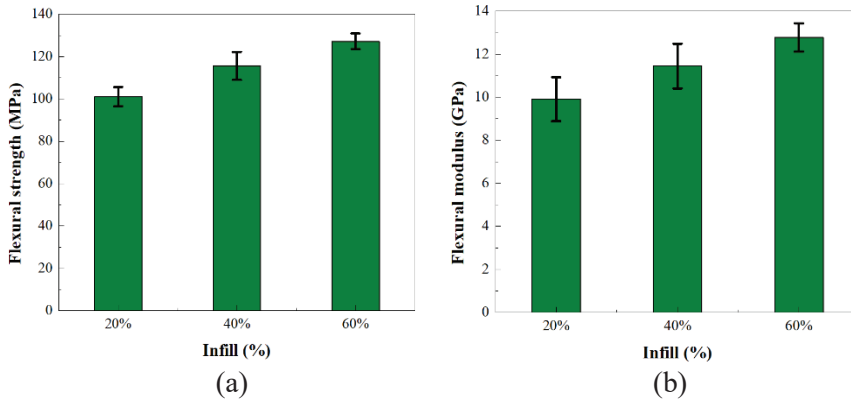


Fig. 3.24 Flexural properties of 3D printed composite with the grid infill pattern: a) flexural strength; b) flexural modulus

Table 3.8 Results of measured flexural properties

Specimens	Flexural Properties			
	Grid infill pattern		Triangular infill pattern	
	Flexural strength (MPa)	Flexural modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
20%	101.1 ± 4.51	9.91 ± 1.02	92.9 ± 5.48	9.24 ± 0.81
40%	115.62 ± 6.55	11.49 ± 1.04	95.67 ± 7.23	10.32 ± 0.55
60%	127.24 ± 3.68	12.77 ± 0.66	117.53 ± 8.87	12.66 ± 0.70

3.8.2. Triangular infill pattern

The tensile test was used to examine the tensile characteristics of the specimens printed at various infill densities. In Fig. 3.25 (a), the typical tensile stress-strain trends of specimens with triangle infill patterns printed at 20%, 40%, and 60% infill densities are shown. The specimen printed with a 60% infill density reaches the highest stress

level, according to the stress-strain curves, whereas the specimens with a 20% infill density showed the lowest stress level. When put through a tensile test, the specimens demonstrated identical DGM and GAT failure mechanisms.

Fig. 3.25 (b & c) displays the average tensile strength and Young's modulus as a function of mass for each individual specimen level. The outcomes exhibited a behavior that was comparable to the grid infill pattern. The maximum level of the tensile strength was observed when the infill density reached 60% and decreased as the infill density decreased. With an increase in the infill density, the strength level is seen to have significantly increased. Meanwhile, the results of Young's modulus as a function of mass revealed the lowest level at 20% infill density and slightly increased when the infill density increased from 40% to 60% infill density, which showed similar level of modulus. In this instance, the printing of individual specimen levels is more uniform. Table 3.7 provides a summary of the findings on the uniaxial tensile properties.

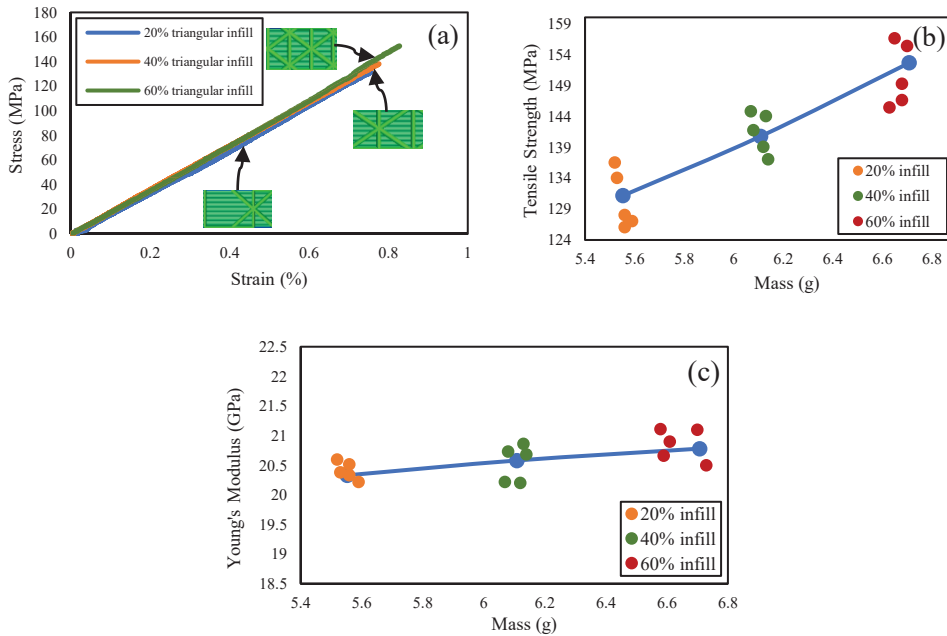


Fig. 3.25 Triangular infill pattern data for tensile: a) stress-strain curves; b) strength as a function of mass; c) Young's modulus as a function of mass

The range of each printed group specimen's scores regarding the tensile properties is shown in Fig. 3.26. The bar plots use the mean values to show the trend of the specimens of each printed group. The composite specimen with a 60% triangular infill had the highest mean tensile strength measuring 152.62 MPa. The average tensile strength values for the specimens printed with the 40% and 20% triangular pattern infill were 140.75 MPa and 131.15 MPa, respectively, which demonstrates how an increase in the infill density increased the strength value. The infill density rises from 20% to 40%, thus increasing the tensile strength by 7.3%. The

strength value increased by 8.4% between the infill densities of 40% and 60% according to changes in the tensile strength value (Fig. 3.26 a). Figure 3.26 (b) depicts the effects of the infill density on Young's modulus. The composite specimen with the highest mean Young's modulus value of 20.78 GPa was found in a sample with the triangular infill pattern printed at 60% infill density. Meanwhile, the average Young's modulus values for the 20% and 40% infill density CCFRPC specimens were 20.33 GPa and 20.58 GPa, respectively. With the increasing infill density, there was a slight increase in the Young's modulus values in each case (Fig. 3.26 b).

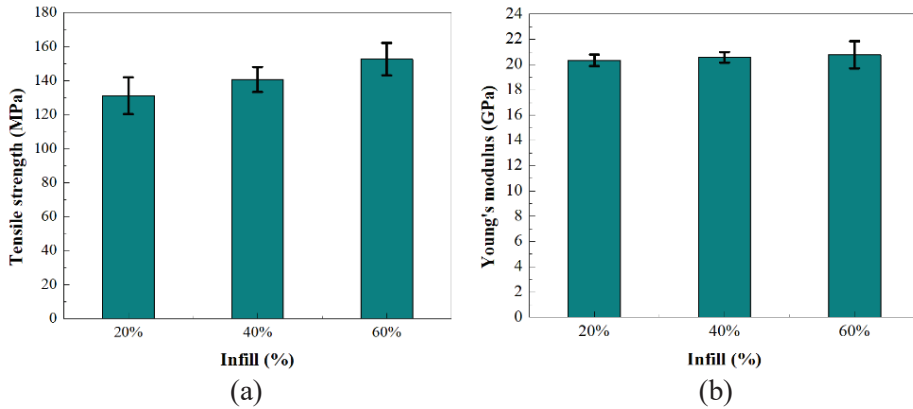


Fig. 3.26 Tensile properties of 3D printed composites with the triangular infill pattern: a) tensile strength; b) Young's modulus

The flexural test was performed to determine the flexural properties of cellular CCFRPC specimens that had been 3D printed with the triangular infill pattern at three different infill densities. Fig. 3.27 (a) illustrates a typical flexural stress-strain curve for the manufactured triangle infill pattern specimens. When compared to the grid infill pattern, the samples displayed a comparable behavior. The specimen printed with a 60% triangle infill density reached the highest level of the flexural stress, according to the stress-strain curve, while the specimen fabricated with a 20% infill density reached the lowest level of the flexural stress. The infill density levels of 20% and 40% cannot be distinguished by any significant changes. Fig. 3.27 (b & c) demonstrates the average flexural strength and modulus as a function of mass for each specimen level printed at three different infill densities, and for each individual specimen infill level, respectively. These results indicate that, as the mass increases, the values of stress and modulus increase as well. When the infill density increases from 20% to 40%, there are no discernible differences between the two situations. However, the stress and modulus values substantially rise when the infill density is raised from 40% to 60%. This significant increase in the strength and modulus may be caused by a sudden increase in the mass of the specimen. In this instance, individual specimen levels produced more uniform 3D printing results than the grid infill scheme.

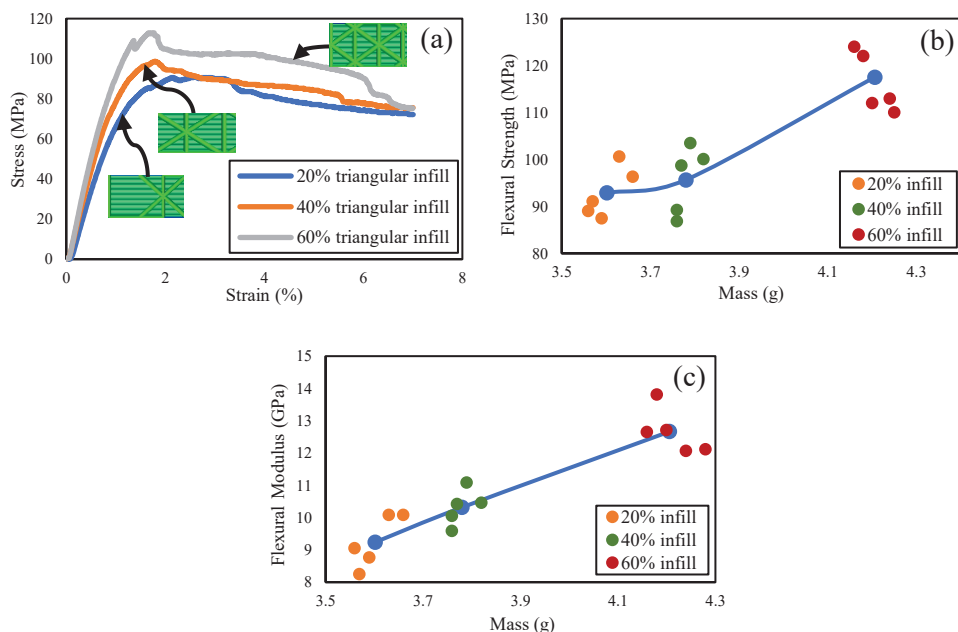


Fig. 3.27 Triangular infill pattern data for flexural: a) stress-strain curves; b) strength as a function of mass; c) modulus as a function of mass

The results of the flexural test measurements of the flexural properties are displayed in Table 3.8. Each CCFRPC specimen with the triangular infill pattern printed at three different infill density levels is compared in terms of its flexural properties (the flexural stress and flexural modulus) in Fig. 3.28. The specimen printed with a 20% infill density displayed the minimum mean flexural strength value of 92.9 MPa according to the bar graph plot (Fig. 3.28 a). When continuing to increase the infill density, the flexural stress also increases. A composite specimen fabricated with a 60% infill density displayed the highest stress of 117.53 MPa, while those printed with a 40% infill density displayed an average flexural stress value of 95.67 MPa. When the infill density rises from 20% to 40%, the strength increases slightly (by 3%), but when it rises from 40% to 60%, the strength increases significantly (by 22.8%). Therefore, the findings showed that the infill density level increases with the flexural strength.

The specimen printed with 60% infill reached the highest mean flexural modulus value of 12.66 GPa (Fig. 3.28 b), while the specimens printed with 20% and 40% infills had average flexural modulus values of 9.24 GPa and 10.32 GPa, respectively. The flexural modulus result also showed that raising the infill density level would also raise the CCFRPC specimen's flexural modulus value.

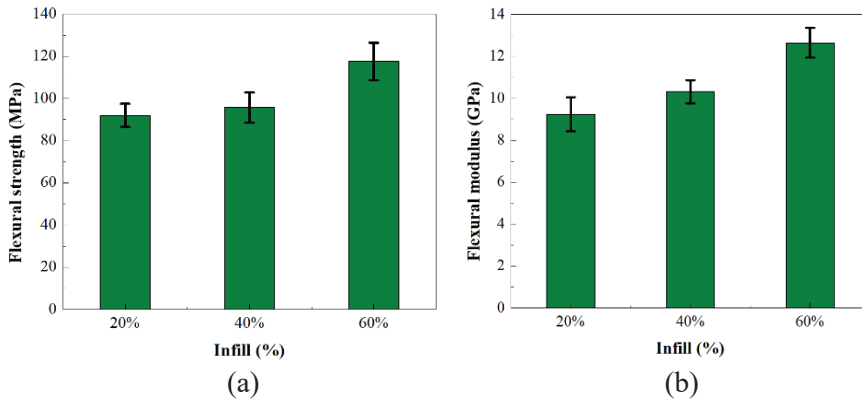


Fig. 3.28 Flexural properties of 3D printed composite with the triangular infill pattern: a) flexural strength; b) flexural modulus

3.8.3. Comparison of fabricated cellular CCFRPCs

The grid and triangular infill patterns at three infill densities were used to create the cellular CCFRPC specimens by the FDM technology, which resulted in dissimilar structure, mass, and strength levels. In all situations, the grid infill pattern demonstrated higher mechanical properties (the tensile and flexural tests) than the triangular infill pattern due to the more compact and denser structure. The results of the tensile and flexural tests showed an increase in the strength levels as the infill density increased, which is clearly a condition of the mechanical response in the case of the grid and triangle infill patterns. In terms of the tensile and flexural performance, the grid infill pattern yielded better results. This may be the result of the infill pattern's internal design structure, the anisotropic behavior of the structure and the bonding of the layers among each other that exhibited such a tensile loading response, as the triangular infill pattern is isotropic in the plane. This confirms that, in contrast to the grid infill design, the triangular infill pattern had no discernible impact on the tensile response. Similar levels of the tensile strength were displayed by the specimen with a 60% triangle infill design and the specimen with a 20% grid infill pattern. A specimen with a 60% triangular infill pattern demonstrated a nearly equivalent strength to a specimen with a 40% grid infill pattern under equal flexural strength. In terms of the results of mechanical tests, the grid infill pattern is more significant. When comparing the same infill density (60%) of the specimen with the grid infill pattern to the triangle infill pattern, the tensile strength and the flexural stress increase by 6.74% and 8.26%, respectively. In terms of the specific tensile strength and modulus, the square infill structure (highly anisotropic) likewise delivered the best mechanical performance [77]. The reasons for developing and fabricating such cellular CCFRPC structures are the reduction of the mass, efficient utilization of materials, energy consumption and waste generation that helps to create a lightweight composite structure with approximately the same mechanical properties compared to the fully dense structure. The highest tensile strength of 165 MPa for the previously created CCF reinforced PLA composite with 100% infill [72] is nearly identical to that for the grid infill pattern with 60% infill density (163 MPa). When compared to the previously

produced fully dense CCF reinforced PLA thermoplastic composite components that attained strength levels up to 61.4 MPa [45] and 91 MPa [65], 20% infill density with both designs even demonstrated a superior tensile strength. The maximum flexural strength of a printed composite part (with 60% grid infill) was 127.24 MPa, compared to 156 MPa for fiber-reinforced PLA composites discussed in the literature [65, 84, 99]. These findings imply that 3D printed cellular CCFRPCs showed an even higher mechanical performance, especially in the areas of the tensile strength and the elastic modulus without a significant difference in terms of the flexural loading. The importance of perimeter shells and their impact on mechanical properties cannot be overstated. The perimeter shells represent the number of layers that have been applied to the outer surface of the specimen prior to filling the inner part. The higher number of perimeter shells improved the strength and stiffness of the printed part under tensile and flexural loading [77], but also increased the complexity of the printing process.

Hence, as a result, the findings of this study and their comparison to the literature demonstrated that there is great potential for replacing fully dense and solid structures with cellular ones as these would consume less material, reduce waste, and increase the mass while maintaining nearly equivalent mechanical performance and would thus be suitable for structural applications.

3.9. Influence of the control cooling effect on the mechanical properties of composite specimens⁹

To study the mechanical properties of CCFRPC parts manufactured by using the FDM technology under a controlled air flow cooling at 40 l/min, the optimum printing parameters which represented the higher mechanical strengths achieved from the above study were selected. The composite specimens were additively manufactured by using the printing process parameters of E.W. -1.2 mm E.M. -0.5, E.W. -1.2 mm E.M. -0.7, and E.W. -1.3 mm E.M. -0.5 in order to evaluate the tensile and flexural properties.

Table 3.9 Mechanical properties obtained with CCE

Specimen's Extrusion Width (E.W.) mm	Specimen's Extrusion Multiplier (E.M.)	Tensile Properties		Flexural Properties	
		Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
1.2	0.5	271.5 ± 10.49	30.77 ± 1.73	230.75 ± 11.65	13.42 ± 0.52
1.2	0.7	294.46 ± 9.74	30.19 ± 1.56	247.24 ± 9.48	12.44 ± 1.08
1.3	0.5	239.34 ± 10.77	31.50 ± 1.13	192.63 ± 6.85	15.68 ± 0.88

⁹ Reproduced from Ref. [189] with permission. Research [189] is one of the publications by the author of this dissertation

3.9.1. Tensile properties

From the curves obtained through the tensile test, the composite specimen printed with the parameters of E.W. -1.2 mm and E.M. -0.7 reached the highest stress level, followed by E.W. -1.2 mm E.M. -0.5, and E.W. -1.3 mm E.M. -0.5 (Fig. 3.29 a). When a specimen was created without CCE, the same maximum tensile stress was likewise noted. The results of the tests of tensile properties for the tensile strength and Young's modulus are shown in Fig. 3.29 (b & c), respectively. The printing parameters of E.W. -1.2 mm E.M. -0.7 resulted in the greatest level of the tensile strength of 294.46 MPa. When comparing the final outcome to the composite specimen that was manufactured without the cooling effect, the strength level increased by 17%. The outcome is impacted due to improvement in the quality of 3D printed CCFRPC parts, where the lines and layers are dispersed more uniformly, and cooling allows for better interfacial bonding and adhesion. Meanwhile, when the composite specimen was created by using CCE with the printing parameters of E.W.-1.2 mm E.M.-0.5, a 10% increase in strength was observed. The specimen with E.W. 1.3 mm and E.M. 0.5 had the highest mean Young's modulus value of 31.50 GPa, which could also be validated by the outcome when the CCFRPC specimen was constructed without CCE while still using the same printing parameters.

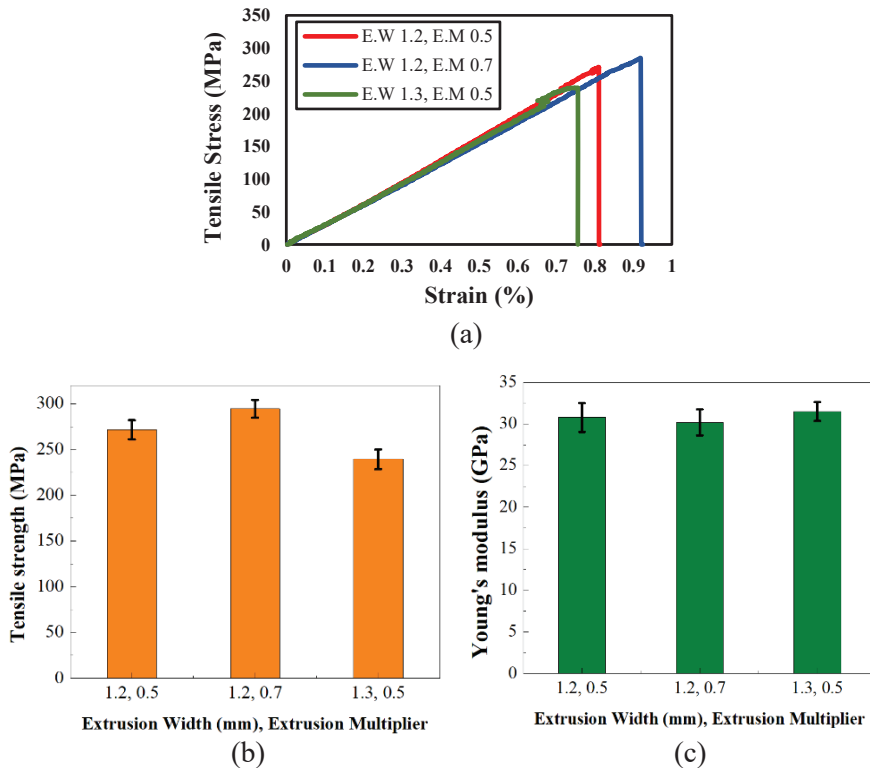


Fig. 3.29 Results obtained by using control air flow cooling for: a) tensile stress-strain curves; b) tensile strength; c) Young's modulus

3.9.2 Flexural properties

The flexural stress-strain curves obtained from the three-point bending test are shown in Fig. 3.30 (a). The results showed that the composite specimen manufactured with the printing parameters of E.W. -1.2 mm and E.M. -0.7 showed the highest achieved level of flexural stress. The composite specimen of E.W. -1.2 mm and E.M. -0.5 showed a sudden fracture, and such an intensely decreasing behavior in the curve may have occurred due to the highest content of the reinforcement in the composite. The results for the flexural strength and flexural modulus are shown in Fig. 3.30 (b & c), respectively. The findings showed that the CCFRPC specimen printed by using the E.W. -1.2 mm and E.M. -0.7 parameters, reached the highest flexural strength of 247.24 MPa. The flexural strength increased by 25% and 19.4%, respectively, when CCE was used and the printing parameters were E.W. -1.2 mm E.M. -0.7 and E.W. -1.2 E.M. -0.5. The specimen with the parameters of E.W. -1.3 mm E.M. -0.5 was found to have the greatest mean flexural modulus measuring 15.68 GPa. Due to improvements in quality, bonding between all lines and layers of the extruded composite, the uniform layer distribution, and the minimum void volume, the results achieved with the use of CCE were improved if compared to the composite specimens printed without CCE. The composite specimen printed with the E.W. -1.3 mm and E.M. -0.5 printing parameters displayed the peak modulus values in both situations (tensile and flexural). Table 3.9 provides a summary of the findings on the tensile and flexural properties.

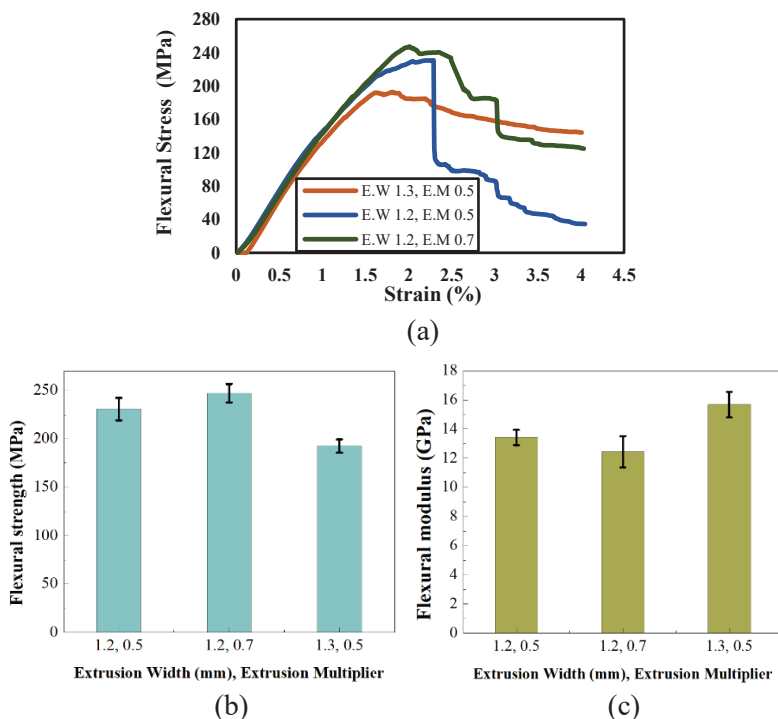


Fig. 3.30 Results obtained by using control air flow cooling for: a) flexural stress-strain curves; b) flexural strength; c) flexural modulus

3.10. Influence of the layer height and layer orientation on mechanical properties

To investigate the influence of the layer height and orientation of the composite manufactured with the FDM 3D printing technique on the mechanical properties, four different groups were prepared to analyze the mechanical performance. Two different layer heights of 0.4 mm and 0.5 mm, and the layer orientation of 0° and $0^\circ - 90^\circ$ were selected to draw a comparison among these groups in terms of the mechanical performance.

3.10.1 Tensile response of composite specimens

A tensile test was performed to evaluate the tensile properties obtained in the course of testing. The same testing conditions were used to evaluate each composite in the group. Fig. 3.31 (a) describes a typical stress-strain curve derived from a tensile test. The resulting curve demonstrated that Group 2 obtains the maximum stress level with a layer orientation of 0° and a layer height of 0.4 mm, followed by Groups 1, 4, and 3. The tensile stress level falls with the layer height in both layup directions, which is a considerable difference from the other layup directions. Due to delamination during testing, Groups 1, 3, and 4 showed considerable variations and non-uniformities in the curves. Fig. 3.31 (b & c) shows the tensile strength and Young's modulus results, respectively. According to the results, the composite specimen with a layer orientation of 0° and a layer height of 0.4 mm withstood a maximum tensile strength of 332.48 MPa. The tensile strength was the lowest among the composite samples with a layer orientation of $0^\circ - 90^\circ$ and a layer height of 0.5 mm at 202.20 MPa. The tensile strength and Young's modulus rise with a decreasing layer height when both scenarios of the layer orientation are taken into account. The Young's modulus of Group 2 achieves a maximum value of 40.15 GPa, which is comparable to the trend of the tensile strength, whereas the lowest Young's modulus of 22.11 GPa was found in Group 3. Table 3.10 presents the measured tensile properties.

It is important to look into the printing process parameters for 3D printed composite parts and to consider how porosity impacts the quality and mechanical properties, even though it is obvious that the tensile strength and Young's modulus drop with an increasing porosity. M. Rimašauskas *et al.* have previously demonstrated how the lowering of the layer height and the line width can enhance the structure's mechanical characteristics [121].

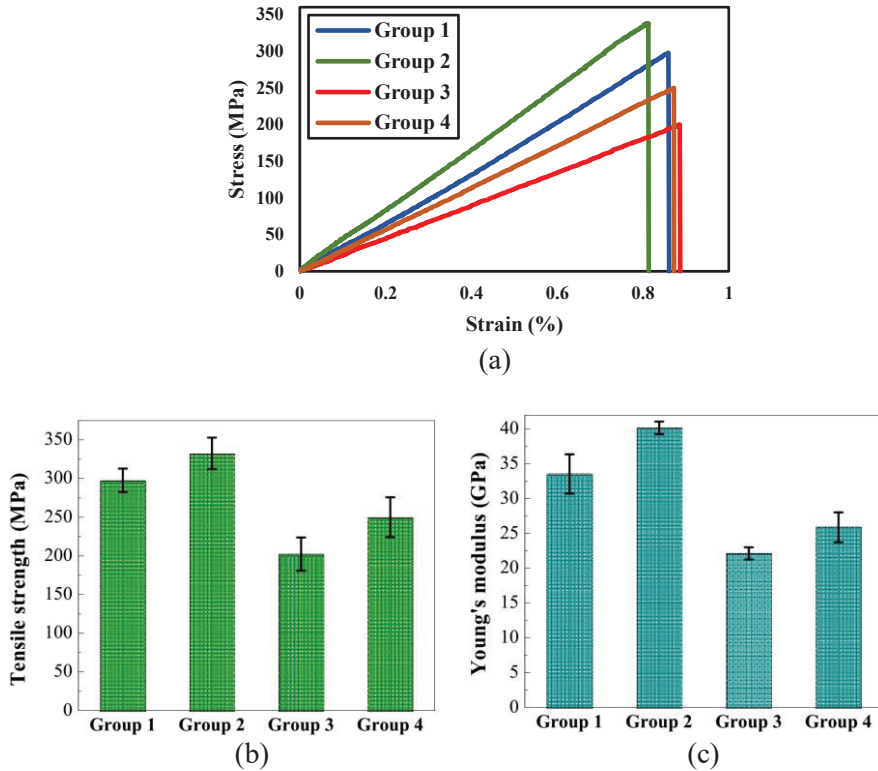


Fig. 3.31 Results obtained from the tensile test for each group: a) stress-strain curves; b) tensile strength; c) Young's modulus

Table 3.10 Mechanical properties measured from tensile and flexural tests

Specimen groups	Tensile Properties		Flexural Properties	
	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
Group 1	297.55 ± 15.15	33.54 ± 2.83	203.85 ± 21.17	22.80 ± 0.93
Group 2	332.48 ± 20.39	40.15 ± 0.91	229.89 ± 18.63	26.91 ± 2.22
Group 3	202.20 ± 21.53	22.11 ± 0.89	99.18 ± 21.31	20.35 ± 2.14
Group 4	249.88 ± 25.78	25.86 ± 2.16	110.41 ± 15.57	20.77 ± 0.60

3.10.2 Flexural response of composite specimens

Flexural properties (the flexural strength and flexural modulus) were determined with the three-point bending test. The flexural stress-strain curves for each group are shown in Fig. 3.32 (a). The composite specimen of Group 2 with a layer height of 0.4 mm and an orientation of 0° obtained the highest level of the flexural stress, followed by a minor reduction in the Group 1 curve. When considering the $0^\circ - 90^\circ$ layer

orientation, both Groups 3 and 4 show a striking decrease in the stress level. The decrease in this curve is halved compared to the layer orientation of 0° . One phenomenon of this behavior is the delamination which occurred in 3D printed layers of composite materials during the test. Composite layers of $0^\circ - 90^\circ$ orientations were not sufficiently bonded, and delamination was caused when forcibly bent, which caused the layers to separate from each other and left clearly visible gaps during the experiment. A similar behavior was previously observed due to the weak and insufficient interfacial bonding between the layers.

Fig. 3.32 (b & c) shows the flexural strength and flexural modulus results obtained by the three-point bending test. As a result, the average flexural strength of the Group 2 composite specimen with a layer orientation of 0° and a layer height of 0.4 mm was the highest at 229.89 MPa. Group 3 with a layer orientation of $0^\circ - 90^\circ$ and a layer height of 0.5 mm had the lowest flexural strength of 99.18 MPa, whereas the second highest strength level was in Group 1 at 203.85 MPa.

The highest flexural modulus of 26.91 GPa was observed in Group 2, while the second highest modulus achieved in Group 1 averaged 22.80 GPa. Groups 3 and 4 showed relatively similar modulus values. From the available results, it was found that the 0° layer orientation had a higher flexural strength and modulus, while lower layer heights had a better flexural strength capability.

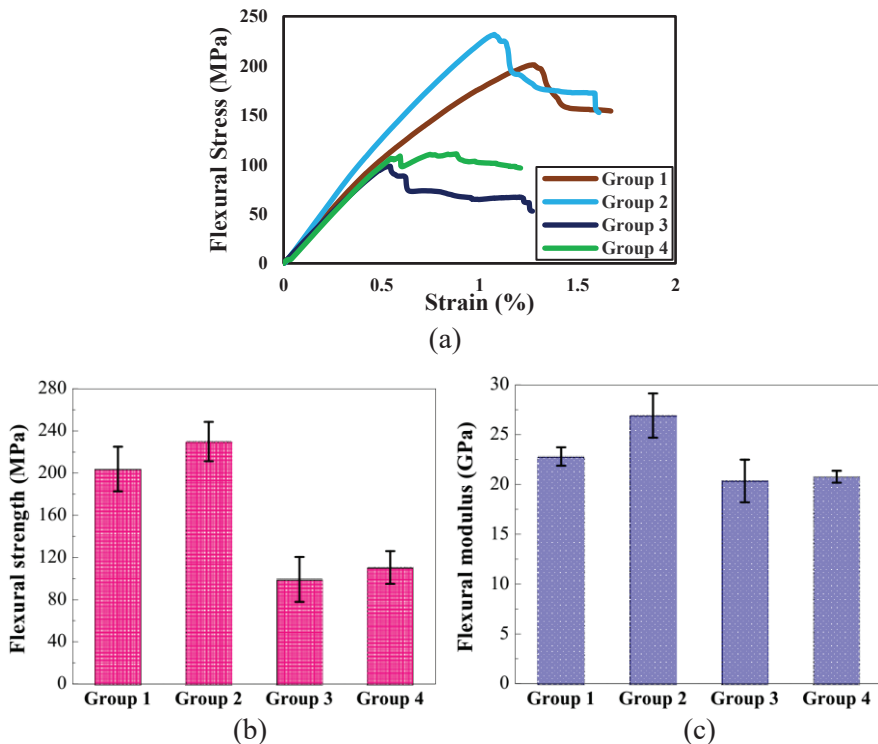


Fig. 3.32 Results obtained from the flexural test for each group: a) flexural stress-strain curves; b) flexural strength; c) flexural modulus

In terms of both mechanical properties (tensile and flexural), the unidirectional 0° layer orientation performed better, particularly in the unidirectional specimens which can support the majority of the load in the applied direction, the stress in the direction of the applied force is always high, which gives the printed lines the optimal strength by distributing the load between them and is similar to bending, which resists breaking but distributes the load throughout the layers. The load is transferred from the top layer, which is initially exposed to the load, to the lower layer, until reaches the last layer. However, the unidirectional orientation 0° layer exhibits a stronger resistance to the applied load.

Still, the 3D printed structure has a hollow content with some microporosity. Due to the non-uniformity of the FDM printing process, porosity can significantly affect the quality and mechanical properties of composites. As a result of the evaluation of tensile and flexural properties under this assumption, it can be seen that the mechanical properties are highly dependent on the layer orientation and height. The 0° – 90° layer orientation showed a higher performance, while a reduction of the layer height of the printed layer showed an improved performance for both constraints.

3.11. Carbon fiber reinforcement content in 3D fabricated composite

In designing and development of a composite, the reinforcement content is an important aspect to be considered. The content defines and determines the properties of that manufactured composite in terms of the quality and mechanical performance. In the present research of the fabricated composite when using the FDM 3D printing technique, it is necessary to calculate the reinforcement fiber content in the composite.

For a specimen with a solid fully dense structure of 0° unidirectional 3D printing, it is possible to estimate the carbon fiber content by using the tool length path when knowing the reinforcement density and the number of the layers and lines. When considering the cellular composite structure specimens, it is not possible to calculate the values by using the same method as the structure is cellular with different infill and density levels. Therefore, an alternative dissolution method was chosen in which the matrix was fully dissolved, and the remaining fiber was weighed to calculate the carbon fiber content.

3.11.1. Carbon fiber content measured in the composite fabricated by using a range of printing process parameters¹⁰

The content of the reinforcement in composite has significant importance in the material design and the calculation of the mechanical properties. Each set of groups behaved differently in response to mechanical performance, hence, it is an important aspect to estimate the content of CCF in the fabricated composite structure. The CCF content was estimated by using the length of the tool path, the number of lines in length and the layers in the width of the specimen [87, 99]. From the scheming, the prepared PLA-CCF and PLA-SCF-CCF composite part structures include

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approximately 18.2% and 21.8% carbon fibers, respectively. It is important to note that the calculations did not take the carbon fiber content from the short fiber reinforced filament (XT-CF20) into account.

The number of lines and layers varies with E.W., and each group will have different total numbers of layers and lines. Decreasing E.W. will increase the printed lines of the composite specimen, and therefore the CCF content will increase as well. On the other hand, increasing E.M. decreases the carbon fiber content because the amount of the thermoplastic matrix material will increase. The impact of the CCF content on E.W. and E.M. is depicted in Fig. 3.33. When examining the specimen prepared with an E.W. of 1.2 mm, it can be seen that the carbon fiber content in the composite decreases as E.M. increases. The specimen group with the highest reinforcement content, 47.14wt%, had an E.W. of 1.2 mm and an E.M. of 0.5, while the specimen with the lowest carbon fiber content, 24.68wt%, had the printing parameters of E.W. -1.5 mm and E.M. -0.8.

A high reinforcement content also produces high tensile and flexural strength up to a certain point, which is comparable to the results of mechanical strengths. The strength of the composite improved with an increase in the CCF content up to a predetermined level [99, 128].

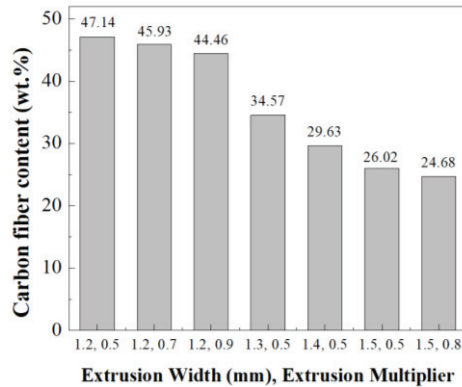


Fig. 3.33 Effect of the carbon fiber content on E.W. and E.M.

3.11.2. Carbon fiber content in cellular fabricated composite¹¹

The approach of dissolving was used to determine the reinforcement content in a composite structure that was created by using two different infill patterns (grid and triangular) printed at three different infill densities (20%, 40%, and 60%). In comparison to the grid infill pattern, the results of the triangular infill pattern showed that the majority of the reinforcing material was consumed.

According to the experimental findings shown in Fig. 3.34, as the infill density level increases, the reinforcing content for both infill schemes also somewhat rises. With a 60% infill density level, the triangular infill pattern revealed the maximum

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fiber content of 31.11wt%. When the infill density level rises from 20% to 40% for the triangular infill design, the reinforcement content increases by 3%, while it increases by 1% when the infill density level climbs from 40% to 60%.

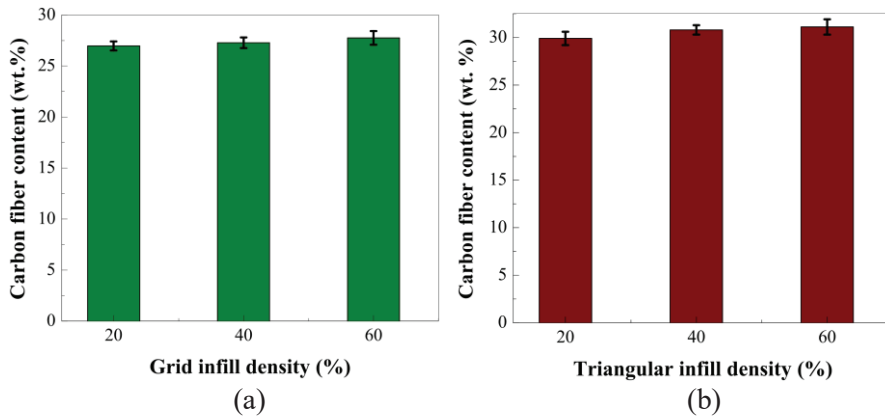


Fig. 3.34 Carbon fiber content in the composite parts for: a) grid infill pattern; b) triangular infill pattern

Likewise, the grid infill pattern with a 60% infill level revealed the highest reinforcement content which was recorded as 27.75wt%. With an increase in the infill density from 20% to 40%, the carbon fiber content rose by 1.1%, and, with an increase in the infill density from 40% to 60%, the carbon fiber content increased by 1.7%. When comparing the two types of infill patterns, it was found that the triangular infill pattern had a greater carbon fiber content overall, even at its lowest density level, as opposed to the grid infill pattern's highest density level. Such differences in the reinforcement content are caused by the difference in the structure that created the paths inside the composite part. Additionally, these qualities are affected by the various infill patterns. The layer distribution and orientation, the printing process parameters, the infill patterns and parameter shells have an effect on the mechanical properties and the carbon fiber content of the composite part.

3.11.3. Carbon fiber content with a varying layer height and layer orientation

The fiber reinforcement content in the composite with a varying layer height and layer orientation was estimated by using the dissolution method. After fully dissolving the matrix, the remaining fiber was weighed and calculated. From the analysis of the results (Fig. 3.35), it could be seen that a composite of Group 2 showed the average highest content of the carbon reinforcement of 36.48wt%, while Group 1, Group 3 and Group 4 showed the average CCF content of 29.8wt%, 29.26wt%, and 32.61wt%, respectively. The obtained results suggested that decreasing the layer height significantly increases the reinforcement content in the 3D printed composite specimens. Moreover, the 0° unidirectional composite specimen consumes slightly more reinforcement content compared to the 0° – 90° layer orientation composite specimen. In contrast to the obtained mechanical properties, Group 2 with the highest CCF content also showed superior tensile and flexural properties.

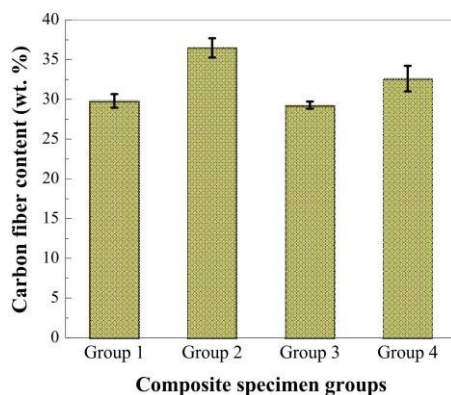


Fig. 3.35 Carbon fiber content in composite groups

3.12. Void volume detection in 3D printed composites

The air void volume in the composites for each group manufactured with two types of the layer height and two-layer orientations was analyzed. The void volume in the fabricated 3D composite was studied by using two different methods (the dissolution method and XCT scan) to conduct a clear and validated comparison within each group.

3.12.1. X-ray computed tomography scan

The mechanical properties of 3D printed CCFRPC significantly depend on the void volume in the structure. Decreasing the void volume in the part will effectively increase its mechanical performance, thus making it more compact and void free [121]. As the composite parts manufactured by using the FDM technology contain air voids, it was decided to evaluate the void performance by using an XCT scan. This advanced method provides more precise results. Three samples from each group were tested, and the average was taken in order to avoid repeatability. Fig. 3.36 shows the results of the content of air voids in each composite group; the measurement was conducted by using the XCT scan. The presented results demonstrate that Group 2 of 3D printed composite showed the lowest average void volume of 5.57%, while the highest average void volume of 17.41% was observed in Group 3 composite specimens. Group 1 and Group 4 attained the average void volume of 7.13% and 10.82%, respectively. The presented results revealed that decreasing the layer height in both layer orientations resulted in a decrease in the void volume. The lower layer height compresses the specimen by providing fewer gaps among the layers, and bonding proceeds more efficiently with minimum disparities, which results in a lower void volume. The composite specimens with a layer orientation of $0^\circ - 90^\circ$ showed more variations in the CT scan results. This may be caused by the overlapping of different orientations of the layers which creates some micro cavities during the printing of the composites. The air void volume results could also be validated with the determined mechanical properties showing that the lowest air void volume in Group 2 delivered the maximum tensile and flexural properties, and the trend continues further as the air void increases while the mechanical properties decrease.

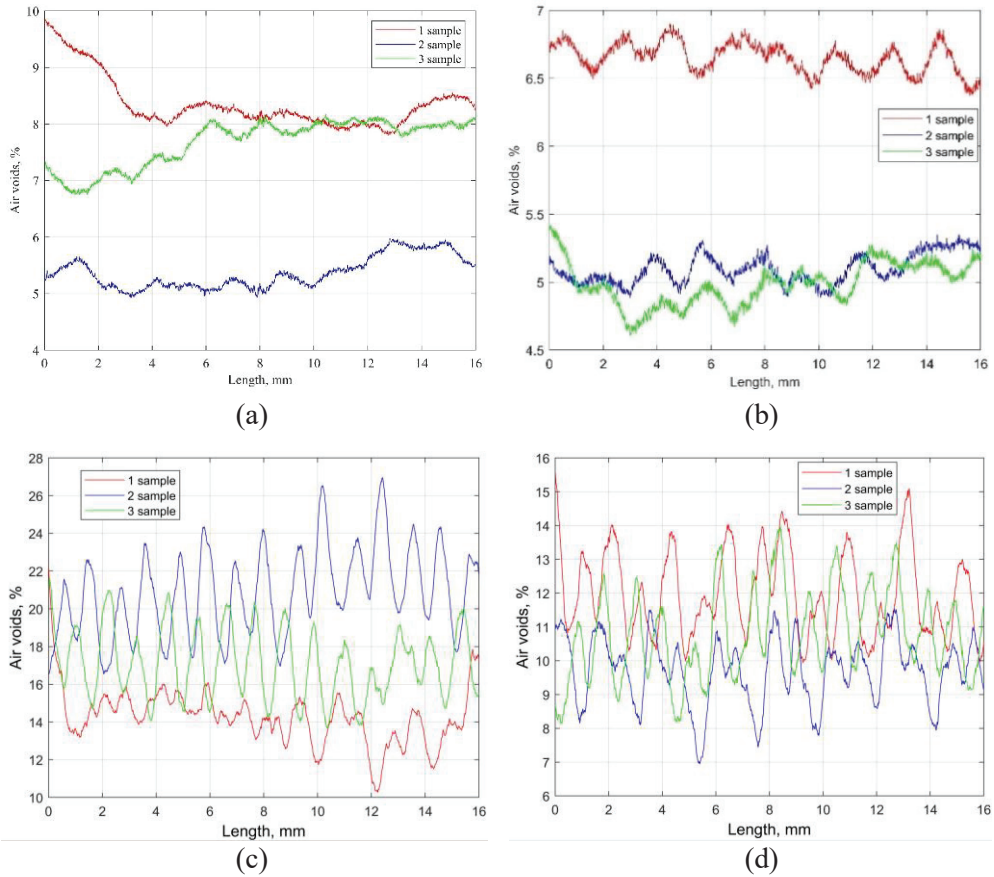


Fig. 3.36 Air voids in composite specimens determined by XCT scan: a) Group 1; b) Group 2; c) Group 3; d) Group 4

3.12.2. Dissolution method

After dissolving the matrix from the composite, the remaining fiber was weighed and calculated by knowing the density of the reinforcement and the composite, as well as the reinforcement and matrix content in the composite. The calculated results showed a similar behavior and trend compared to the XCT scan results for each composite group. The estimated outcomes through the dissolution method demonstrated that CCFRPC Group 3 showed the highest average air void of 19.74%, while the lowest air void of 13.77% was observed in a composite of Group 2. The average air void volume of 13.98% and 15.41% was calculated in Group 1 and Group 4, respectively. The comparison of air voids calculated in the composite specimens when using the dissolution method and the XCT scan is presented in Fig. 3.37.

The major differences in the air void calculation when using the dissolution method and the XCT scan are the length of the composite specimen. The XCT scan was performed with a 16 mm length composite block, and the scanning was performed in the middle of the specimen at a specific area; the air void was calculated at that

region, while, in the case of the dissolution method, the composite specimen block was fully dissolved to eliminate the thermoplastic matrix material so that to estimate the void volume which consists of the total average length of 33 mm. Yet, the air void trend of each composite group and specimen was the same when compared to each other. Such a difference was also observed and registered previously [121]. Both methods are denoted by specific advantages and disadvantages. The XCT scan is a more advanced and expensive method, but it is restricted to a limited length of the specimen scanned at the specific area, and it is also non-destructive, which means that there could be further use for the experimentation process. Meanwhile, the dissolution method is also time-consuming, and the sample is fully dissolved; thus, it cannot be further used for experimentations.

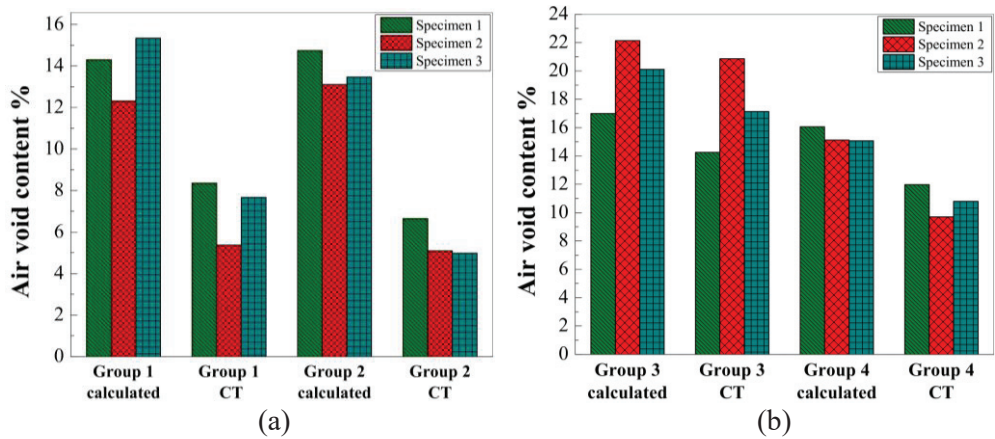


Fig. 3.37 Comparison of air voids in composite specimens when using the dissolution method and XCT scan: a) Group 1 and Group 2; b) Group 3 and Group 4

3.13 Fracture interface analysis of composite structures¹²

3.13.1 Fracture interface observation after mechanical testing

According to the results of the experimental tensile and flexural test, PLA-CCF and PLA-SCF-CCF demonstrated a greater strength than PLA and PLA-SCF. Therefore, it was decided to investigate the fracture interface of 3D printed samples in order to analyze the deformation and fracture processes that occurred during mechanical testing. The fractured interface of each group's CCPRPC specimens was examined under an optical microscope. The specimen from each group that most accurately reflected the failure mode was chosen to explore such outcomes. Optical micrographs were used to explore the specimen's interfacial adhesion between CCF and the PLA thermoplastic matrix.

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Fig. 3.38 presents optical micrographs of specimens from each group following the tensile test. It can be seen that the pure PLA specimen reveals an interface rupture, while exhibiting no interlayer adhesion, and each layer was separated from the other layers. A similar outcome can be seen in the case of PLA-SCF which exhibits a rough surface due to the presence of chopped fibers. After the test, the ruptured area in each 3D printed layer is clearly visible. Although the stiffness of a part increases with the use of short fibers, but the strength is still limited since fiber pullout may occur before fiber breakage [74].

In the PLA-CCF composite specimen, it is possible to see CCF separated from the thermoplastic matrix; still, at various portions of the composite, the fibers and the matrix together are still retained together. After the test, the bonding between CCF and PLA-SCF is visible; carbon fiber separated and caused gaps due to the detachment from the matrix, but carbon fiber is still held within it, which indicates poor adhesion between the matrix and reinforcement. Figure 3.38 (b & d) illustrates that CCF composite parts can be used to support a load during tension, as opposed to PLA and PLA-SCF. This is because the ruptured fibers in the fracture interface demonstrated that the load was successfully transferred from the matrix to the fiber reinforcement for the sake of obtaining superior properties. This can also be proven by better results of the tensile strength.

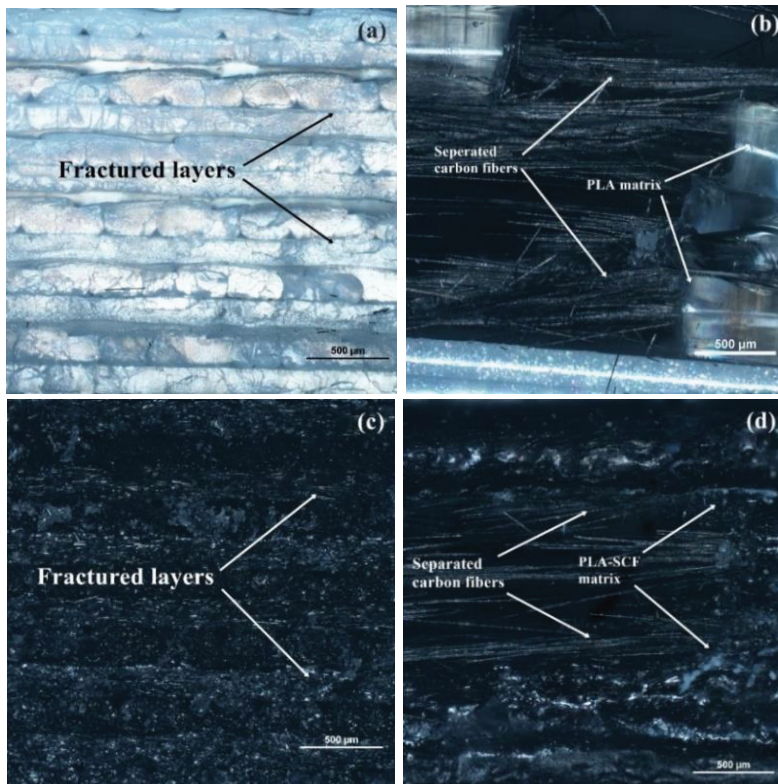


Fig. 3.38 Fracture interface micrographs of the specimens after performing the tensile test of: a) PLA; b) PLA-CCF; c) PLA-SCF; d) PLA-SCF-CCF

Fig. 3.39 shows the optical micrographs of the specimens after flexural testing. Pure PLA showed no such adhesion between the layers, and a visible broken zone could be seen (Fig. 3.39 a). Although there is a rough surface visible between the 3D printed layers, PLA-SCF demonstrated an irregular fractured path and demonstrated better adhesion than pure PLA due to the presence of chopped carbon fibers (Fig. 3.39 c). Fig. 3.39 b, which shows separated CCF at some instant after the test but at various instants it still holds the fibers together within the matrix, demonstrates that the structures of the CCFRPC part can be used to support the load during bending. The ruptured CCF in the fracture interface indicates that the load was effectively transferred from the PLA thermoplastic matrix to carbon fiber. This can also be validated from the highest flexural stress values. Delaminated gaps were created during the test as seen in the PLA-SCF-CCF specimen (Fig. 3.39 d).

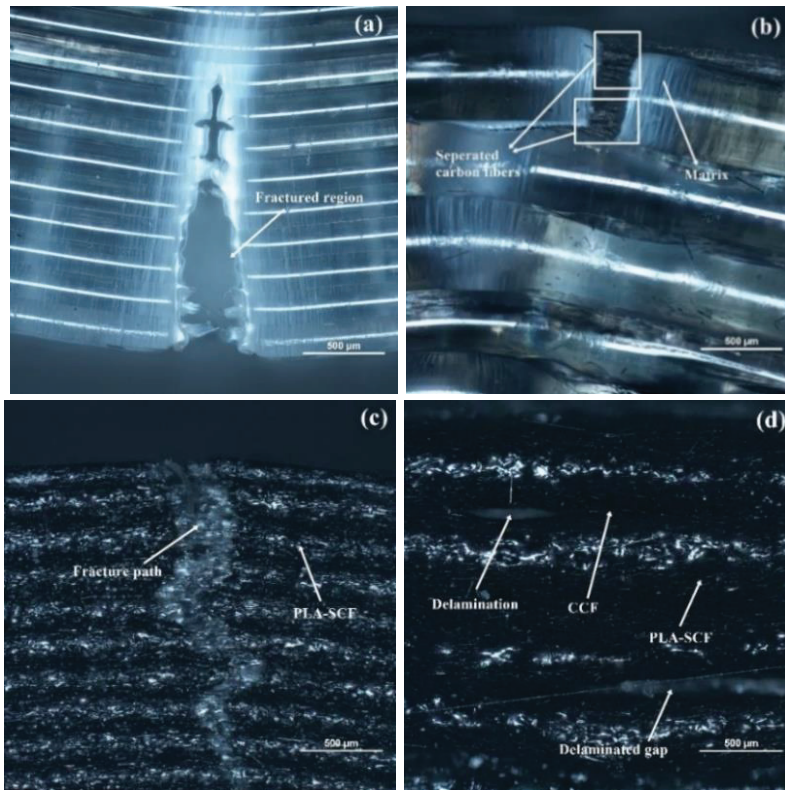


Fig. 3.39 Fracture interface micrographs of the specimens after performing flexural test of: a) PLA; b) PLA-CCF; c) PLA-SCF; d) PLA-SCF-CCF

3.13.2 Fracture interface study of the 3D printed cellular CCFRPC

3.13.2.1 Fracture interface study by using optical microscopy¹³

According to the experimental results of the tensile and flexural tests performed on composite specimens printed with the grid and triangular infill patterns, the fractured mode research revealed a nearly identical behavior for each group. As a result, it was decided to investigate the fracture interface study of the 3D-printed cellular composite with such a structure by taking into account one specimen from both infill patterns which would best reflect the failure mode. It was chosen to observe the fracture performance result as well as the outcome in terms of how the deformation occurred during the test. The fractured interface of CCFRPC specimens was viewed under an optical microscope to investigate the existence of such a condition. The interfacial adhesion of the reinforcement and matrix in the composite construction was observed by using micrographs taken under an optical microscope.

Fig. 3.40 (a & b) displays optical micrographs of cellular composite specimens with grid and triangle infill patterns following tensile testing. When carbon fibers separated from the PLA matrix and left empty spaces during the test, the fragmented region clearly demonstrated CCF separated from the thermoplastic matrix. With certain empty spaces signifying the infills of the 3D-produced parts, the gaps or spaces reveal the interior structure of the cellular composite element. When under tension, the top and bottom layers of the specimen geometry which would cover the infill structure were separated. The infill density controls the spaces produced inside the specimen. The gaps that developed after the test are decreased by raising the infill density level. After the test, bonding between CCF and the PLA matrix can also be seen, which proves that even though carbon fiber and the matrix are separated by gaps, the matrix holds the fiber together within it at different spots nevertheless, which confirming their adherence. Due to the fracture interface's ruptured fibers, which proved that the load was effectively transferred from the matrix to the fiber reinforcement, the results indicated that composite components may be employed to support a load under tension.

The optical micrographs of specimens with the grid and triangular infill patterns after a flexural test are shown in Fig. 3.40 (c & d). There is a ruptured zone where the maximum bending force was exerted, and the layers were fractured. The split carbon fibers were obviously pulled out of the matrix material following the test; however, the fibers are still kept together at various spots. The fracture interface indicates that the load was efficiently transferred from the thermoplastic PLA matrix to the carbon fiber reinforcement, thus proving that the structure of the composite part may be used to support the load during bending. Broken fibers were the predominant failure mode of CCFRPC in both cases. The most serious drawback of 3D printed CCFRPC is a similar fiber rip-out from 3D-printed CCF composite parts [65, 99, 120].

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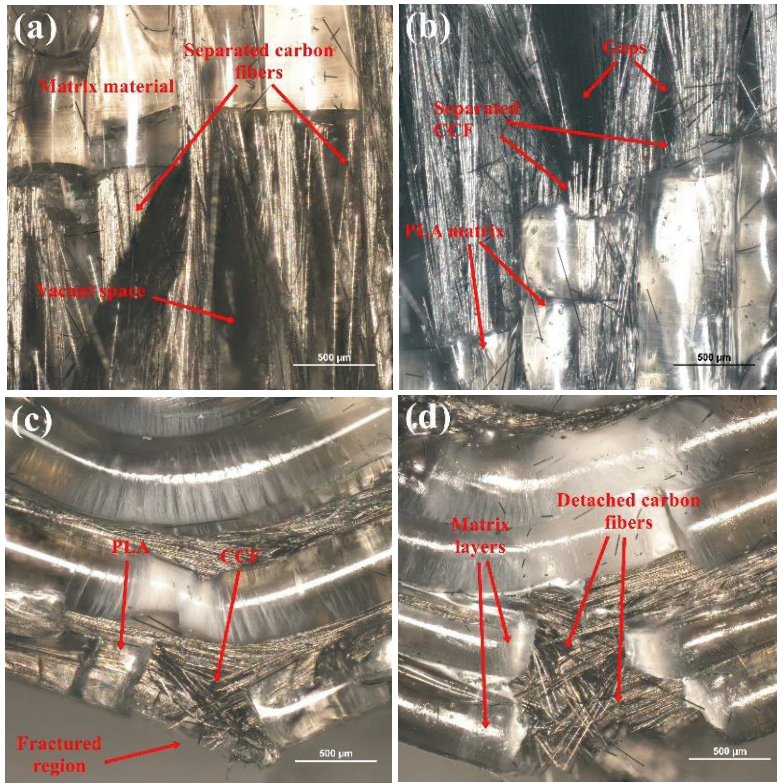


Fig. 3.40 Fracture interface micrographs of 3D printed cellular composite after performing a tensile test with: a) grid; b) triangular infill pattern; and flexural test with: c) grid; d) triangular infill pattern

3.13.2.2 Fracture interface analysis by using the image processing technique¹⁴

Based on the experimental results of the tensile and flexural testing regarding the deformation and fracture behavior that occurred during the mechanical tests of the solid and cellular CCFRPC fractured specimens, fracture interface analysis was conducted. Following the tensile and flexural tests, microscope micrographs were taken to examine such a behavior. Micrographs were taken with a microscope at 1.5 mm scale, and this scale remained constant for all micrographs for each specimen. The resulting micrographs were then subjected to image processing techniques in order to achieve the *edge detection* (E.D.) when utilizing the *source image* (S.I.). S.I. is then subjected to *contrast enhancement* (C.E.) images which are then processed to achieve E.D. on the C.E. image in order to evaluate the voids and to clearly understand the nature of the fracture.

Fracture interface micrographs E.D., C.E. and E.D. on C.E. when using S.I. of the specimen after performing the tensile test of the grid and triangular infill specimen

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are shown in Fig. 3.41 and Fig. 3.42, respectively. As seen from the Figure, after the tensile test, the separated matrix layers were holding the impregnated CCF within them. During the testing, the fracture occurred at the maximum load. The micrographs of the cellular composite specimen are displayed in Fig. 3.41 (a–c). Due to the hollow structure inside the cellular specimens, gaps and larger voids can be detected, while the outer perimeter shell can still be seen. At low infill density specimens, there are more cavities that are readily evident. Gaps and hollow internal structures inside the specimen are reduced as the infill density level is raised. The major reason for the fracture of such a structure is caused by the fiber pull-out [65, 99]. CCF effectively transferred the load from the matrix to the fiber while holding the matrix in place at various points, which allowed it to be employed for load-bearing and structural applications while undergoing tension.

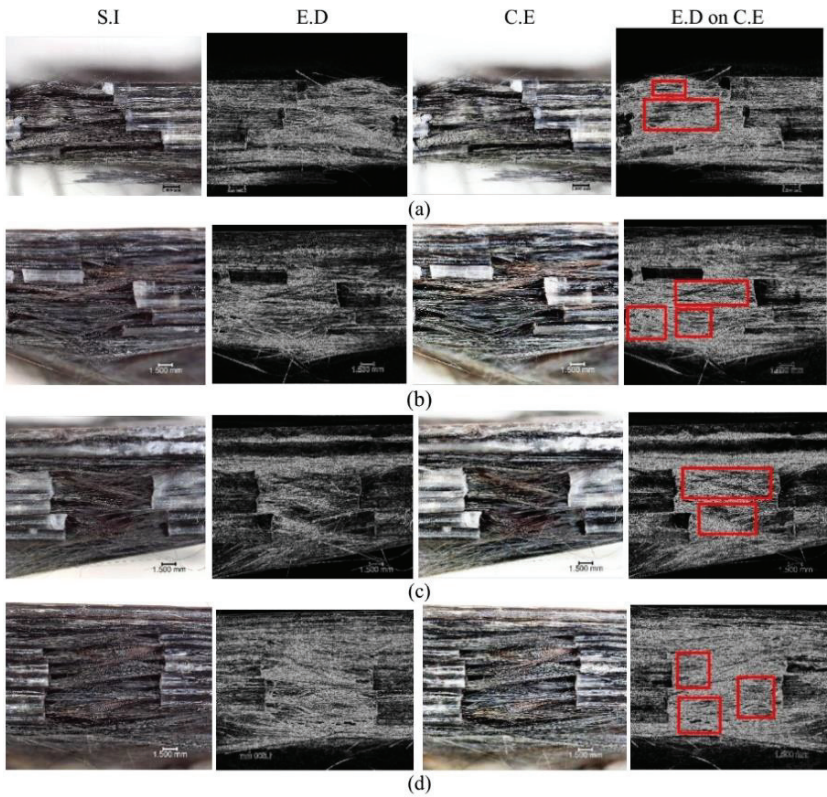


Fig. 3.41 Fracture interface micrographs of the specimen after the tensile test with grid infill density levels: a) 20%; b) 40%; c) 60%; d) 100%

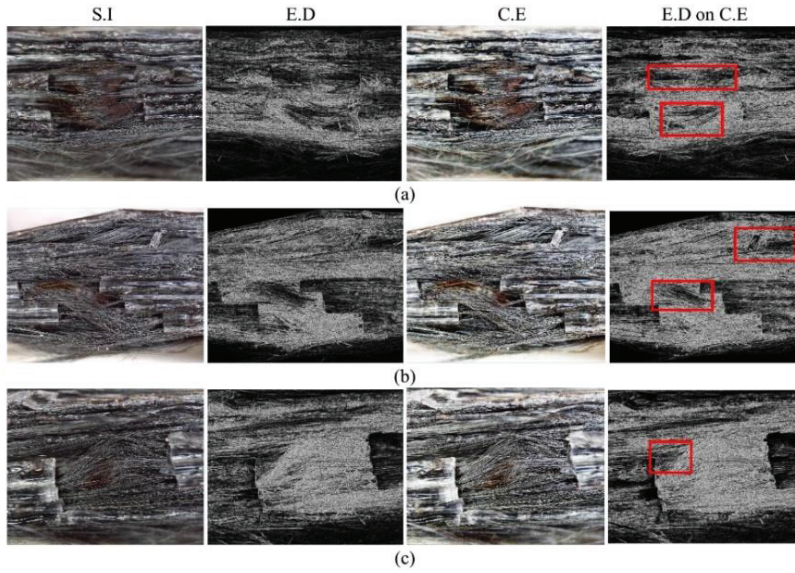


Fig. 3.42 Fracture interface micrographs of the specimen after the tensile test with triangular infill density levels: a) 20%; b) 40%; c) 60%

Fig. 3.43 and Fig. 3.44 show the fracture interface micrographs E.D, C.E and E.D on C.E when using S.I of the specimen after performing the flexural test of the grid and the triangular infill specimen, respectively. Where the breakdown happened due to the bending load, a fractured zone is plainly apparent. The reinforcement material was immediately exposed once the matrix layers had been instantaneously split during bending. When comparing dense and cellular structures, denser structures can be seen in the specimens with the 100% infill density level (Fig. 3.44 d), while hollow regions and voids are more obvious in cellular structures. A denser structure with little porosity developed inside the specimen shell as the infill density level was raised. After being bent, CCF at various points split from the layers of the matrix material. However, this is caused due to broken carbon fibers. Broken fibers primarily served as the cause of the CCFRPC structure's leading failure mechanism [38, 120].

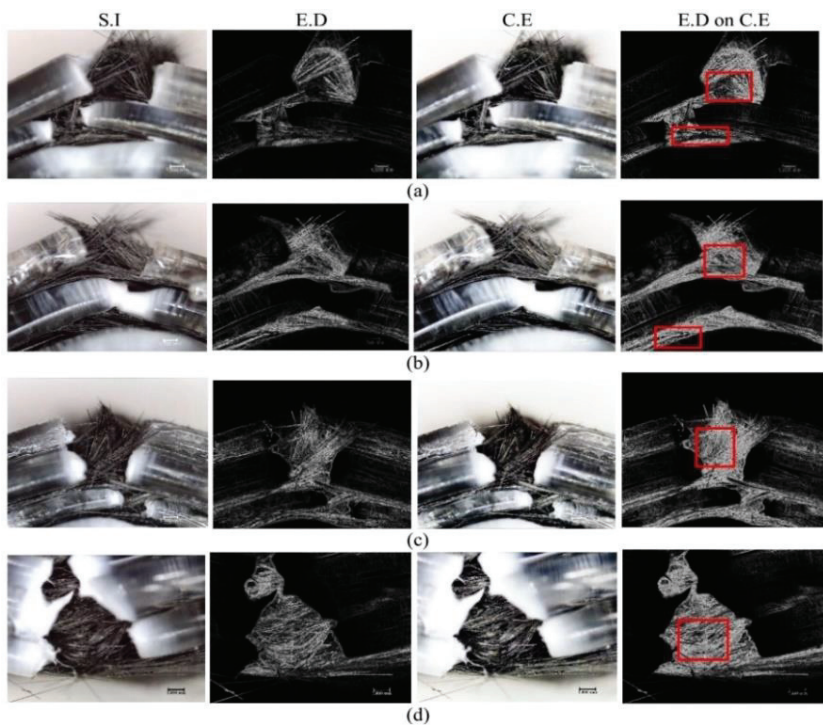


Fig. 3.43 Fracture interface micrographs of the specimen after the flexural test with grid infill density levels: a) 20%; b) 40%; c) 60%; d) 100%

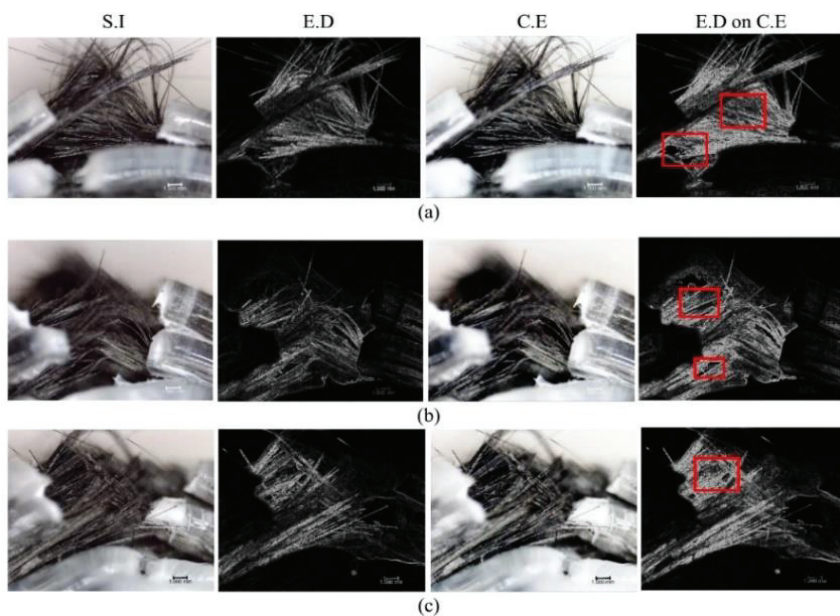


Fig. 3.44 Fracture interface micrographs of the specimen after the flexural test with triangular infill density levels: a) 20%; b) 40%; c) 60%

3.14. Delamination observed in PLA-SCF-CCF specimen during bending^{15, 16}

When a flexural test was performed on PLA-SCF printed with CCF, delamination occurred as opposed to rupture, as illustrated in Fig. 3.45. In the direction of the sides of the applied load, the printed layers of the specimen split, and gaps between them were left. As a result of the load that formed a bond with the PLA-SCF matrix, CCF was displaced. This type of behavior demonstrates that there is lack of sufficient bonding between the printed layers and the matrix, which results in weak adhesion between them.

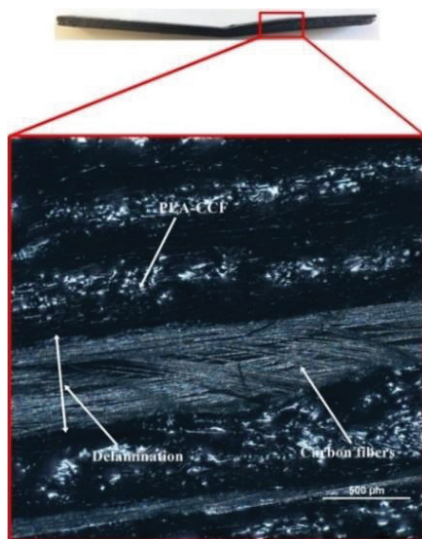


Fig. 3.45 Optical micrograph of delamination caused in PLA-SCF-CCF 3D printed sample during the flexural test

When the composite specimen is bent during the flexural test, delamination between the layers occurs at the applied load's ends as opposed to breakage. During the test with a high standard deviation, abrupt breakage and a rapid drop in the stress value were also observed. Poor interfacial bonding between the composite layers of a 3D printed object may be the cause of this oscillation. The microscope micrograph of the composite specimen following the flexural test is shown in Fig. 3.46. The figure shows that delamination rather than a rupture took place. Poor interfacial adhesion between the printed layers is typically to blame for this. As the force is being applied during the test, the lines of the composite portion split, which left gaps. The impregnated CCF dispersed from the layers without breaking. The top layer lines were the first site of delamination, which then moved to the bottom layer lines.

¹⁵ Reproduced from Ref. [187] with permission. Research [187] is one of the publications by the author of this dissertation

¹⁶ Reproduced from Ref. [191] with permission. Research [191] is one of the publications by the author of this dissertation

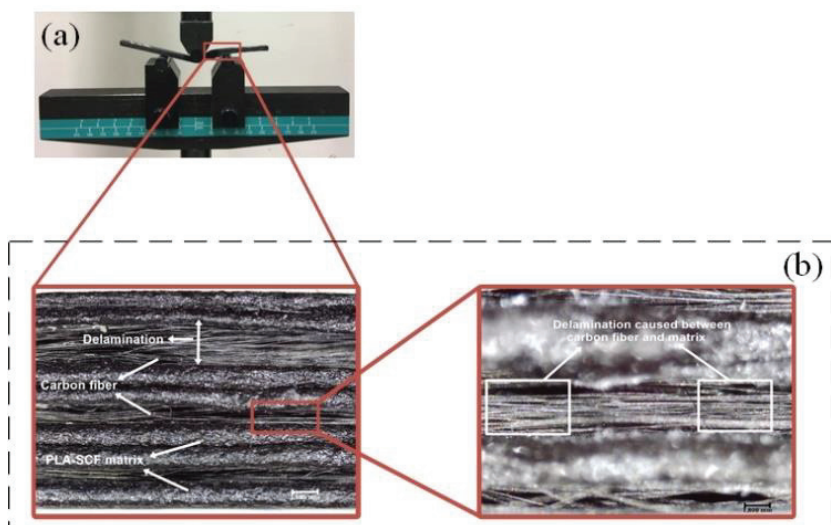


Fig. 3.46 3D printed PLA-SCF-CCF specimen: a) 3-point flexural bending test; b) delamination observed during the flexural test

3.14.1. Suggestion to improve interfacial bonding

Although CCF reinforced with a PLA-SCF composite showed improved flexural strength and modulus levels, the primary issue was the weak interfacial bonding between the matrix material and the reinforcement. Previously, the same composite material was used to attain a high tensile strength up to 227 MPa. More optimized printing parameters could be used to create a composite part from the same material with superior adhesion and interfacial bonding values. By increasing E.T. with a decrease in E.W., their bonding could be improved. To provide enough time for a bond to form that could lead to improved adhesion and performance as well as to prevent delamination during bending, the settling time period after the fabrication process should be provided, whereas rapid cooling of the printed parts should also be avoided.

3.15. Analytical approach to estimate the elastic modulus of the composite

Two types of analytical methods, i.e., RoM and the Halpin-Tsai model were employed to predict the modulus and compare to the results achieved experimentally and by numerical simulation. The extrusion multiplier (E.M.) of 0.7 and a layer height of 0.5 mm were kept constant, while the extrusion width (E.W.) or the layer width varied from 1 mm to 1.5 mm.

3.15.1. Halpin-Tsai Model

When using this model, the maximum elastic modulus of 54.69 GPa was estimated in the composite with an E.W. of 1 mm, and by increasing the E.W. value of the composite further on, the modulus value decreases, and the minimum modulus of 34.15 GPa was observed in the composite specimen with an E.W. of 1.5 mm. Table

3.11 presents a comparison of the elastic modulus regarding the experimental results and analytical approaches (RoM and the Halpin-Tsai model). A comparison between the analytical approaches which showed largely similar predicted values and the experimental results demonstrated higher differences in the predicted modulus. The major differences are caused by a variety of issues. As the analytical model is considered with the assumption that in the manufactured composite, the fibers are uniformly distributed in the matrix, and they are bonded perfectly with no void volume, and also that there are no interface issues, the fibers are stress-free, and that both the matrix and the fiber behave in terms of linear elasticity [180]. Yet, in reality, the 3D printed composite faces a number of concerns which include the quality matters, the void volume, and, sometimes, non-uniformly distributed layers, the extrusion problem and bonding issues, etc. These circumstances limited the capacity of the manufactured composites to achieve the predicted elastic modulus.

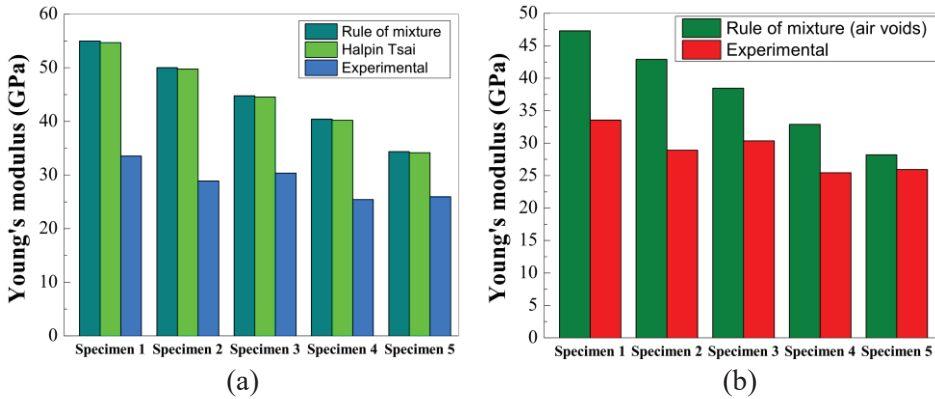
3.15.2. Rule of mixture (RoM)

By applying this technique to PLA and PLA-SCF reinforced with CCF, the samples allowed for the elastic modulus of the composite to be estimated for both specimens. PLA-CCF was determined to have an elastic modulus of 27.82 GPa, while PLA-SCF-CCF had an elastic modulus of 33.54 GPa. In comparison, PLA-SCF reinforced with CCF composite showed a high elastic modulus, as the same trend can be observed by the outcome of the tensile test. RoM estimation in terms of the maximum optimum elastic modulus for the designed composite parts demonstrated that the CCFRPC parts possessed a high elastic modulus. When increasing the content of CCF, both theoretical and experimental values of the modulus increase, and this could result in a decrease in porosity [89].

The RoM of the manufactured composite specimens was also calculated by using various printing parameters. The obtained analytical results were then thoroughly compared with the experimental and numerical simulation results. Five different groups of 3D printed composites were selected to make a comparison among them. An E.M. of 0.7 and a layer height of 0.5 mm were kept constant for each group, while E.W. was used between 1 and 1.5 mm. For each set of group, the volume fraction of the fiber was changed. The obtained results demonstrated that the highest modulus of 54.98 GPa was determined with the E.W. of 1 mm, and an increase of E.W. resulted in a decrease of the modulus value and the lowest elastic modulus of 34.34 GPa was determined for the specimen with an E.W. of 1.5 mm. A similar trend was registered and also validated from the experimentally obtained modulus. Fig. 3.47 (a) illustrates a comparison of analytically and experimentally calculated elastic modulus.

Table 3.11 Comparison of elastic modulus of the 3D printed composite

CCFRPC	Printing Parameter E.W. (mm)	Experimental E_c (GPa)	Halpin-Tsai E_c (GPa)	RoM E_c (GPa)
Specimen 1	1.0	33.54	54.69	54.98
Specimen 2	1.2	28.9	49.75	50.01
Specimen 3	1.3	30.36	44.53	44.77
Specimen 4	1.4	25.43	40.21	40.43
Specimen 5	1.5	25.94	34.15	34.34

**Fig. 3.47** Comparison results of analytical approaches of Young's modulus considering: a) ideal case; b) air void volume in the composite

The void volume in a composite material represents the volume of the empty space within the material. To incorporate the void volume in the RoM, one approach is to modify the formula to include the void volume fraction, which is the ratio of the void volume to the total volume of the composite. In the RoM, the void volume can be included by adjusting the volume fractions of the constituent materials. The RoM is a mathematical model used to predict the properties of a composite material based on the properties of its constituent materials. It assumes that the composite material is made up of a combination of two materials, with each material occupying a certain volume fraction. To include the void volume in the RoM, the volume fraction of the voids must be considered. This can be done by adjusting the volume fractions of the constituent materials so that to take into account the volume occupied by the voids. The modified RoM formula would be:

$$V_f + V_m + V_v = 1 \quad (20)$$

$$E_c = E_f(1 - V_m - V_v) + E_m(1 - V_f - V_v) \quad (21)$$

where:

V_f – volume fraction of the fiber;
 V_m – volume fraction of the matrix;
 V_v – volume void in the composite;
 E_c – elastic modulus of the composite;
 E_m – elastic modulus of the PLA matrix;
 E_f – elastic modulus of CCF.

In this modified formula, the void volume fraction is incorporated as a weighting factor between the density of the matrix material and the density of the filler material. The void volume fraction reduces the overall density of the composite material, thereby reflecting the fact that voids displace the material and increase the overall volume of the composite. It is important to note that this modified RoM is a simplified approach which assumes that the voids are evenly distributed within the composite material. In reality, voids may be unevenly distributed and may have different sizes and shapes which can affect the overall properties of the composite material. An increase of E.W. in 3D printed composites will increase the air void volume and lower the reinforcement content if the volume of each specimen is kept constant. By increasing E.W. in the printed lines, more gaps will be formed in between each line, and the number of lines will be lower if the dimensions are the same, which results in a higher void volume and a lower fiber content. The air void volume calculated for each composite specimen printed with an E.W. of 1 mm, 1.2 mm, 1.3 mm, 1.4 mm and 1.5 mm was 13.98%, 16.54%, 20.26%, 24.63% and 30.12%, respectively. Considering these void volumes in the composite and incorporating them in the modified RoM equation will result in lowered modulus values compared to the ideal case. It follows from Table 3.12 that, by including the void volume, the trend of the result is the same, and it shows the highest elastic modulus of 47.29 GPa in Specimen 1 and continues an increase in E.W.; the lowest elastic modulus of 28.20 GPa was seen in Specimen 5. Yet, by including the void volume in RoM, the elastic modulus is lowered compared to the composite obtained under ideal conditions, still, the difference between the experimentally achieved modulus and the RoM modulus is evident. This existence of such a difference is due to various concerns which include the printing process that still involves bonding issues between the layers and the lines of the composite, and interface issues are observed. Another reason could be the experimental testing of the composite which include the testing procedure, the gripping of the specimen as well as environmental conditions which may affect the ideal specifications. Meanwhile, in the case of RoM, it is still considered to be an ideal case, and we considered only the void volume, and there are many more conditions to be assumed in order to conform to the experimental results. A comparison of the experimental elastic modulus and RoM considering the void volume is presented in Fig. 3.47 (b).

Table 3.12 Comparison of experimental and RoM elastic modulus of composite considering the air void volume

CCFRPC	Printing Parameter E.W. (mm)	Air void content (%)	Experimental E_c (GPa)	RoM E_c (GPa)
Specimen 1	1.0	13.98	33.54	47.29
Specimen 2	1.2	16.54	28.9	42.90
Specimen 3	1.3	20.26	30.36	38.45
Specimen 4	1.4	24.63	25.43	32.89
Specimen 5	1.5	30.12	25.94	28.20

3.16. Chapter Conclusions

In this chapter, a composite with a thermoplastic matrix material and CCF reinforcement was manufactured by using the FDM 3D printing technique. Solid and cellular CCFRPC was fabricated, and their comparison was made. The range of the printing parameters was also studied to analyze and determine the optimum parameters. Firstly, impregnated CCF was prepared from the standard non-impregnated CCF spool. The impregnation process was performed in the solution mixture of PLA pellets by dissolving them in methylene chloride. The cross-section of impregnated CCF was observed under an optical microscope to confirm the presence of polymer impregnation solution; some void spaces were also seen. Secondly, the printing head of an FDM printer was modified. The original printing head was able to print only with pure thermoplastic materials. The custom-made printing head was designed with two inputs (one for a thermoplastic filament and one for impregnated CCF) and one output channel. A thermoplastic PLA material was semi-melted in the extrusion head where it fused together with the CCF, thus making a bond, extruded through the printing nozzle and printed on the bed surface of borosilicate glass mounted on an aluminum plate.

After the preparation of impregnated CCF and the modification of the extrusion head of the FDM printer, the process of the manufacturing of the composite was initiated by using the standard printing parameters. Initially, for the printing of composites, two matrix materials PLA and PLA-SCF were used to print with CCF reinforcement. PLA, PLA-SCF, PLA-CCF and PLA-SCF-CCF unidirectional 0° specimens were 3D-printed by using two different 3D printers with their standard printing parameters. Following the fabrication of the polymer and composite specimens, it was decided to analyze and observe the mechanical (tensile and flexural) properties. The achieved results showed that the highest tensile and flexural strength of 245.40 MPa and 168.88 MPa, respectively, was observed in the PLA-CCF composite specimen, while the highest Young's and flexural modulus of 27.93 GPa and 10.85 GPa, respectively, was determined in the composite specimens prepared with PLA-SCF-CCF. Afterwards, cellular CCFRPC structures were successfully fabricated by using the FDM technology. Cellular composite parts were fabricated by

using two types of infill patterns, i.e., the grid and the triangular pattern with one perimeter shell and two top and two bottom unidirectional 0° layers printed at 20%, 40% and 60% infill density levels. The mechanical testing revealed that the grid infill pattern composite with a 60% infill density level showed the highest tensile and flexural strength of 162.9 MPa and 127.24 MPa, respectively. Meanwhile, the triangular infill pattern with a 60% infill density level showed the maximum tensile and flexural strength of 152.62 MPa and 117.53 MPa, respectively.

The range of the printing process parameters (E.T., E.M., and E.W.) was considered to study their effect on the mechanical properties. When considering the E.T., an increase of the temperature leads to an increase in the mechanical strength by achieving the maximum tensile and flexural strength of 218.19 MPa and 172.27 MPa, respectively, at an E.T. of 230°C . The same E.T. level was considered for the further printing of composite specimens with different E.W. and E.M. The maximum tensile and flexural strength of 251.62 MPa and 197.81 MPa, respectively, was detected when the composite was fabricated with the printing parameters of E.W. -1.2 and E.M. -0.7, while the highest Young's and flexural modulus of 30.36 GPa and 15.07 GPa, respectively, was observed when the composite part was fabricated with the printing parameters of E.W. -1.3 and E.M. -0.5.

CCE was introduced to the FDM printing process by using a controlled pressure regulator to improve the quality of the manufactured composite parts in which the layers and lines were distributed more uniformly. After making composite specimens by using CCE, more consistency was found in the manufactured parts which were then tested to examine the improvement in the mechanical properties as well. It was noticed that the tensile and flexural strength increased by $\sim 17\%$ and 25% , respectively, when compared to the specimens printed without CCE. This also relates to the correlation of the relationship between the quality and the mechanical properties. The influence of the layer height (0.4 mm and 0.5 mm) and the layer orientation (0° and $0^\circ - 90^\circ$) of the 3D printed composite was also studied regarding the effect on the mechanical properties. The result showed a greatly enhanced outcome by using the optimized printing process parameters, while the layer height of 0.4 mm and the layer orientation of 0° presented the highest tensile and flexural strength of 332.48 MPa and 229.89 MPa, respectively.

Following the composite fabrication and mechanical testing, it was decided to explore the fracture interface of the manufactured CCFRPC parts after mechanical testing so that to analyze the major reason of the fracture in the composite and to observe the fracture mechanism. For this purpose, an optical microscope was used to reflect the fractured interface. It was stated that fiber pullout was the major reason of the breakage, and, during the mechanical loading after the rupture of the matrix, the load was efficiently transferred to the fiber reinforcement which showed that CCF was still holding each other after even the fracture. Delamination also occurred during the flexural test.

The CCF reinforcement content was estimated and calculated by using the tool length path and the dissolution method which showed an important aspect in defining the mechanical properties. The cellular composite structure's reinforcement content was calculated by using the dissolution process in which the matrix was fully

dissolved, and the remaining fiber was weighed to calculate the content. It was found that the triangular infill pattern consumes more fiber content compared to the grid infill pattern. The highest CCF content of 31.11wt% was found in the cellular composite with the triangular infill pattern with a 60% infill density level. The dissolution method was also used to calculate the void volume in the composite specimen fabricated with a layer height of 0.4 mm and 0.5 mm and a layer orientation of 0° and $0^\circ - 90^\circ$. An advanced method of calculating the void volume in the composite by using the XCT scan was employed. The accomplished results showed that Group 2 of 3D-printed composite showed the lowest average void volume of 5.57%, while the highest average void volume of 17.41% was found in Group 3 composite specimen. The presented results revealed that decreasing the layer height in both layer orientations resulted in a decrease in the void volume.

At the end, analytical methods (RoM and the Halpin-Tsai model) were considered and used to predict the elastic modulus of the composites while considering samples without and with air void volumes by using the same V_f and material properties. Five groups of composite specimens were considered with varying E.W. values (1.0 mm – 1.5 mm) to obtain different elastic modulus values so that to make a comparison with the experimentally achieved results.

CONCLUSIONS

The literature analysis did not provide sufficient extent of reported research on CCF composites fabrication, or the development of cellular structures with different infill patterns so that to analyze their mechanical performance and the optimized printing parameters process with the objective to improve the quality of 3D printed CCFRPC parts with enhanced mechanical properties. The reinforcement content and the void volume of the composite structure were measured by using dissolution and XCT scan for the in-depth study. The following conclusions were drawn from this dissertation.

1. Specimens from pure PLA, PLA with SCF and these materials reinforced with continuous carbon fiber were produced by using a modified printing head. PLA-CCF and PLA-SCF-CCF groups were produced with approximately 18.2% and 21.8% carbon fiber content. PLA-CCF showed the highest tensile and flexural strength of 245.40 MPa and 168.88 MPa, respectively, among the fabricated specimen groups (PLA, PLA-SCF, PLA-SCF-CCF). The highest Young's and flexural modulus of 27.93 GPa and 10.85 GPa, respectively, was found in PLA-SCF-CCF composite group. The tensile strength of the PLA-CCF composite specimens was about 460% higher than that of the pure PLA and PLA-SCF specimens, and 7.84% higher than that of PLA-SCF-CCF composite. The flexural strength of the PLA-CCF composite group increased by 121%, 103% and 44.6% compared to PLA-SCF, pure PLA, and PLA-SCF-CCF groups.
2. The printing process parameters, the extrusion temperature, the line width and the extrusion multiplier were investigated in order to find the optimized printing parameters and their effect on the mechanical properties. The composite specimens fabricated at 230°C extrusion temperature showed the maximum tensile and flexural strength of 218.19 MPa and 172.27 MPa, respectively. The ranges of the extrusion multiplier (0.5–0.9) and the extrusion width (1.2 mm – 1.5 mm) were further investigated with the extrusion temperature of 230°C. The maximum tensile and flexural strength of 251.62 MPa and 197.81 MPa, respectively, was achieved when the composites were fabricated with an extrusion width of 1.2 mm and an extrusion multiplier of 0.7. The highest Young's and flexural modulus of 30.36 GPa and 15.07 GPa, respectively, was observed when the composites were fabricated with an extrusion width of 1.3mm and an extrusion multiplier of 0.5.
3. Cellular composite structures were successfully fabricated by using the FDM technology. The cellular parts were prepared with one perimeter shell and two solid and two bottom unidirectional solid layers while using two types of infill patterns (grid and triangular) printed at 20%, 40%, and 60% infill density levels. On the grounds of the mechanical testing when subjected to tensile and flexural bending loadings, the grid infill structure with a 60% infill density attained the maximum tensile strength, Young's modulus, flexural strength and flexural modulus of 162.9 MPa, 16.82 GPa, 127.24 MPa, and 12.77 GPa, respectively. Meanwhile, the triangular infill pattern with a 60% infill density reached the highest tensile strength, Young's modulus, flexural strength and flexural modulus

of 152.62 MPa, 20.78 GPa, 117.53 MPa and 12.66 GPa, respectively. The achieved results also demonstrated that, by increasing the infill density level, the strength level became higher.

4. A controlled cooling methodology with the appropriate equipment was developed and tested to investigate its influence on the quality and mechanical performance. It was found that controlled cooling allows fabricating parts with uniformly distributed layers and lines. It was found that the air flow rate of 40 l/min allow producing composite structures featuring a better quality and superior mechanical properties. It was noticed that the highest tensile strength of 294.46 MPa and a flexural strength of 247.24 MPa was achieved with the extrusion width 1.2 mm and 0.7 extrusion multiplier. The obtained results showed an increase of the tensile and flexural strength by 17% and 25%, respectively, when compared to the composite specimens printed without controlled cooling.
5. The influence of the layer height and the layer orientation of the 3D printed composite significantly affects the mechanical properties and reveals that decreasing the layer height will increase the strength. Unidirectional 0° composite specimens showed better results compared to 0° – 90° layer orientation specimens. The highest tensile strength of 332.48 MPa and a flexural strength of 229.89 MPa was found in the composite group printed with the layer height of 0.4 mm and a layer orientation of 0°. The highest carbon fiber content of 36.48wt% was found in composite Group 2, while Group 1, Group 3 and group 4 showed a carbon fiber content of 29.8wt%, 29.26% and 32.61% wt, respectively. The obtained results suggested that a decrease of the layer height significantly increases the reinforcement content in the 3D printed composite specimen. The XCT scan results disclosed the lowest air void volume of 5.57% in Group 2, while the highest void volume of 17.41% was observed in Group 3 composites. The presented results revealed that decreasing the layer height in both layer orientations resulted in a decrease in air voids.

SANTRAUKA

IVADAS

Temos aktualumas

Šiuo metu gamybos pramonė smarkiai plečiasi, per ribotą laiką reikia pagaminti didelį kiekį naujų, inovatyvių gaminių, naudojant skirtingas medžiagas, skirtas įvairioms inžinerinėms reikmėms. Kita vertus, gamybos pramonėje egzistuojantys vidiniai ir išoriniai reikalavimai pagerinti gaminių kokybę, sumažinti atliekų kiekį, pagerinti gaminių mechanines charakteristikas, užtikrinant didesnę tvarumą, skatina inžinierius ir mokslininkus ieškoti naujų alternatyvių medžiagų ir gamybos technologijų. Šie reikalavimai įgyvendinami įprastinę gamybos sistemą keičiant į skaitmeninę, kuri leidžia padidinti gamybos greitį, tikslumą ir lankstumą bei sumažinti medžiagų sunaudojimą.

Adityvioji gamyba (AG), dar vadinama 3D spausdinimu arba sparčia prototipų gamyba, yra pažangus gamybos procesas, kurio metu detalė gaminama sluoksnis po sluoksnio pagal kompiuterinio projektavimo metu sukurtą 3D CAD modelį, kol gaunamas galutinis gaminys. Priešingai nei taikant pjovimo technologijas medžiaga čia ne pašalinama nuo ruošinio, o pridodama sluoksnis po sluoksnio. Šios technologijos naudojamos sudėtingos geometrinės formos metalinėms, keraminėms, plastikinėms bei kompozicinėms detalėms gaminti. Palyginus su tradicinėmis gamybos technologijomis, adityviosios gamybos technologijos leidžia sutrumpinti projektavimo ir gamybos ciklo trukmes, todėl sumažėja gamybos sąnaudos ir padidėja įmonių konkurencingumas [1, 2]. Šiuo metu adityvi gamyba tampa viena iš sparčiausiai augančių ir plačiausiai diegiamų inovacijų įvairiose inžinerinės pramonės šakose. Pastaraisiais metais šios inovacinės technologijos pažengė į priekį tiek, kad gali būti sėkmingai naudojamos ne tik prototipo bet ir galutinio gaminio gamybai. Paprastai gaminio gamybai naudojant adityvios gamybos technologijos yra išskiriami trys pagrindiniai etapai:

1. 3D CAD modelio projektavimas ir jo konvertavimas į (.STL) formatą.
2. Spausdinimo įrenginio parametrų nustatymas.
3. Gaminio gamyba sluoksnis po sluoksnio [3].

Adityvi gamyba plačiai naudojama polimerinėms detalėms gaminti – nuo prototipų iki galutinių gaminių [4]. Polimerų, o ypač polimerinių kompozitų, panaudojimas įvairiose inžinerinės pramonės šakose, pavyzdžiui, aviacijos ir gynybos pramonėje, sudėtingoms, lengvoms konstrukcijoms, biomedicinoje – laikantiesiems karkasams ir implantams bei protezams spausdinti, architektūriniais modeliams spausdinti, automobilių, statybos ir maisto produktų pramonėje yra plačiai žinomas [3, 5]. Visų minėtų gaminių gamybai taip pat gali būti naudojamos ir adityvios gamybos technologijos.

Lydzios masės formavimo technologija, kuri grindžiama medžiagos ekstrudavimu, yra viena iš plačiausiai paplitusių ir dažniausiai naudojamų gaminant sudėtingas konstrukcines detales iš grynų polimerų ar kompozicinių medžiagų. Ši technologija žinoma dėl savo paprastumo, lengvo naudojimo, didelės medžiagų įvairovės, mažesnio medžiagų sunaudojimo ir ekonomiško. Anksčiau lydzios masės formavimas buvo išskirtinai naudojamas tik gaminant termoplastiko gaminius, tačiau, termoplastinę matricą sustiprinus ištisiniu anglies pluoštu, labai padidėja gaminio mechaninės charakteristikos ir išsiplečia panaudojimo sritys. Žinoma, yra daug įvairių veiksnių, darančių įtaką ištisiniu anglies pluoštu armuoto polimerinio kompozito struktūros kokybei ir mechaninėms savybėms. Pirma, anglies pluošto impregnavimo procesas atlieka labai svarbų vaidmenį, nes pagerina spausdinamumą ir pagaminto kompozito kokybines charakteristikas. Antra, optimalių spausdinimo proceso parametrų parinkimas gaminant lydziosios masės formavimo būdu yra kritiškai svarbus. Tinkamų parametrų parinkimas leidžia užtikrinti ne tik gaminio kokybę, bet ir mechanines charakteristikas bei pagaminamumą.

Tyrimo aktualumą lemia tai, kad adityvios gamybos technologijos, o daugiausia lydziosios masės formavimo (LMF) technologija, yra itin svarbios gaminant lengvas vientisas ir gardelines kompozicines konstrukcijas, kuriose kaip armuojamoji medžiaga yra naudojamas ištisinis anglies pluoštas. Šios konstrukcijos, pagamintos su nustatytais optimaliais parametrais, atitiks tokio tipo konstrukcijoms keliamus aukštus reikalavimus.

Darbo tikslas ir uždaviniai

Sukurti ir ištirti aukštos kokybės ir mechaninių savybių ištisiniu anglies pluoštu armuotas kompozicines konstrukcijas, gamybą grindžiant lydzios masės formavimo technologija. Šiam tikslui pasiekti buvo iškelti šie uždaviniai:

1. Pagaminti kompozicines konstrukcijas, armuotas trumpu ir ištisiniu anglies pluoštu, naudojant modifikuotą lydzios masės formavimo technologijos spausdinimo modulį ir nustatyti kompozitų mechaninę elgseną.
2. Ištirti įvairių spausdinimo parametrų (spausdinimo temperatūros, plastiko kiekio, spausdinimo gijos pločio) įtaką ištisiniu anglies pluoštu armuotų kompozicinių konstrukcijų mechaninėms charakteristikoms.
3. Sukurti gardelinių anglies pluoštu armuotų kompozicinių konstrukcijų gamybos metodiką ir gamybos procesą ir nustatyti jų mechanines charakteristikas.
4. Ištirti kontroliuojamo aušinimo poveikio įtaką ištisiniu anglies pluoštu armuotų kompozicinių konstrukcijų kokybei ir mechaninėms savybėms.
5. Ištirti sluoksnio aukščio ir orientacijos įtaką pagamintų kompozicinių konstrukcijų mechaninėms savybėms ir kokybei, nustatant oro porų turį ir anglies pluošto kiekį kompiuterinės tomografijos ir matricos tirpinimo metodais.

Metodai ir priemonės

Tyrimas apima projektavimą, eksperimentinius, analitinius, skaitinius ir teorinius tyrimus, siekiant gauti apibendrintus ir išsamius rezultatus. Kompiuteriniams bandinių ir konstrukcijų modeliams kurti naudota PTC Pro Engineer Wildfire 5.0 programinė įranga. Bandiniams 3D spausdinti naudota programinė įranga Simplify 3D, Prusa Slicer. Eksperimentiškai nustatant mechanines savybes naudota universali bandymų mašina Tinius Olsen H25KT. Morfologiniam kompozicinių konstrukcijų lūžio zonos tyrimui atlikti buvo naudojami Nikon Eclipse LV100ND ir Delta mikroskopai, su programine įranga NIS Elements D ir Delta Optical SmartAnalysis. Oro ertmių kiekis 3D spausdintuvu atspausdintuose kompozicinėse konstrukcijose nustatytas naudojant kompiuterinės tomografijos įrenginį RayScan 250E.

Mokslinis naujumas

Disertaciniame tyrime pristatoma ir nagrinėjama ištisiniu anglies pluoštu armuotų kompozicinių konstrukcijų gamyba 3D spausdintuvu, naudojant modifikuotą lydzios masės formavimo technologijos spausdinimo modulį. Pristatytas naujas metodas, leidžiantis spausdinti gardelines ištisiniu anglies pluoštu armuotas konstrukcijas. Dviejų tipų, trikampio ir tinklelio, užpildymo strategijos ir skirtingas užpildymo tankis buvo ištirtas ir nustatytas anglies pluošto kiekis tokio tipo konstrukcijose. Ištirti spausdinimo proceso parametrai (spausdinimo gijos plotis, plastiko kiekis, sluoksnio aukštis, spaudimo temperatūra ir sluoksnio orientacija), kai naudojamas kontroliuojamas aušinimas, ir nustatyta jų įtaka mechaninėms savybėms.

Praktinė darbo vertė

Mokslinio darbo metu atliktais eksperimentais ir gautais rezultatais įrodyta, kad naudojamas modifikuotas lydzios masės formavimo procesas leidžia atspausdinti lengvas funkcinės ištisiniu anglies pluoštu armuotas vientisas ir sudėtingas gardelines konstrukcijas. Tyrimų metu gauti optimalūs spausdinimo parametrų deriniai, kurie leidžia atspausdinti geresnės kokybės ir mechaninių savybių kompozicines konstrukcijas. Pagamintos funkcinės dalys gali būti sėkmingai naudojamos automobilių, aviacijos, kosmoso bei robotikos pramonėse. Sukurta metodika, leidžianti naudoti kontroliuojamą aušinimą, ateityje suteiks galimybes spausdinti dar sudėtingesnės konstrukcijos gaminius. Atliktų tyrimų ir gautų rezultatų visuma suteikia pagrindą tolimesniam šios technologijos vystymui.

Ginamieji teiginiai

1. Sukurtos ir pagamintos sudėtingos geometrinės formos gardelinės konstrukcijos gali būti naudojamos norint pakeisti vientisas konstrukcijas, atsižvelgiant į jų mechanines charakteristikas ir spausdinimo trukmę.

2. Spausdinimo proceso parametrai (spausdinimo gijos plotis, plastiko kiekis, sluoksnio aukštis, spausdinimo temperatūra ir sluoksnių orientacija) turi didelę įtaką 3D spausdintų kompozicinių konstrukcijų mechaninėms savybėms.
3. Įdiegus kontroliuojamą aušinimą, pagamintos detalės bus kokybiškesnės dėl tolygaus 3D spausdinto kompozito sluoksnių ir linijų pasiskirstymo.

Darbo aprobavimas

Disertacijoje pateikti rezultatai paskelbti šešiuose moksliniuose straipsniuose įvairiuose tarptautiniuose žurnaluose. Iš jų trys publikacijos yra paskelbtos Web of Science citavimo indeksą turinčiuose žurnaluose.

Be to, mokslinių tyrimų rezultatai buvo pristatyti 5 tarptautinėse konferencijose: „Pažangiosios medžiagos ir technologijos 2020“ (Palanga, Lietuva), „OTEH 2020“ (Belgradas, Serbija), „Mechanika-2021“ (Kaunas, Lietuva), „POLCOM 2021“ (Bukareštas, Rumunija) ir „ICIMA 2022“ (Coimbatore, Indija).

Dalis mokslinių tyrimų taip pat atlikta vykdant M-ERA.NET projektą „Adityviomis technologijomis pagamintos sumanios kompozitinės struktūros su įterptais optiniais (FBG) jutikliais“.

Disertacijos struktūra

Disertaciją sudaro šie skyriai: įvadas, literatūros apžvalga, medžiagos ir metodai, rezultatai ir išvados, po kurių pateikiama santrauka lietuvių kalba, literatūros sąrašas ir autoriaus mokslinių publikacijų sąrašas. Literatūros apžvalgos skyriuje aptariamos žinios apie adityvios gamybos technologijas akcentuojant kompozicinių konstrukcijų gamybą. Vėliau išsamiai pristatomos ir aptariamos įvairiomis medžiagomis armuotos vientisos ir gardelinės konstrukcijos, pateikiamos pasiektos mechaninės charakteristikos ir naudotų spausdinimo proceso parametrų diapazonas. Medžiagų ir metodų skyriuje išsamiai paaiškinama spausdinimo proceso metodika, jo parametrai, mechaninių bandymų atlikimo eiga, oro ertmių tūrio ir anglies pluošto kiekio skaičiavimo ir lūžio zonos įvertinimo metodikos. Rezultatų skyriuje išsamiai aptariami gauti rezultatai ir atliekamas jų paaiškinimas. Iš viso disertaciją sudaro 172 puslapiai, 73 paveikslai ir 22 lentelės, o literatūros sąrašė yra 191 šaltinis.

1. LITERATŪROS APŽVALGA

1.1 Adityvi gamyba

Adityvioji gamyba, dar vadinama 3D spausdinimu, šiuo metu plačiai naudojama įvairiose inžinerijos pramonės šakose, kad būtų galima greitai gaminti įvairias detales nuo prototipų iki galutinio gaminio. Adityvi gamyba pasižymi tuo, kad leidžia gaminti itin sudėtingos geometrinės formos gaminius, tačiau su mažesnėmis laiko sąnaudomis ir praktiškai visiškai išvengiant atliekų. Dėl šių priežasčių naujoviška, lanksti gamybos technologija dabar pamažu keičia tradicinius gamybos procesus. Svarbiausios mechaninės medžiagų, pagamintų naudojant adityvią gamybą, savybės yra stiprumas, standumas. Palyginti su tradiciniais gamybos metodais, adityvi gamyba turi keletą privalumų, įskaitant greitą sudėtingos konstrukcijos gaminių gamybą, didelį pritaikomumą, aukštą automatizavimo lygį ir lankstumą, mažesnę energijos suvartojimą ir medžiagų atliekų kiekį [1, 10]. Dėl minėtų privalumų ir technologijų plėtros AG technologijos plačiai taikomos įvairiose inžinerijos srityse: automobilių pramonėje [11], aviacijos ir kosmoso pramonėje [12], biomedicinos pramonėje [13, 14], maisto pramonėje [15], statybos ir architektūros srityse [16], elektronikoje [17], karinėje pramonėje [18], robotikoje [19] ir mados pramonėje [20]. Pagrindinė problema, ribojanti dar platesnę adityvių technologijų taikymą, yra ribotas spausdinimo medžiagų pasirinkimas ir ribotos medžiagų mechaninės savybės. Šiuo metu dažniausiai naudojamos termoplastinės medžiagos, tarp jų akrilnitrilo butadien stirenas (ABS), polilaktidas (PLA), polikarbonatas (PC), poliamidas (PA) ir polietileno tereftalato glikolis (PETG) [21, 22]. Tačiau AG technologijos neapsiriboja vien termoplastinių medžiagų panaudojimu, šiuo metu galime matyti, kad gamyboje sėkmingai naudojamos metalinės [23, 24], keraminės [25, 26] ir kompozicinės [27, 28] medžiagos.

1.2 Polimerų ir polimerinių kompozitų adityvi gamyba

Polimerai užima svarbią vietą 3D spausdinimo technologijose ir tampa vis populiariesni dėl jų prieinamumo ir kitų savybių, paprastos gamybos, santykinai nesudėtingų techninių spausdinimo procesų [7, 35]. Pirmieji sukurti adityvios gamybos metodai buvo taikomi detalėms iš polimerų gaminti [38]. Polimerams spausdinti taikomi tokie AG metodai: sluoksniuotų objektų gamyba naudojant plastiko ar kitus lakštus [40], stereolitografija naudojant skystą fotopolimerą [41], lydžios masės formavimas naudojant termoplastiko giją [42], selektyvus lazerinis suldydymas ir 3D spausdinimas naudojant polimero miltelius ir juos rišančią medžiagą [37, 44]. Tačiau šiais metodais pagamintos gryno polimero detalės turi santykinai prastas mechanines savybes dėl mažesnio medžiagos stiprumo ir standumo [10, 45], nes gryni polimerai pasižymi prastomis mechaninėmis savybėmis [37, 46].

Pats spausdinimo procesas labai priklauso nuo medžiagos būvio. Beveik visos polimerų formos (skystis, milteliai ir t. t.) gali būti panaudotos 3D spausdinimo technologijose ir paverstos kietomis funkcinėmis detalėmis, kurios galėtų būti panaudotos įvairioms reikmėms.

PLA yra biologinės kilmės biologiškai skaidus ir aplinkai nekenksmingas polimeras, gaunamas iš atsinaujinančių išteklių, pasižymintis lėtu skilimo greičiu ir naudingas kai kuriose biomedicinos srityse. Jis yra biologiškai suderinamas su biologiniais skysčiais, todėl gali būti naudojamas biomedicinoje ir neturi toksinio ar kancerogeninio poveikio [47]. Anksčiau detalės iš PLA medžiagos paprastai buvo gaminamos naudojant liejimo, išpūtimo, pluošto verpimo ir plėvelės formavimo būdus [48, 49], dabar dėl skaitmeninės gamybos pažangos 3D spausdinimo technologijos gali būti naudojamos sudėtingos geometrinės formos gaminiams iš PLA medžiagos gaminti. Šiuo metu PLA yra vienas iš plačiausiai naudojamų termoplastikų įvairiems objektams kurti naudojant lydzios masės formavimo (LMF) technologiją [50, 51]. PLA plačiai naudojamas ekologiškose pakuotėse ir tekstilės pramonėje, o dabar dėl mažos kainos, lengvo apdorojimo ir patenkinamų mechaninių savybių jis tampa išskirtiniu polimeru, naudojamu ir adityvioje gamyboje [52, 53].

1.3 Polimerinių kompozitų gamyba naudojant lydzios masės formavimo technologiją

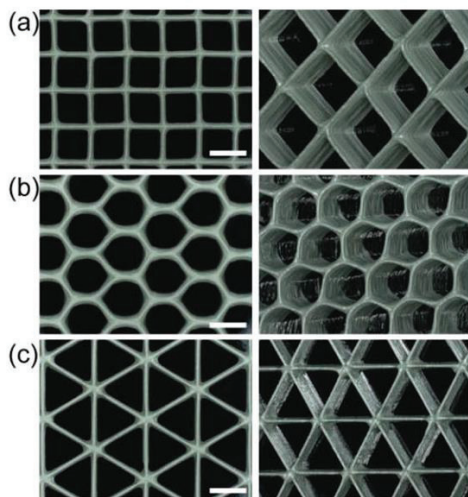
Dauguma 3D spausdintuvu atspausdintų polimerinių gaminių vis dar negali būti naudojami kaip visaverčiai funkciniai komponentai ypač sudėtingose, apkrautose konstrukcijose. Tai yra todėl, kad grynai polimeriniai gaminiai, pagaminti naudojant LMF technologiją, pasižymi nepakankamomis mechaninėmis savybėmis [37, 83]. Todėl, norint pagerinti medžiagų stiprumą ir standumą, ieškoma įvairių būdų, pavyzdžiui, į polimero matricą maišant armavimo medžiagos elementus, mikrodaleles, pluoštus ar nanodaleles ir taip suformuojant pluoštu sustiprintus polimerinius kompozitus, kurie pasižymi puikiomis funkcinėmis ir mechaninėmis savybėmis [84, 85]. Dažniausiai tokio tipo kompozicinėse konstrukcijose naudojamos tokios armuojamosios medžiagos, kaip anglies, stiklo ir aramido pluoštai, kurie gali būti ištisiniai arba smulkinti [87, 88]. Kompozitai, sustiprinti trumpais pluoštais ar dalelėmis, pasižymi prastesnėmis mechaninėmis savybėmis, palyginti su kompozitais, sustiprintais ištisiniais pluoštais [39, 86]. Galimybė įterpti ištisinį armuojamosios medžiagos sluoksnį ar elementą į matricos medžiagą gali lemti, kad detalė pasižymės daug geresnėmis mechaninėmis savybėmis [72, 89]. Ankstesnių eksperimentų rezultatai taip pat parodė, kad LMF procesu atspausdintų polimerinių kompozitų mechaninis stipris smarkiai padidėjo, palyginti su grynomis 3D spausdintuvu spausdintomis termoplastinėmis konstrukcijomis [5, 111].

Spausdinimo parametrai, tokie kaip sluoksnio aukštis, spausdinimo gijos plotis, plastiko kiekis, spausdinimo temperatūra, spausdinimo greitis ir anglies pluošto kiekis, turi didelę įtaką gaminio mechaninėms ir eksploatacinėms savybėms [91, 92], taip pat kompozicinių konstrukcijų kokybei [121, 155]. Pastebėta, kad buvo atlikta nedaug tyrimų, kai kompozicinėms detalėms gaminti naudojamas ištisinis anglies pluoštas, ir dauguma jų buvo orientuoti į mechaninių savybių gerinimą naudojant modifikuotą anglies pluoštą [24, 156]. Kai kurie tyrimai taip pat buvo atliekami keičiant spausdinimo parametrus ir bandant nustatyti jų įtaką kompozicinių konstrukcijų mechaninėms savybėms [89, 157].

1.4 Adityvi gardelinių konstrukcijų gamyba

Gardelinės konstrukcijos yra sudarytos iš grandinės individualių gardelių, kurios tarpusavyje susijungdamos suformuoja visą konstrukciją. Gardelinės struktūros yra plačiai žinomos dėl daug žadančių savybių lengvose konstrukcijose. Gardelinės struktūros gali būti sudarytos iš vienos medžiagos arba sujungiant kelias medžiagas, t. y. suformuojant kompozitus [130–132]. Nedidelės masės gardelinės kompozicinės konstrukcijos su puikiu stiprumo ir masės santykiu, dideliu standumu ir pralaidumu yra gaminamos iš atskirų vientisų elementų, kurie formuoja gardeles dvimatėje ar trimatėje erdvėje, tačiau tokias konstrukcijas yra sąlyginai sudėtinga projektuoti ir pagaminti [133–135]. Gardelinės konstrukcijos pasižymi anizotropinėmis savybėmis, jų mechaninės savybės bei elgsena labai priklauso nuo apkrovimo krypties.

Lengvos kompozicinės konstrukcijos gali būti sukuriamos naudojant gardelines struktūras, kurios leidžia smarkiai sumažinti medžiagų sunaudojimą, energijos sąnaudas, skirtas gamybai, atliekų kiekį ir užtikrinti patenkinamas mechanines charakteristikas [139]. Taip pat moksliniai šaltiniai teigia, kad, nepaisant masės sumažėjimo, adityvios gamybos metu pagamintos gardelinės konstrukcijos išvengia tarpsluoksninės adhezijos problemų [91]. Yra nustatyta, kad užpildymo santykis ir strategija turi labai svarbią reikšmę gardelių susidarymui ir mechaninėms savybėms [77, 144]. 1.1 paveiksle matyti trijų tipų gardelinės konstrukcijos, spausdintos naudojant epoksidinės dervos matricą ir silicio karbido užpildą.



1.1 pav. Gardelinės konstrukcijos: a) kvadratinė struktūra, b) šešiakampė struktūra, c) trikampė struktūra [139]

Lydžios masės formavimo technologija gali būti naudojama gardelinėms konstrukcijoms iš įvairių polimerų gaminti [145]. Gryno PLA gardelinės konstrukcijos buvo atspausdintos norint ištirti gardelių sienelės storio įtaką smūginėms apkrovoms ir tarpsluoksninei adhezijai [146, 148], spausdinimo kokybei ir stiprumo ribai gniuždant [147].

1.5 Literatūros apžvalgos santrauka

Lengvų kompozicinių medžiagų pritaikomumas labai padidėjo pradėjus jas naudoti įvairiose inžinerijos srityse, daugiausia aviacijos ir automobilių pramonėje. Tokių kompozitų paklausa sparčiai didėja dėl geresnių mechaninių savybių. O rinka reikalauja, kad konstrukcijos būtų sudėtingos geometrinės formos, pagaminamos greičiau ir pigiau. Šie reikalavimai skatina mokslininkus kurti inovatyvias kompozicines medžiagas ir konstrukcijas, pasižyminčias geresnėmis mechaninėmis savybėmis ir gaminamas naudojant adityvias gamybos technologijas.

Ištisinis anglies pluoštas dėl savo nedidelės masės, didelio standumo ir stiprumo bei ilgaamžiškumo dabar naudojamas kaip armuojamoji medžiaga termoplastiko matricos kompozite, norint, kad būtų pasiektas puikus stiprumo tempiant ar lenkiant ir masės santykis, leidžiantis konstrukcijoms atlaikyti didesnes mechanines apkrovas ar temperatūros svyravimus. Norint greitai pagaminti minėtas anglies pluoštu armuotas konstrukcijas, naudojama LMF adityvios gamybos technologija. Atlikus literatūros apžvalgą pastebėta, kad, į polimero matricą įterpus armuojamųjų medžiagų, stiprumo riba tempiant padidėjo iki 8 kartų, palyginti su gryno termoplastiko savybėmis. Taip pat pastebėta, kad gardelinių, lengvų konstrukcijų gamyba daugiausia vykdoma naudojant armavimui trumpo pluošto medžiagas arba visiškai gryną termoplastiko medžiagą, taip pat naudojant skirtingus užpildus ir užpildo tankį. Tačiau nebuvo rasta nė vieno tyrimo, kuriame būtų nagrinėjama gardelinių konstrukcijų gamyba naudojant ištisiniu anglies pluoštu armuotus kompozitus. Todėl labai svarbu sukurti ir ištirti gardelinių konstrukcijų su skirtingais užpildais ir skirtingais tankio lygiais gamybos metodiką ir nustatyti tokių konstrukcijų mechanines charakteristikas bei palyginti su vientisų konstrukcijų savybėmis. Spausdinimo proceso parametrų ir kompozicinių konstrukcijų gardelių ir kokybės ryšys taip pat bus nustatytas šiame moksliniame darbe.

2. METODOLOGIJA

Šis mokslinis darbas gali būti suskirstytas į tris pagrindines dalis. Pirmiausia buvo atspausdintos vientisos ištisinio anglies pluoštu armuotos konstrukcijos ir nustatytos jų pagrindinės mechaninės charakteristikos. Antroji tiriamojo darbo dalis buvo skirta gardelinių anglies pluoštu armuotų konstrukcijų gamybos metodikos sukūrimui, bandinių gamybai bei mechaninių charakteristikų tyrimui. Trečioji dalis buvo skirta kompozicinių konstrukcijų kokybinių parametrų, tokių kaip anglies pluošto kiekis, bendras porų tūris, nustatymui, analitiniam mechaninių charakteristikų tyrimui bei suirimo pobūdžio įvertinimui.

2.1 Medžiagos naudotos kompozicinėms konstrukcijoms

Šiuo metu PLA yra dažniausiai naudojama termoplastiko medžiaga 3D objektams spausdinti. Ši medžiaga pasirinkta dėl lengvo spausdinimo, žemos spausdinimo temperatūros, geresnio sukibimo, galimybės perdirbti ir tinkamų mechaninių savybių.

Šiame tyrime naudotos dviejų tipų matricos medžiagos. Pirmą, naudota 1,75 mm skersmens PLA termoplastiko gija PolyLite PLA (Polymaker). Termoplastinės gijos spausdinimo temperatūra svyruoja tarp 190°C ir 230°C, spausdinimo greitis gali kisti nuo 40 mm/s iki 60 mm/s, o platformos temperatūra nuo 25°C iki 60°C. Pagrindinės medžiagos mechaninės savybės yra pateiktos 2.1 lentelėje.

2.1 lentelė. Medžiagos PolyLite PLA savybės [163]

Tankis	Stiprumo riba tempiant	Jungo modulis	Stiprumo riba lenkiant	Stiklėjimo temperatūra
1,24 g/cm ³	46,6 ± 0,9 MPa	2,6 ± 0,33 GPa	85,1 ± 2,9 MPa	61°C

Kitoje tyrimų dalyje kaip matricos medžiaga buvo naudojama 1,75 mm skersmens gija XT-CF20 (ColorFabb). XT-CF20 yra kompozicinė medžiaga, pagaminta iš PLA, įterpus 20 % smulkinto anglies pluošto. Rekomenduojama XT-CF20 spausdinimo temperatūra yra 240–260°C, spausdinimo greitis 40–70 mm/s, o platformos temperatūra 60–70°C. Pagrindinės XT-CF20 medžiagos mechaninės savybės yra pateiktos 2.2 lentelėje.

2.2 lentelė. Medžiagos XT-CF20 savybės [164]

Tankis	Stiprumo riba tempiant	Pailgėjimas tempiant	Stiprumo riba lenkiant	Lenkimo modulis
1,35 g/cm ³	76 MPa	7,5 %	110 MPa	6,2 GPa

Anglies pluoštas yra lengva, tvirta ir standi medžiaga, paprastai naudojama kaip armuojamoji medžiaga įvairiose kompozicinėse konstrukcijose, norint pagerinti jų

mechanines charakteristikas. Anglies pluoštas sveria apie 40 % mažiau nei aliuminis, 70 % mažiau nei plienas ir net mažiau nei stiklo pluoštas.

Eksperimentiniame tyrime buvo naudotas gamintojo Toray (*Lacq*, Prancūzija) ištisinis 3K anglies pluoštas T300B-3000. T300-3000 yra lengvas, gerų mechaninių savybių pluoštas, pagamintas iš poliakrilonitrilo, pluoštą sudaro 3000 atskirų nesupintų gijų, kurių skersmuo yra 7 μm . Pagrindinės anglies pluošto T300B-3000 mechaninės savybės yra pateiktos 2.3 lentelėje.

2.3 lentelė. Pagrindinės T300B-3000 charakteristikos [165]

Medžiaga	Tankis	Stiprumo riba tempiant	Jungo modulis	Pailgėjimas tempiant, %
T300B-3000	1,76 g/cm ³	3530 MPa	230 GPa	1,5

2.2 3D spausdinimo ir kompozitų gamybos proceso parametrai¹

Bandinio geometrijai modeliuoti buvo naudota PTC Pro-engineer Wildfire 5.0 programinė įranga. Gautas CAD modelis eksportuotas kaip STL failas ir įkeltas į 3D spausdinimo programinę įrangą spausdinimo procesui paruošti. Kompozitams gaminti buvo naudojamas 3D spausdintuvas McCreator 2 (*Geeetech*) su modifikuota spausdinimo galvutės versija, kuriuo buvo gaminami PLA bandiniai, armuoti ištisiniu anglies pluoštu. Prusa i3 MK3S spausdintuvu buvo spausdinami gryno PLA bandinių grupė, taip pat PLA bandinių grupė, kuri buvo armuota smulkintu anglies pluoštu. Šie spausdintuvai buvo pasirinkti dėl jų paprastumo ir patogumo naudoti. Šiame etape pagal medžiagų tiekėjų rekomendacijas buvo parinkti pagrindiniai spausdinimo proceso parametrai ir kompozitiniai bandiniai norint įvertinti spausdinimo proceso ir bandinių kokybę. Spausdinimo parametrai pateikti 2.4 lentelėje.

2.4 lentelė. Spausdinimo parametrai

Parametrai	3D spausdintuvo tipas			
	McCreator 2		Prusa i3 MK3S	
	PLA-CCF	PLA-SCF-CCF	PLA	PLA-SCF
Spausdinimo antgalio skersmuo	1,5 mm	1,5 mm	0,4 mm	0,4 mm
Medžiagos kiekis	0,5	0,5	1	1
Spausdinimo gijos plotis	1,5 mm	1,5 mm	0,45 mm	0,45 mm
Sluoksnio aukštis	0,5 mm	0,5 mm	0,2 mm	0,2 mm
Spausdinimo greitis	3,0 mm/s	3,0 mm/s	25 mm/s	25 mm/s
Pirmo sluoksnio spausdinimo greitis	1,20 mm/s	1,20 mm/s	20 mm/s	20 mm/s

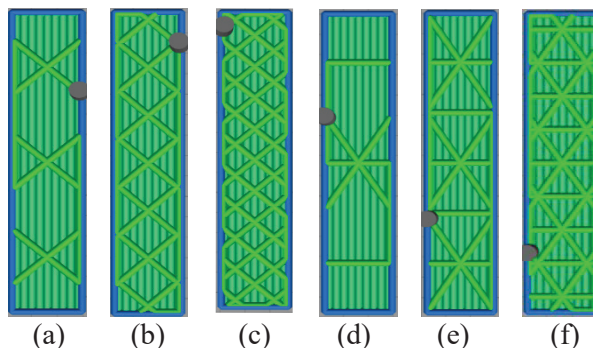
¹ Šio skyriaus medžiaga anksčiau buvo publikuota [187].

Spausdinimo temperatūra	210°C	250°C	210°C	250°C
Platformos temperatūra	90°C	90°C	60°C	75°C
Aušinimo efektyvumas	60%	60%	30%	30%
Užpildymas	0°	0°	0°	0°
Užpildymo tankis	100%	100%	100%	100%

Kaip matyti pateiktoje lentelėje, šio eksperimento metu buvo atspausdintos keturios bandinių grupės. Norint patikrinti matricos medžiagos savybes buvo atspausdinta bandinių grupė iš gryno polilaktido, ji įvardinta kaip PLA. Kita bandinių grupė PLA-SCF – tai bandiniai, kurie buvo atspausdinti iš polilaktido su 20 % smulkinto anglies pluošto. Grupės PLA-SCF-CCF bandiniai gaminti naudojant polilaktidą su 20 % smulkinto anglies pluošto ir dar armuoti ištisiniu anglies pluoštu. Grupės PLA-CCF bandiniai gaminti iš gryno PLA, kuris buvo armuotas ištisiniu anglies pluoštu.

2.3. Gardelinių kompozicinių konstrukcijų spausdinimas²

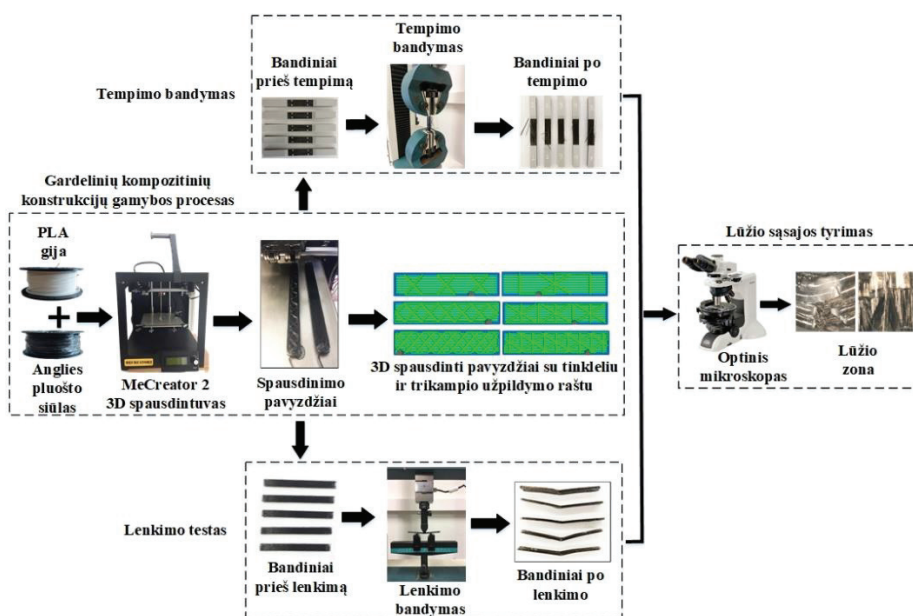
Gaminant gardelines kompozicines konstrukcijas, buvo pasirinkti dviejų skirtingų tipų užpildai (tinklelio ir trikampio formos) su trimis skirtingais užpildų tankiais (20 %, 40 % ir 60 %).



2.1 pav. Gardelinės konstrukcijos: tinklelio (a, b, c) ir trikampio (d, e, f) tipo; a) 20%; b) 40%; c) 60% d) 20%; e) 40%; f) 60%

Vidinė gardelinė konstrukcija buvo padengta dviem viršutiniais ir dviem apatiniais vienkrypčiais 0° kryptimi orientuotais sluoksniais.

² Šio skyriaus medžiaga anksčiau buvo publikuota [188].



2.2 pav. Bandinių gamybos ir eksperimentų atlikimo schema

Tinklelio vidinio užpildo spausdinimo orientacija buvo 45° , -45° , o trikampio užpildo orientacija atitinkamai 60° , -60° . Priežastis, dėl kurių tinklelio užpildui pasirinkta 45° , -45° , išdėstymas buvo spausdinimo sluoksnių sudėtingumas. Didinant užpildo tankį, bandinių vidinės struktūros sienelių ilgis mažėja, nes gardelinė konstrukcija papildoma naujais elementais. Tai buvo pastebėta atlikus užpildų spausdinimo kelių, sugeneruotų programos Simplify 3D, analizę. Taip pat pastebėtas skirtingas gardeles jungiančių elementų kiekis. Žinoma, kad trikampė struktūra, kurios mazgų jungiamumas lygus 3, yra izotropinė plokštumoje, o tinklinė struktūra, kurios mazgų jungiamumas lygus 4, yra anizotropinė [77, 167]. Gardelinių konstrukcijų gamybos proceso, bandymų ir eksperimentų schema pateikiama 2.2 pav. Kaip matyti iš pateiktų paveikslų, šio tyrimo metu buvo pagaminti ir ištestuoti šešių skirtingų grupių bandiniai.

Kadangi buvo norima nustatyti konstrukcijų elgseną ir pagrindines mechanines charakteristikas, todėl buvo atliekami lenkimo ir tempimo bandymai, o suirimo zonos buvo ištirtos naudojant optinį mikroskopą. Norint nustatyti anglies pluošto kiekį skirtingo tipo konstrukcijose, buvo paimta po mechaninių bandymų po tris bandinius ir ištirpinta matricos medžiaga pagal standarto ASTM D3171 reikalavimus.

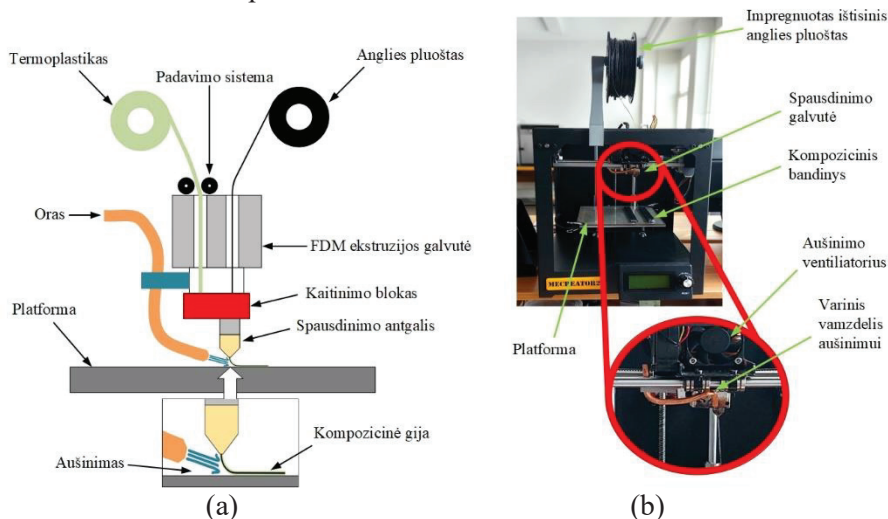
2.4. Kontroliuojamo aušinimo įdiegimas į 3D spausdinimo procesą³

Pagrindinis šio eksperimento metu atliktas pakeitimas buvo kontroliuojamo oro srauto aušinimo įdiegimas spausdinimo procese. Tokio pakeitimo priežastis yra noras užtikrinti aukštą spausdinamų kompozicinių konstrukcijų kokybę ir didesnę 3D

³ Šio skyriaus medžiaga anksčiau buvo publikuota [189].

spausdinimo tikslumą. Tam tikslui buvo naudotas 3 mm vidinio skersmens varinis vamzdelis, kuris buvo pritvirtintas šalia spausdinimo antgalio, o tai leidžia kompozitą tolygiai atspausdinti ant spausdinimo platformos. 2.3 paveiksle, a, pavaizduota modifikuoto 3D spausdintuvo McCreator 2, naudoto kompozicinėms konstrukcijoms gaminti, spausdinimo galvutės schema su integruotu aušinimo kanalu. 2.3 paveiksle, b, pavaizduotas spausdintuvas su integruotu aušinimu. Aušinimo srautas buvo valdomas skaitmeniniu slėgio reguliavimo vožtuvu. Dalis kompozicinių bandinių buvo gaminama su ir be aušinimo, kad būtų galima palyginti abiem atvejais pasiektą kokybę. Aušinimas buvo kontroliuojamas esant 30 l/min, 40 l/min, 50 l/min, 55 l/min ir 55 l/min oro srautams ir išlaikomas pastovus, kol detalės buvo visiškai pagaminamos.

Varinis aušinimo vamzdelis buvo laikomas 9 mm atstumu nuo spausdinimo antgalio. Varinio vamzdelio kryptis nukreipta tiesiai į spausdinimo platformos paviršių ir į kompozicinę medžiagą, ekstruduojamą per spausdinimo antgalį. Aušinimo tikslas greitai ir efektyviai aušinti ekstrudotą kompozicinę giją iki temperatūros, kuri neleidžia medžiagai deformuotis, tačiau užtikrina savalaikį sukibimą su spausdinimo platforma arba prieš tai atspausdinta gija. Atliekant eksperimentinius tyrimus, 0° vienos krypties kompoziciniai bandiniai buvo spausdinami su 100 % užpildu.



2.3 pav. 3D spausdinimas su kontroliuojamu aušinimu: a) spausdinimo galvutės schema, b) 3D spausdintuvas su integruotu aušinimu

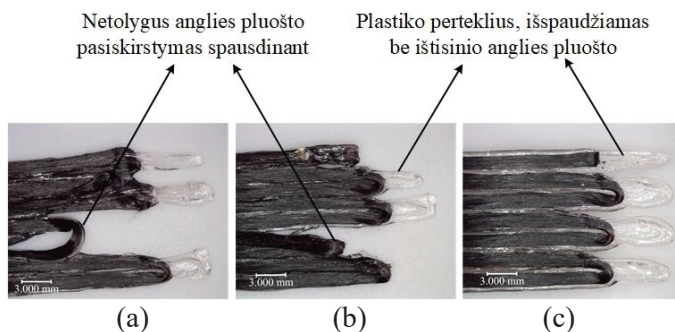
Siekiant ištirti aušinimo įtaką kompozicinių bandinių mechaninėms savybėms, buvo nuspręsta pagaminti trijų grupių bandinius. Šios trys bandinių grupės skyrėsi dviem parametrais, spausdinimo linijos pločiu ir plastiko kiekiu. Pirmoji bandinių grupė buvo atspausdinta naudojant 1,2 mm atstumą tarp spausdinimo linijų ir 0,5 plastiko kiekį. Antros bandinių grupės atstumas tarp spausdinimo linijų buvo 1,2 mm, o plastiko kiekis 0,7, trečios bandinių grupės atstumas tarp spausdinimo linijų buvo 1,3 mm, o plastiko kiekis 0,5. Tyrimų metu buvo ištirtos minėtų grupių tempimo ir

lenkimo savybės, o gauti rezultatai lyginti su rezultatais bandinių, kurie buvo atspausdinti be kontroliuojamo aušinimo. Taip buvo siekiama išsiaiškinti, ar kontroliuojamas aušinimas gali turėti tiesioginės įtakos adityvia gamyba gamintų kompozicinių bandinių mechaninėms savybėms. Eksperimentiniams tyrimams buvo atspausdinti 0° vienkrypčiai bandiniai su 100 % užpildymu. Visų trijų grupių gamyboje buvo naudojamas 40 l/min oro srautas, nes ankstesnės analizės metu buvo nustatyta, kad toks aušinimas leidžia atspausdinti geriausios kokybės bandinius.

3. REZULTATAI

3.1. Be aušinimo 3D spausdintų kompozitinių bandinių kokybės vertinimas⁴

Siekiant aiškiai įvertinti ir palyginti spausdinimo kokybę, kompoziciniai bandiniai buvo pagaminti naudojant spausdinimo procesus su ir be kontroliuojamo aušinimo. Norint įvertinti, kaip sluoksniai ir linijos pasiskirsto ir išsidėsto platformos paviršiuje, pradinis bandinio sluoksnis buvo atspausdintas be kontroliuojamo aušinimo. Kiekvienos bandinių grupės pirmajam sluoksniui stebėti buvo naudojamos mikroskopu darytos nuotraukos. Pirmo sluoksnio linijos, pagamintos be kontroliuojamo aušinimo, pavaizduotos 3.1 paveiksle. Iš 3.1 paveikslo a ir b matyti, kad kompozicinės linijos pasiskirsčiusios netolygiai, ypač linijų galuose. Spausdinant termoplastikas nurodytoje vietoje nesukietėjo pakankamai greitai, todėl anglies pluoštas buvo patrauktas atgal, ir toje vietoje nesusiformavo sklandi kompozicinė gija. Dėl anglies pluošto gijos patraukimo sumažėjo bandinio ilgis, o nekontroliuojamas patraukimas gali labai atsiliepti ir viso gaminio kokybei.



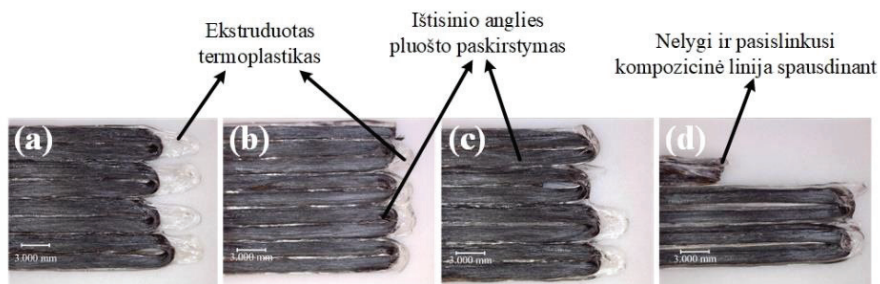
3.1 pav. Pirmojo sluoksnio vaizdas be papildomo aušinimo

Pavyzdžiui, 3.1 paveiksle a ir b matyti, kad anglies pluošto patraukimas yra labai netolygus, t. y. viena gija patraukiama daugiau, todėl bandinio galinėje dalyje susiformuoja tuštuma, o tai galima vertinti kaip ryškų kokybės trūkumą. 3.1 paveiksle, a, dar matyti ir susiformavusi kilpa, kuri gali turėti didelę įtaką kompozicinėje konstrukcijoje susidarančiam oro ertmių tūriui. 3.1 paveiksle, c, matome pakankamai lygų anglies pluošto gijų išsidėstymą, tačiau taip pat matyti, kad projektuoto ir realaus bandinio ilgiai skirsis dėl anglies pluošto gijos patraukimo. Norint sumažinti minėtus kokybinius neatitikimus, reikia padidinti aušinimo efektyvumą, ypač kritinėse gaminio vietose, galuose ar ten, kur keičiama spausdinimo kryptis.

⁴ Šio skyriaus medžiaga anksčiau buvo publikuota [189].

3.2. Su aušinimu 3D spausdintų kompozitinių bandinių kokybės vertinimas

Antroje eksperimento dalyje pirmasis kompozito bandinio sluoksnius buvo spausdinamas esant skirtingiems oro srautams (30 l/min, 40 l/min, 50 l/min ir 55 l/min), o linijų sklaidai įvertinti buvo naudojamos mikroskopu darytos nuotraukos, pateiktos 3.2 paveiksle. Gauti rezultatai parodė, kad nors linijų pasiskirstymas ant platformos yra tolygesnis, kai oro srautas buvo 30 l/min, dėl mažo aušinimo vis tiek matomas plastiko perteklius prieš grįžtant ir pradedant naują liniją arba, kitaip tariant, turimas per didelis anglies pluošto gijos patempimas. Šiek tiek padidinus aušinimo srautą iki 40 l/min, linijos pasiskirstė tolygiau, o pradedant naują liniją ištisinis anglies pluoštas buvo visiškai padengtas termoplastine matrica ir kompozicinė gija nebuvo tempiama. Be to, šioje situacijoje taip pat buvo pasiektas geresnis viso ploto užpildymas. Panašūs rezultatai gauti ir kai oro srauto greitis buvo padidintas iki 50 l/min, tačiau jau buvo matomas ir per didelis plastiko aušinimas, dėl ko taip pat prarandamas proceso sklandumas. Galiausiai, kai srautas padidinamas iki 55 l/min, aušinimas tampa per didelis, medžiaga nespėja patekti ant platformos ir pernelyg greitai sustingsta. Didelis aušinimas pagreitino matricos sukietėjimą, dėl to linijų ilgiai tapo netolygūs, todėl galima vertinti, kad buvo gautas prastesnės kokybės bandinys. Apibendrinant galima teigti, kad kompozicinė detalė, atspausdinta esant 40 l/min aušinimo srautui, pasižymėjo geresne kokybe, o sluoksnių sklaida buvo tolygesnė, palyginti su kitais testuotais aušinimais.

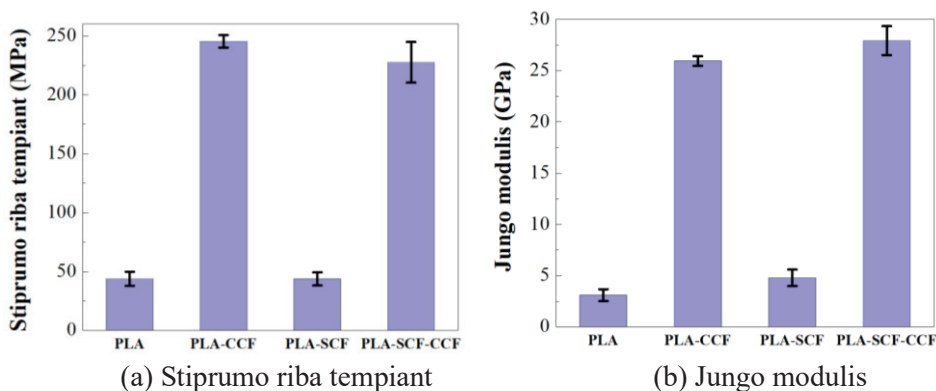


3.2 pav. Pirmojo sluoksnio vaizdas kai naudojami skirtingi aušinimo lygiai: a) 30 l/min, b) 40 l/min, c) 50 l/min, ir d) 55 l/min.

3.3. 3D spausdintų kompozitinių konstrukcijų mechaninių savybių tyrimas⁵

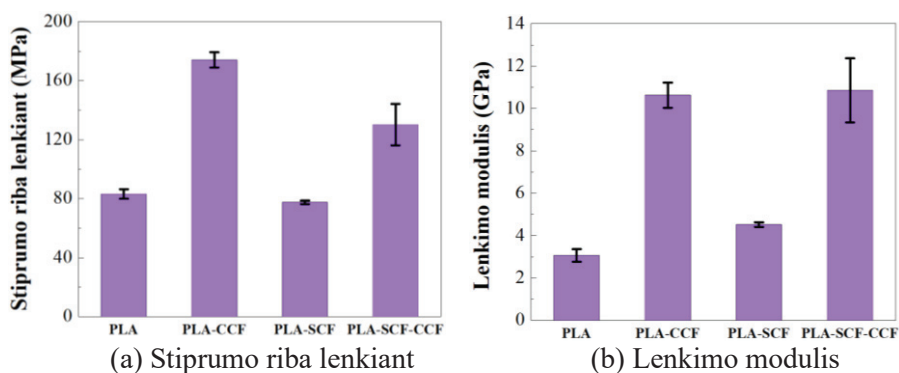
Šio tyrimo metu atlikus mechaninius bandymus buvo nustatytos keturių bandinių grupių pagrindinės mechaninės charakteristikos. Bandiniai, spausdinti iš matricos medžiagos PLA, kuri buvo armuota trumpu anglies pluoštu, turėjo 43,75 MPa stiprumo ribą tempiant, o gryno PLA bandinių stiprumo riba tempiant yra 43,83 MPa.

⁵ Šio skyriaus medžiaga anksčiau buvo publikuota [187].



3.3 pav. 3D spausdintų bandinių tempimo rezultatai

Taigi galima daryti išvadą, kad trumpo anglies pluošto įterpimas visiškai nepagerina šios mechaninės charakteristikos. O bandinių grupės PLA-SCF-CCF stiprumo riba tempiant yra 227,56 MPa. Ištyrus grynos PLA matricos, armuotos ištisiniu anglies pluoštu, bandinius (PLA-CCF) buvo nustatyta, kad stiprumo riba tempiant yra 245,40 MPa. Apibendrinant galima teigti, kad didžiausiu tempimo stipriu pasižymėjo PLA bandiniai, atspausdinti su impregnuotu ištisiniu anglies pluoštu, kurių rezultatai yra apie 6 kartus geresni už gryno PLA ir PLA, armuoto trumpu anglies pluoštu, bandinių rezultatus. Stiprumo riba tempiant padidėjo 460 %, palyginti su gryno PLA ir PLA-SCF grupės bandiniais, ir 7,84 %, palyginti su PLA-SCF-CCF grupės bandiniais. PLA-SCF-CCF bandinių grupei nustatyta Jungo modulio vertė, kuri siekė 27,93 GPa, toliau pagal rezultatus eina PLA-CCF, PLA-SCF ir PLA grupių bandiniai, kurių vidutinės Jungo modulio vertės atitinkamai yra 25,94 GPa, 4,79 GPa ir 3,09 GPa. Rezultatai rodo, kad, didinant anglies pluošto kiekį matricioje, didėja Jungo modulio vertė, t. y. medžiagos standumas didėja.



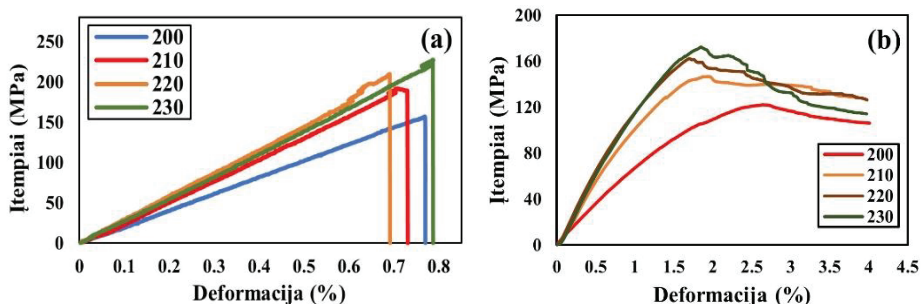
3.4 pav. 3D spausdintų bandinių lenkimo rezultatai

Iš stulpelinės diagramos, pateiktos 3.4 paveiksle, matyti, kad PLA-CCF grupės bandinių stiprumo riba lenkiant yra didžiausia, t. y. 168,88 MPa, o PLA-SCF-CCF bandinių grupės rezultatas yra 116,75 MPa. Vertindami gryno PLA ir PLA-SCF

bandinių grupių stiprumo ribos lenkiant vertes matome, kad jos yra atitinkamai 83,18 MPa ir 76,33 MPa. Apibendrinant galima teigti, kad bandiniai, atspausdinti su ištisiniu anglies pluoštu, pasižymėjo didžiausiu lenkimo stipriu, kuris atitinkamai 121 %, 103 % ir 44,6 %, didesnis, palyginti su PLA-SCF, PLA ir PLA-SCF-CCF grupių bandiniais. Vertindami lenkimo modulio rezultatus galime matyti, kad didžiausią lenkimo modulio vertę, 10,85 GPa, turėjo PLA-SCF-CCF grupės bandiniai. Kita vertus, tą pačią tendenciją buvo galima pastebėti ir atliekant tempimo bandymą. PLA-CCF, PLA-SCF ir grynojo PLA grupių bandinių lenkimo modulio vertės yra atitinkamai 10,63 GPa, 4,52 GPa ir 3,06 GPa.

3.4. Spausdinimo proceso parametrų įtaka mechaninėms savybėms⁶

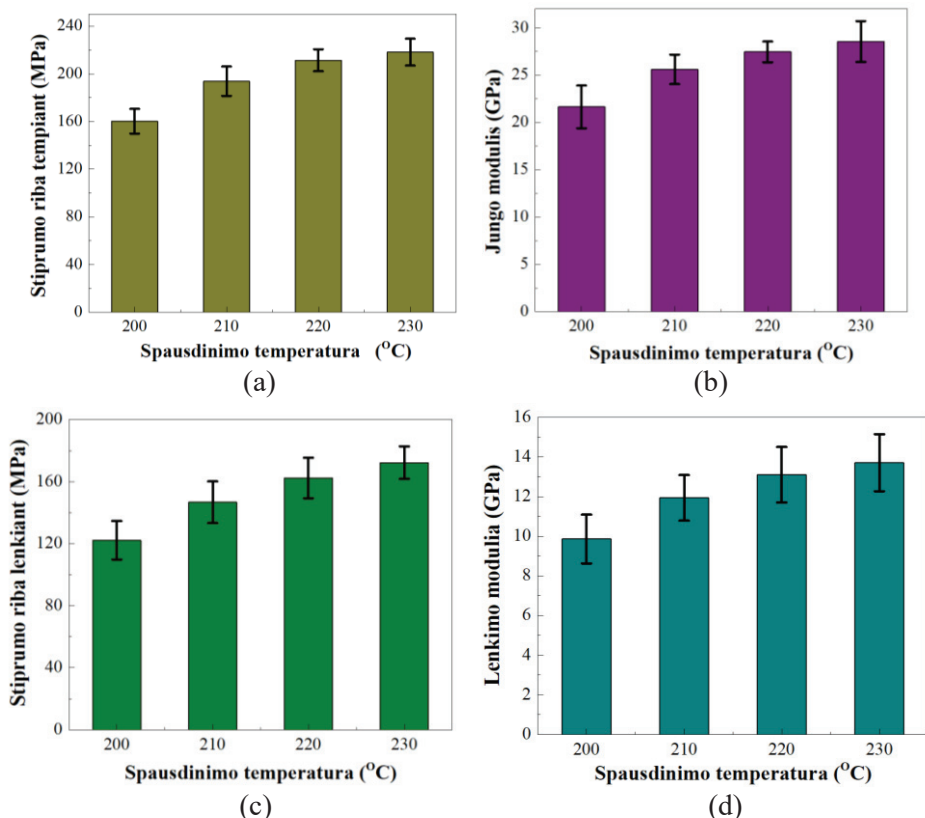
Atlikus šiuos tyrimus buvo nustatyta, kokią įtaką pagrindinėms mechaninėms charakteristikoms turi 3D spausdinimo temperatūra. Remiantis gautais rezultatais, galima daryti išvadą, kad temperatūra turi didelę įtaką tempimo bandymo metu nustatomoms savybėms. 3.5 paveiksle pateiktos įtempių ir deformacijų kreivės bandinių, kurie buvo spausdinti naudojant skirtingas spausdinimo temperatūras. Galima matyti, kad tempimo ir lenkimo įtempiai nuosekliai didėja keliant spausdinimo temperatūrą, tačiau ryškaus kreivių pokyčio nepastebėta, kas rodo, kad pats kompozicinių konstrukcijų suirimo mechanizmas yra panašus. 3.6 paveiksle a ir b pateiktos tempimo savybės (atitinkamai stiprumo riba tempiant ir Jungo modulis). Remiantis stulpelinėje diagramoje pateiktais rezultatais, geriausios charakteristikos yra esant aukštai spausdinimo temperatūrai.



3.5 pav. Įtempių ir deformacijų kreivės: a) tempimo bandymo, ir b) lenkimo bandymo

Mažiausia stiprumo riba tempiant 160,2 MPa ir Jungo modulis 21,65 GPa atitinkamai buvo nustatyti, kai bandiniai buvo spausdinti naudojant 200°C temperatūrą. Didžiausia stiprumo riba tempiant 218,19 MPa ir Jungo modulis 28,56 GPa buvo gauti, kai kompoziciniai bandiniai buvo pagaminti naudojant 230°C spausdinimo temperatūrą. Taigi, padidinus spausdinimo temperatūrą nuo 200°C iki 230°C, stiprumo riba tempiant padidėjo 36,2 %. Lenkimo bandymo rezultatai taip pat panašūs. Didėjant spausdinimo temperatūrai, didėja stiprumo riba lenkiant, taip pat ir lenkimo modulis.

⁶ Šio skyriaus medžiaga anksčiau buvo publikuota [189].



3.6 pav. Rezultatai, gauti esant įvairioms temperatūroms: a) stiprumo riba tempiant, b) Jungo modulis, c) stiprumo riba lenkiant, ir d) lenkimo modulis

Kompozicinių bandinių lenkimo savybės (stiprumo riba lenkiant ir lenkimo modulis), nustatytos atliekant lenkimo bandymą, parodytos 3.6 paveikslo c ir d dalyse. Iš gautų rezultatų matyti, kad grupės bandinių, kurie buvo spausdinti esant 230°C temperatūrai, stiprumo riba lenkiant ir lenkimo modulio vertės buvo didžiausios, atitinkamai 172,27 MPa ir 13,71 GPa. Charakteristikos reikšmingai padidėjo didinant temperatūrą nuo 200°C iki 210°C ir nuosekliai didėjo didinant temperatūrą iki 230°C. Vertinant spausdinimo temperatūros įtaką stiprumo ribai lenkiant, nustatyta, kad, padidinus temperatūrą nuo 200°C iki 230°C, stiprumo riba lenkiant padidėjo 41 %.

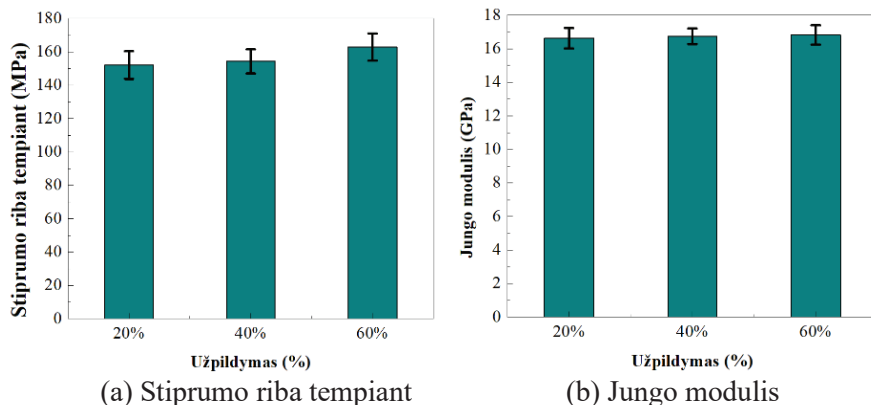
3.5. 3D spausdintų gardelinių kompozicinių konstrukcijų tyrimai⁷

3.5.1. Tinklelio užpildymas

Šis tyrimas buvo atliktas norint išsiaiškinti, kokią įtaką mechaninėms savybėms turi gardelinių struktūrų tipas ir medžiagos užpildymo tankis. Iš stulpelinės diagramos, pateiktos 3.7 paveiksle, matyti, kad bandiniai, kurių užpildo tankis 60 %,

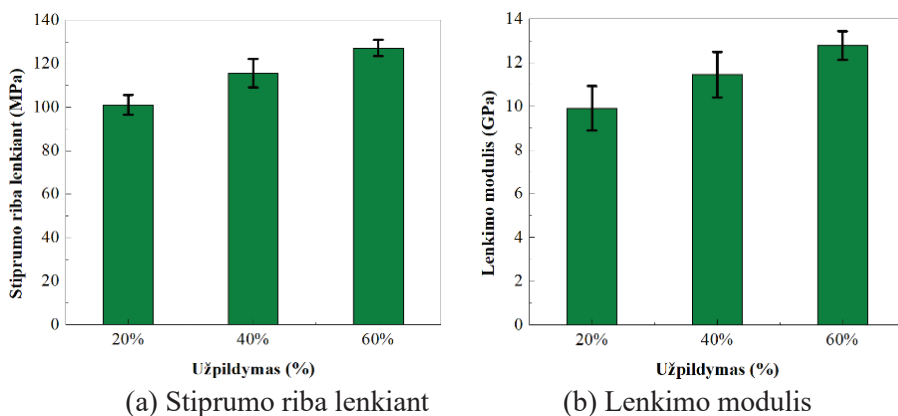
⁷ Šio skyriaus medžiaga anksčiau buvo publikuota [188].

pasiekia didžiausią stiprumo ribą tempiant 162,9 MPa, o 40 % ir 20 % užpildo tankio bandinių grupių rezultatai yra atitinkamai 154,28 MPa ir 152,1 MPa.



3.7 pav. 3D spausdintų tinklelio užpildymo bandinių tempimo savybės

Akivaizdu, kad, didėjant užpildo tankiui, stiprumo ribos tempiant vertė didėja, tačiau didėjimas yra nedidelis. Užpildo tankio poveikio Jungo moduliui analizės rezultatai, kurie pateikti 3.7 paveikslo b dalyje, parodė, kad, didėjant užpildo tankiui, modulio vertė keičiasi nedaug.



3.8 pav. 3D spausdintų tinklelio užpildymo bandinių lenkimo savybės

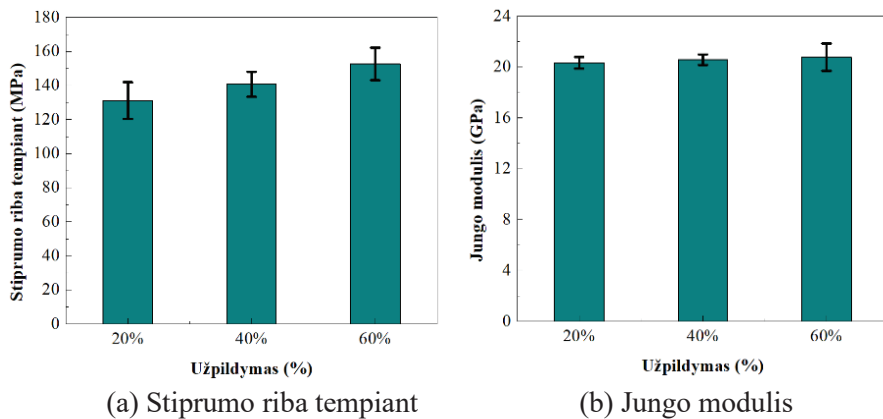
Esant 20 % užpildo tankiui, vidutinė Jungo modulio vertė yra 16,62 GPa, toliau didinant užpildo tankį iki 40 %, Jungo modulio vertė padidėjo iki 16,74 GPa, o didžiausia 16,82 GPa vertė nustatyta esant 60 % užpildo tankiui. Yra žinoma, kad kompozicinės konstrukcijos standumui didelę įtaką turi anglies pluošto kiekis, kuris keičiant užpildo tankį didėja nedaug. Šie rezultatai yra pateikiami tolesniuose skyriuose.

Rezultatai, pateikti 3.8 paveiksle, rodo, kaip, didėjant užpildo tankiui, didėja stiprumo ribos lenkiant vertė. Didžiausią stiprumo ribą lenkiant 127,82 MPa pasiekė

bandinių grupė, kurių užpildo tankis buvo 60 %. O bandinių, atspausdintų su 40 % ir 20 % užpildo tankiu, stiprumo ribos lenkiant vertės atitinkamai buvo 115,6 MPa ir 101,1 MPa. Grupės bandinių, atspausdintų su 60 % užpildu, vidutinė lenkimo modulio vertė buvo didžiausia, t. y. 12,77 GPa, o bandinių, atspausdintų su 40 % ir 20 % užpildu, grupių vidutinės lenkimo modulio vertės buvo atitinkamai 11,49 GPa ir 9,91 GPa. Remiantis šiais duomenimis galima teigti, kad kompozicinių bandinių lenkimo modulio vertė didėja užpildo tankio lygiui didėjant. Taigi galima daryti išvadą, kad užpildo tankis turi didesnę įtaką lenkimo savybėms nei tempimo savybėms.

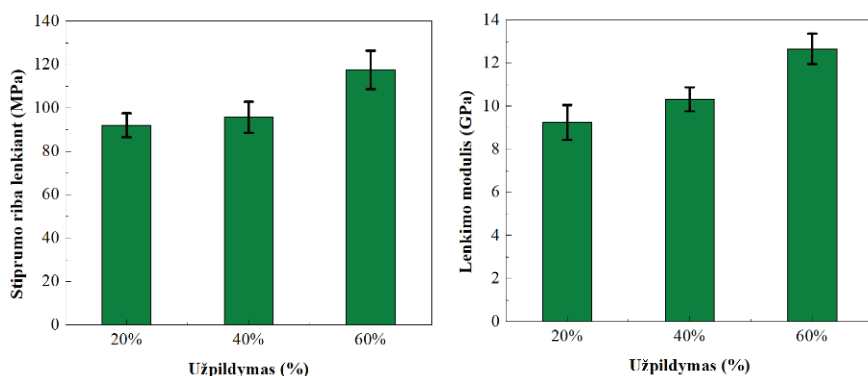
3.5.2. Trikampio formos užpildymas

Kiekvienos atspausdintos bandinių grupės rezultatai parodyti 3.9 paveiksle. Bandinių su 60 % trikampio formos užpildu vidutinė stiprumo riba tempiant buvo didžiausia ir siekė 152,62 MPa. Atitinkamai bandinių, atspausdintų su 40 % ir 20 % trikampio užpildo tankiu, vidutinės stiprumo ribos tempiant vertės buvo 140,75 MPa ir 131,15 MPa. Gauti rezultatai rodo, kad didėjantis užpildo tankis leido padidinti stiprumo ribos tempiant vertę.



3.9 pav. 3D spausdintų kompozitų su trikampiu užpildymu tempimo savybės

3.9 paveikslo b dalyje pavaizduota užpildo tankio įtaka Jungo moduliui. Didžiausią vidutinę Jungo modulio vertę 20,78 GPa turėjo bandinių, atspausdintų su 60 % užpildo tankiu, grupė. 20 % ir 40 % užpildo tankio bandinių vidutinė Jungo modulio vertė buvo atitinkamai 20,33 GPa ir 20,58 GPa. Didėjant užpildo tankiui, kiekvienu atveju nedaug didėja ir Jungo modulio vertės.



(a) Stiprumo riba lenkiant

(b) Lenkimo modulis

3.10 pav. 3D spausdintų kompozitų su trikampių užpildymu lenkimo savybės

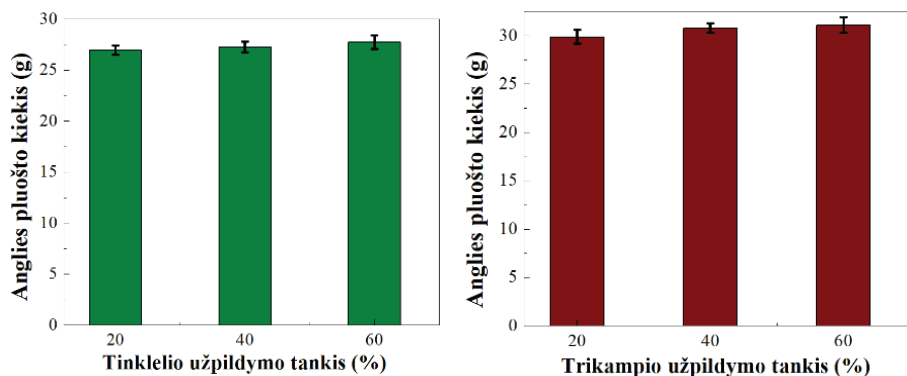
Atitinkamai 3.10 paveiksle pateikti lenkimo bandymo rezultatai. Matyti, kad grupė bandinių, atspausdintų su 20 % užpildo tankiu, turėjo mažiausią 92,9 MPa stiprumo ribą lenkiant. Didėjant užpildo tankiui, stiprumo riba lenkiant tolygiai didėja, galima matyti, kad bandiniai, pagaminti su 60 % užpildo tankiu, pasižymėjo 117,53 MPa stiprumo riba lenkiant. Grupė bandinių, atspausdintų su 40 % užpildo tankiu, turėjo 95,67 MPa stiprumo ribą lenkiant. Bandiniai, atspausdinti su 60 % užpildu, pasiekė didžiausią lenkimo modulio vertę, kuri buvo 12,66 GPa, o bandinių, atspausdintų su 20 % ir 40 % užpildu, vidutinės lenkimo modulio vertės buvo 9,24 GPa ir 10,32 GPa. Rezultatai parodė, kad, didinant užpildo tankio lygį, reikšmingai didėja lenkimo modulio vertė. Apibendrinant galima teigti, kad didesnė užpildymo tankio įtaka buvo pastebėta lenkimo savybėms abiejų užpildymo tipų bandiniuose.

3.5.3. Anglies kiekio gardelinėse konstrukcijose tyrimas⁸

Ištirpinimo metodas buvo taikomas nustatant armuojamosios medžiagos kiekį kompozitinėse konstrukcijose, sukurtose naudojant du skirtingus užpildų tipus (tinklėlio ir trikampio formos), atspausdintus trimis skirtingais užpildų tankiais (20 %, 40 % ir 60 %).

Remiantis 3.11 paveiksle pateiktais eksperimentų rezultatais, galima matyti, kad, didėjant užpildo tankio lygiui, šiek tiek didėja armuojamosios medžiagos kiekis. Esant 60 % užpildo tankiui, trikampio formos bandiniuose didžiausias anglies pluošto kiekis buvo lygus 31,11 % (pagal masę). Kai trikampio užpildo tankio lygis padidėja nuo 20 % iki 40 %, armuojamosios medžiagos kiekis padidėja 3 %, o kai užpildo tankio lygis pakyla nuo 40 % iki 60 %, anglies pluošto kiekis padidėja vienu procentu.

⁸ Šio skyriaus medžiaga anksčiau buvo publikuota [190].

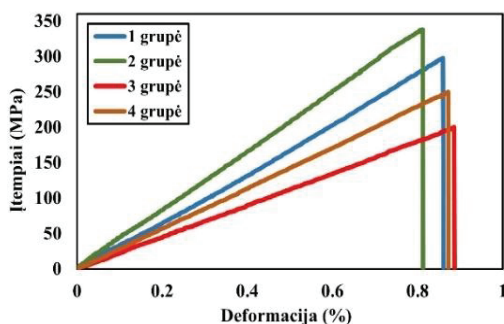


3.11 pav. Anglies pluošto kiekis tinkelio ir trikampio užpildymo konstrukcijose

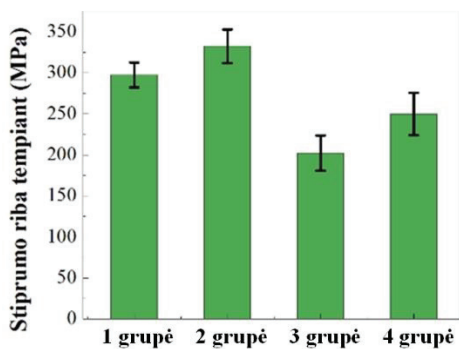
Atlikus tyrimus panašūs rezultatai matomi tinkelio užpildymo tipą turinčiuose bandiniuose, kurių užpildymo tankis yra 60 %. Šiuo atveju nustatytas didžiausias armuojamosios medžiagos kiekis yra 27,75 % (pagal masę). Padidinus užpildo tankį nuo 20 % iki 40 %, anglies pluošto kiekis padidėjo 1,1 %, padidinus užpildo tankį nuo 40 % iki 60 %, anglies pluošto kiekis padidėjo 1,7 %.

3.6. Aukščio ir orientacijos įtaka mechaninėms savybėms

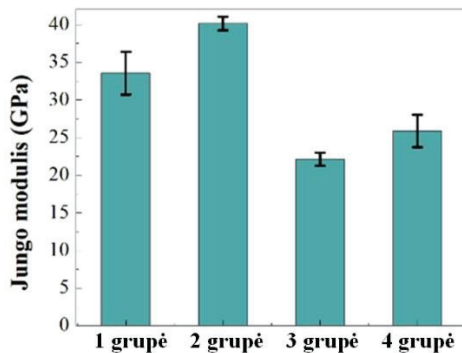
Adityvia gamyba pagamintų kompozicinių bandinių tempimo savybėms įvertinti buvo atliktas tempimo bandymas. Kiekvienai bandinių grupei vertinti naudotos tos pačios bandymo sąlygos. 3.12 paveikslo a dalyje pateiktos tipinės įtempių ir deformacijų kreivės, gautos atlikus tempimo bandymą. 3.12 paveikslo b ir c dalyse pavaizduoti stiprumo ribos tempiant ir Jungo modulio rezultatai. Remiantis gautais rezultatais, bandinių grupė, kurių sluoksnių orientacija 0° , o sluoksnio aukštis 0,4 mm, pasižymėjo didžiausia 332,48 MPa stiprumo riba tempiant. Mažiausia 202,20 MPa stiprumo riba tempiant buvo kompozicinių bandinių, kurių sluoksnių orientacija $0^\circ-90^\circ$, o sluoksnio aukštis 0,5 mm. Įvertinus abu sluoksnių orientacijos būdus galima teigti, kad stiprumo riba tempiant ir Jungo modulis didėja mažėjant spausdinimo sluoksnio aukščiui.



(a)



(b)

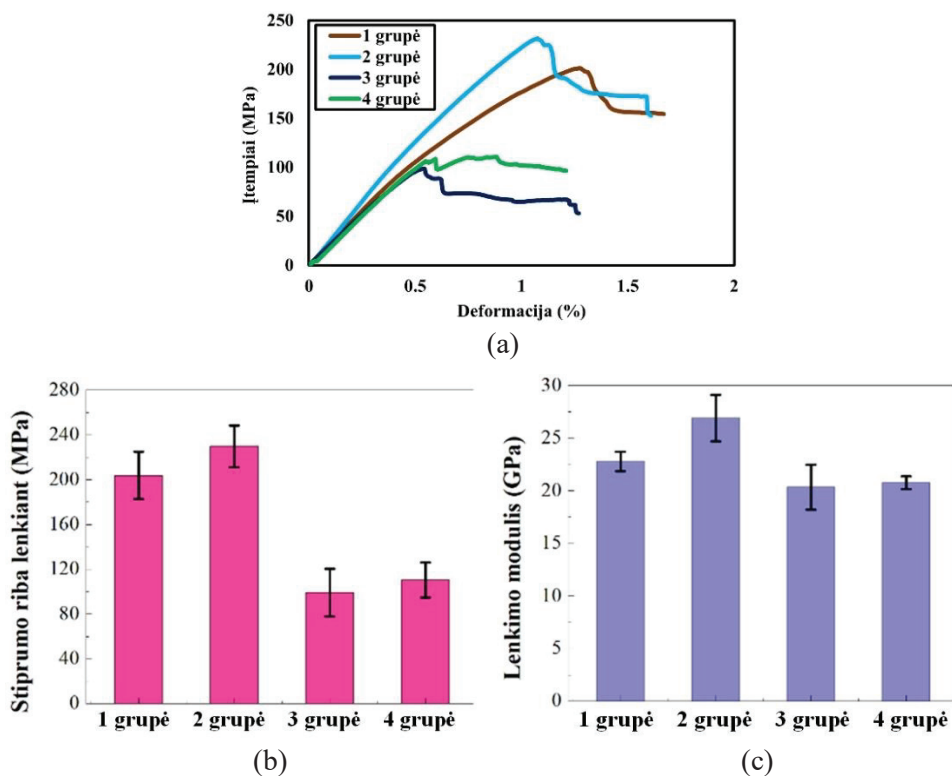


(c)

3.12 pav. Tempimo bandymo rezultatai: (a) įtempių ir deformacijų kreivės, (b) stiprumo riba tempiant, (c) Jungo modulis

Tai galima sieti su tuo, kad, mažėjant sluoksnio aukščiui, gaunama homogeniškesnė konstrukcija, turinti mažiau oro ertmių, taip pat mažėjant sluoksnio aukščiui padidėja atskirų sluoksnių skaičius, kas lemia ir anglies pluošto kiekio padidėjimą. Didžiausia Jungo modulio vertė, nustatyta 2 grupės bandiniams, yra 40,15 GPa, o mažiausias Jungo modulis 22,11 GPa buvo nustatytas 3 grupės bandiniams.

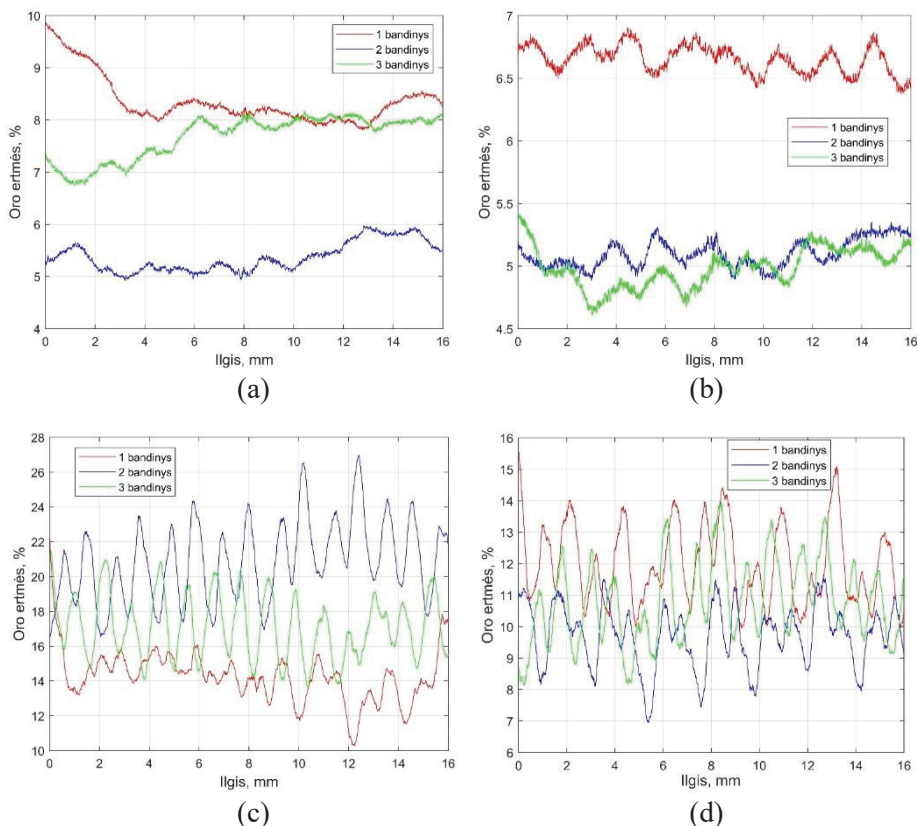
Lenkimo savybės (stiprumo riba lenkiant ir lenkimo modulis) nustatytos atliekant trijų taškų lenkimo bandymą. Kiekvienos bandinių grupės įtempių ir deformacijų reprezentuojančios kreivės pateiktos 3.13 paveiksle. Didžiausius lenkimo įtempius turėjo 2 grupės bandiniai, kurių sluoksnio aukštis 0,4 mm, o spausdinimo orientacija 0° . Įvertinant bandinių, spausdintų naudojant 0° – 90° sluoksnių orientaciją, rezultatus galima matyti, kad 3 ir 4 grupės bandiniai pasižymi ryškiu įtempių lygio sumažėjimu. Viena iš tokios elgsenos priežasčių yra bandymų metu tarp atspausdintų kompozicinių medžiagos sluoksnių atsiradęs atsisluoksniavimas. 3.13 paveikslo b ir c dalyse pavaizduoti stiprumo ribos lenkiant ir lenkiamojo modulio rezultatai, gauti atlikus trijų taškų lenkimo bandymą. Matyti, kad 2 grupės kompozicinių bandinių, kurių sluoksnių orientacija 0° , o sluoksnio aukštis 0,4 mm, stiprumo riba lenkiant buvo didžiausia, t. y. 229,89 MPa. 3 bandinių grupės, kurios sluoksnių orientacija 0° – 90° , o sluoksnio aukštis 0,5 mm, stiprumo riba lenkiant buvo mažiausia – 99,18 MPa. Didžiausias lenkimo modulis 26,91 GPa nustatytas antroje bandinių grupėje, toliau eina pirmosios grupės bandiniai, kur lenkimo modulis buvo lygus 22,80 GPa. Likusių bandinių grupių rezultatai yra labai panašūs. Iš turimų rezultatų galime daryti išvadą, kad bandinių, kurie buvo spausdinti 0° kryptimi, atsparumas lenkimui ir lenkimo modulis buvo didesni. Vertinant sluoksnio storį, galima teigti kad mažesnio sluoksnio aukščio bandinių atsparumas lenkimui yra geresnis.



3.13 pav. Lenkimo bandymų rezultatai: a) įtempių – deformacijų kreivės, b) stiprumo riba lenkiant, c) lenkimo modulis

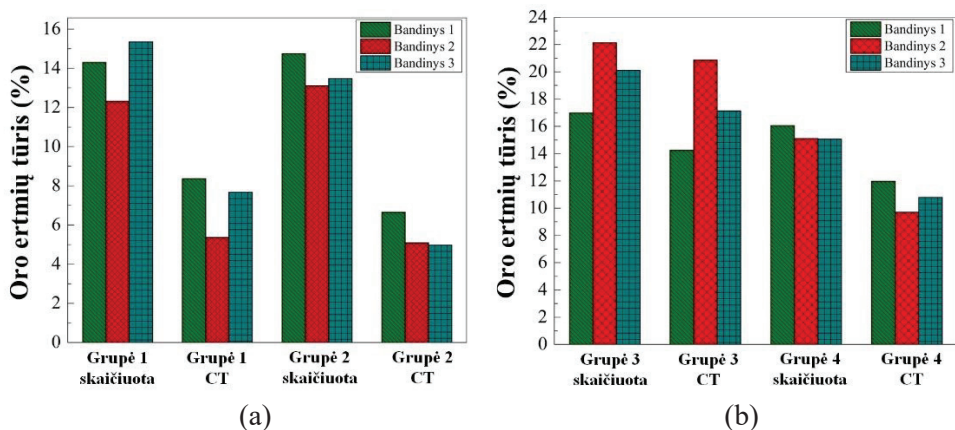
3.7 Oro tuštumų aptikimas 3D spausdintuose kompozituose

3D spausdintuvu atspausdintų kompozicinių konstrukcijų mechaninės savybės labai priklauso nuo struktūroje esančio oro ertmių arba tuštumų tūrio. Sumažinus oro ertmių tūrį detalėje, reikšmingai padidėja jos mechaninės charakteristikos, o kartu ir pačios konstrukcijos kokybė [121]. Kadangi lydzios masės formavimo technologija pagamintose kompozicinėse detalėse yra oro ertmių, todėl buvo nuspręsta įvertinti jų skaičių naudojant kompiuterinę tomografiją. Šis pažangus metodas leidžia gauti tikslesnius rezultatus. Iš kiekvienos bandinių grupės buvo tiriami trys bandiniai ir skaičiuojamas vidurkis bei standartinis nuokrypis. 3.14 paveiksle galime matyti oro ertmių kiekį kiekvienoje bandinių grupėje.



3.14 pav. Oro ertmių tūris bandiniuose nustatytas naudojant kompiuterinę tomografiją: a) 1 grupė, b) 2 grupė, c) 3 grupė, d) 4 grupė

Gauti rezultatai rodo, kad antros bandinių grupės vidutinis oro ertmių skaičius buvo mažiausias ir siekė 5,57 %, o didžiausias vidutinis oro ertmių skaičius 17,41 % buvo nustatytas 3 grupės bandiniuose. Atitinkamai 1 grupės ir 4 grupės bandiniuose buvo 7,13 % ir 10,82 % oro ertmių tūris. Pateikti rezultatai patvirtino, kad, mažinant sluoksnio aukštį, oro ertmių tūris mažėja, nepriklausomai nuo spausdinimo orientacijos. Mažesnis sluoksnių aukštis leidžia sumažinti ertmių tūrį, nes tarp sluoksnių lieka mažesni tarpai, ir jie patys efektyviau sukimba. Kompozicinių bandinių, kurių sluoksnių orientacija yra 0° – 90° , kompiuterinės tomografijos rezultatų sklaida buvo didesnė. Taip gali būti dėl 90° sluoksnio kryptyje susidarančių oro ertmių tarp gretimų spausdinimo linijų. Oro ertmių tūrio rezultatus taip pat galima papildyti gautomis mechaninėmis charakteristikomis, kurios parodo, kad mažiausias oro ertmių tūris, nustatytas antroje bandinių grupėje, leido pasiekti geriausias tempimo ir lenkimo savybes. Atitinkami lyginant mechaninių tyrimų ir oro ertmių rezultatus galima pastebėti, kad, didėjant oro ertmių tūriui, mechaninės savybės prastėja.



3.15 pav. Oro ertmių kompozito bandiniuose palyginimas taikant tirpinimo metodą ir XCT skenavimą: a) 1 grupė ir 2 grupė, b) 3 grupė ir 4 grupė

Norint nustatyti, koks tiriamuose bandiniuose buvo anglies pluošto kiekis, buvo naudojamas matricos medžiagos ištirpinimo metodas. Ištirpinus matricą iš kompozito, likęs pluoštas buvo pasvertas ir skaičiavimai atlikti žinant armuojamosios medžiagos ir matricos tankį bei masę kompozite. Apskaičiuoti oro ertmių rezultatai yra labai panašūs į tuos, kurie buvo nustatyti naudojant kompiuterinę tomografiją. Buvo nustatyta, kad trečios grupės bandiniuose buvo didžiausias 19,74 % oro ertmių tūris, o mažiausias oro ertmių tūris (13,77 %) buvo pastebėtas antros grupės kompoziciniuose bandiniuose. Pirmos ir ketvirtos grupės kompoziciniuose bandiniuose apskaičiuotas vidutinis oro ertmių tūris buvo 13,98 % ir 15,41 %. Tirpinimo metodu ir kompiuterinės tomografijos būdu apskaičiuotų oro ertmių palyginimas pateiktas 3.15 paveiksle. Analizuojant duomenis buvo nustatyta, kad gali būti kelios priežastys dėl nevaisingo duomenų atitikimo tarp analitiškai skaičiuotų ir eksperimentiškai gautų duomenų. Viena iš svarbių priežasčių yra subjektyvus pilkumo lygio nustatymas duomenų analizės metu vertinant tomografijos nuotraukas. Dėl kompozitą sudarančių medžiagų tankių panašumo sunku nustatyti objektyvų pilkumo lygį, kuris leistų įvertinti, kur bandinyje yra matricos medžiaga, armuojamoji medžiaga ar oro ertmės. Kita priežastis yra susijusi su tirpinimo metodikoje naudojamų bandinių matmenų netikslumais. Nors bandiniai ir buvo specialiai paruošti, tačiau matavimuose atsirandančios paklaidos gali labai nemažai prisidėti prie rezultatų skirtumų.

IŠVADOS

Atlikus literatūros analizę buvo pastebėta, kad nepakanka mokslinių duomenų apie ištisiniu anglies pluoštu armuotas kompozicines konstrukcijas, gardelinių struktūrų sukūrimą ir gamybą, naudojant skirtingus užpildymo tipus ir tankius, bei tokių konstrukcijų mechanines savybes. Disertacijoje atlikti gardelinių konstrukcijų gamybos, mechaninių savybių charakterizavimo tyrimai, taip pat pateiktas vientisų

konstrukcijų kokybinis vertinimas, apimantis anglies pluošto kiekį ir oro ertmių tūrio nustatymą. Atlikus numatytus tyrimus buvo padarytos tokios išvados:

1. Naudojant modifikuotą lydžios masės formavimo technologijos spausdinimo galvutę buvo pagaminti bandiniai iš gryno PLA, PLA su smulkintu anglies pluoštu ir šių medžiagų, sustiprintų ištisiniu anglies pluoštu. PLA-CCF ir PLA-SCF-CCF bandinių grupės buvo pagamintos su maždaug 18,2 % ir 21,8 % anglies pluošto kiekiu. Tarp ištirtų šios grupės bandinių PLA-CCF bandinių grupė pasižymėjo didžiausia stiprumo riba tempiant (245,40 MPa) ir lenkiant (168,88 MPa) tarp pagamintų bandinių grupių (PLA, PLA-TAP, PLA-TAP-IAP). Didžiausias Jungo ir lenkimo modulis, atitinkamai 27,93 GPa ir 10,85 GPa, buvo nustatytas PLA-SCF-CCF grupės bandiniuose. PLA-CCF kompozicinių bandinių grupės stiprumo riba tempiant buvo ~ 460 % didesnė nei gryno PLA ir PLA-SCF bandinių grupių ir 7,84 % didesnė nei PLA-SCF-CCF bandinių grupės. PLA-CCF grupės kompozitų atsparumas lenkimui padidėjo 121 %, 103 % ir 44,6 %, palyginti su PLA-SCF, gryno PLA ir PLA-SCF-CCF bandinių grupėmis.
2. Spausdinimo proceso parametrai, spausdinimo temperatūra, spausdinimo linijos plotis ir plastiko kiekis buvo tiriami siekiant nustatyti optimalius parametrus ir jų poveikį mechaninėms savybėms. Kompoziciniai bandiniai, pagaminti esant 230 °C spausdinimo temperatūrai, pasižymėjo didžiausia 218,19 MPa stiprumo riba tempiant ir didžiausia 172,27 MPa stiprumo riba lenkiant. Toliau atitinkamuose intervaluose buvo ištirti plastiko kiekis (0,5–0,9) ir spausdinimo linijos plotis (1,2–1,5 mm), kai spausdinimo temperatūra buvo pastovi 230 °C. Didžiausia 251,62 MPa stiprumo riba tempiant ir didžiausia 197,81 MPa stiprumo riba lenkiant buvo pasiekta, kai kompozicinės konstrukcijos buvo pagamintos naudojant spausdinimo gijos plotį 1,2mm ir plastiko kiekį 70 proc. Didžiausi Jungo ir lenkimo moduliai, atitinkamai 30,36 GPa ir 15,07 GPa, buvo nustatyti, kai kompozicinės konstrukcijos buvo pagamintos naudojant 1,3 mm spausdinimo gijos plotį ir 50 procentų plastiko kiekį.
3. Gardelinės kompozicinės konstrukcijos buvo sėkmingai pagamintos naudojant lydžios masės formavimo technologiją su vienu išoriniu sluoksniu ir dviem vienkrypčiais apačios ir viršaus sluoksniais, naudojant dviejų tipų užpildus (tinklelio ir trikampio formos) ir tris skirtingus 20 %, 40 % ir 60 % užpildo tankio lygius. Atlikus mechaninius bandymus buvo nustatyta, kad tinklelio užpildo konstrukcija su 60 % užpildo tankiu turėjo didžiausią 162,9 MPa stiprumo ribą tempiant, 16,82 GPa Jungo modulį, 127,24 MPa stiprumo ribą lenkiant ir 12,77 GPa lenkimo modulį. Trikampio formos užpildo grupės bandiniai su 60 % užpildo tankiu pasiekė didžiausią 152,62 MPa stiprumo ribą tempiant, 20,78 GPa Jungo modulį, 117,53 MPa stiprumo ribą lenkiant ir 12,66 GPa lenkimo modulį. Gauti rezultatai taip pat parodė, kad, didinant užpildo tankį, mechaninės charakteristikos palaipsniui didėja.
4. Kontroluojamo aušinimo metodika ir įranga buvo sukurtos ir išbandytos siekiant ištirti jo įtaką kokybei ir mechaninėms savybėms. Buvo nustatyta, kad kontroliuojamas aušinimas leidžia pagaminti detalę tolygiau paskirstant sluoksnius ir atskiras linijas naudojant lydžios masės formavimo technologiją.

Naudojant 40 l/min aušinimą buvo pagaminti geresnės kokybės ir mechaninių savybių bandiniai. Nustatyta, kad didžiausia 294,46 MPa stiprumo riba tempiant ir 247,24 MPa stiprumo riba lenkiant buvo esant tokiems spausdinimo parametrams: 1,2 mm spausdinimo gijos pločiui ir 70 proc. plastiko kiekiui. Gauti rezultatai parodė, kad minėtos mechaninės charakteristikos padidėjo apie 17 % ir 25 %, palyginti su bandiniais, kurie buvo atspausdinti be kontroliuojamo aušinimo.

5. Buvo nustatyta, kad 3D spausdintų kompozitų sluoksnio aukščio ir sluoksnio orientacijos įtaka turi reikšmingą poveikį mechaninėms savybėms, mažinant sluoksnio aukštį mechaninės savybės gerėja. Vienakrypčiai 0° grupės bandinių rezultatai buvo geresni, palyginti su 0° – 90° orientacijos bandinių grupėmis. Didžiausia 332,48 MPa stiprumo riba tempiant ir didžiausia 229,89 MPa stiprumo riba lenkiant nustatyta grupėje bandinių, atspausdintų esant 0,4 mm sluoksnio aukščiui ir 0° sluoksnių orientacijai. Didžiausias anglies pluošto kiekis 36,48 % pagal masę nustatytas 2 grupės bandiniuose, o 1, 3 ir 4 grupės bandiniuose anglies kiekis buvo 29,8 %, 29,26 %, ir 32,61 % pagal masę. Gauti rezultatai leidžia teigti, kad mažinant sluoksnio aukštį gerokai padidėja armuojamosios medžiagos kiekis 3D spausdintose kompozicinėse konstrukcijose. Kompiuterinės tomografijos rezultatai parodė oro ertmių tūrį bandiniuose: mažiausias oro ertmių tūris 5,57 % buvo nustatytas 2 bandinių grupėje, o didžiausias 17,41 % oro ertmių tūris buvo nustatytas 3 grupės bandiniuose. Pateikti rezultatai atskleidė, kad, mažinant sluoksnio aukštį, nepriklausomai nuo sluoksnių orientacijos, oro ertmių tūris mažėja.

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CURRICULUM VITAE

Name/Surname: Nabeel Maqsood

Date of Birth: 03 November 1992

Email: nabeel.maqsood@ktu.edu, nab.max@hotmail.com

Education:

2011–2015 Bachelor of Science in Mechanical Engineering

International Islamic University, Islamabad, Pakistan

2015–2017 Master of Science in Mechanical Engineering

University of Engineering and Technology Peshawar, Pakistan

2019–2023 Doctor of Philosophy in Mechanical Engineering

Kaunas University of Technology, Kaunas, Lithuania

Work experience:

2016–2017

Researcher, National Institute of Vacuum Science & Technology, National Centre for Physics, Islamabad, Pakistan

2017–2018

Laboratory Engineer, University of Engineering and Technology Peshawar, Pakistan

2018–2019

Lecturer, Department of Mechanical Engineering, Sarhad University of Science and Information Technology, Peshawar, Pakistan

2020–2023

Junior Researcher, Department of Production Engineering, Faculty of Mechanical Engineering and Design, Kaunas University of Technology, Kaunas, Lithuania

Research interests:

Additive Manufacturing, Composite Materials, Mechanical Properties, Materials Processing, Coatings, Mechanical Testing

PUBLICATION OF THE RESEARCH RESULTS

The results of this dissertation have been published in 6 scientific papers: 3 in journals with the impact factor indexed in the *Web of Science* database, and 3 without it. The research results have also been presented at 4 international scientific conferences:

List of Scientific Publications Related to the Dissertation

ARTICLES IN PEER-REVIEWED SCIENTIFIC PUBLICATIONS

Indexed in the Web of Science with Impact Factor

International Publishers

1. **Maqsood, Nabeel**; Rimašauskas, Marius. Influence of printing process parameters and controlled cooling effect on the quality and mechanical properties of additively manufactured CCFRPC // Composites communications. Oxford: Elsevier. ISSN 2452-2139. 2022, Vol. 35, art. No. 101338, p. 1–6. DOI:10.1016/j.coco.2022.101338. [Science Citation Index Expanded (Web of Science); Scopus] [IF: 7.568; AIF:6.552; IF/AIF: 1.155; Q1 (2021, InCites JCR SCIE)] [FOR: T 009] [Input: 0.500]
2. **Maqsood, Nabeel**; Rimašauskas, Marius. Development and fabrication of continuous carbon fiber reinforced thermoplastic porous composite structures with different infill patterns by using additive manufacturing // Journal of thermoplastic composite materials. London: SAGE. ISSN 0892-7057. eISSN 1530-7980. 2022, Early access, p. 1–26. DOI: 10.1177/08927057221088468. [Science Citation Index Expanded (Web of Science); Scopus] [IF: 3.027; AIF: 6.552; IF/AIF: 0.461; Q3 (2021, InCites JCR SCIE)] [FOR: T 009] [Input:0.500]
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Nabeel Maqsood

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Išleido Kauno technologijos universitetas, K. Donelaičio g. 73, 44249 Kaunas
Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, 51424 Kaunas

