INVESTIGATION OF THE MECHANICAL PROPERTIES CHANGES FOR MULTI-MATERIAL COMPOSITE 3D PRINTING

LEE ZHAN SHIN

UNIVERSITI TUNKU ABDUL RAHMAN

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LEE ZHAN SHIN

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of MECHANICAL Engineering with Honours

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

MAY 2022

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature	:	lee
Name	:	Lee Zhan Shin
ID No.	:	1703966
Date	:	09/09/2022

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"INVESTIGATE THE MECHANICAL PROPERTIES CHANGES FOR MULTI-MATERIAL COMPOSITE 3D PRINTING"** was prepared by **LEE ZHAN SHIN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature	:	
Supervisor	:	Tey Jing Yuen
Date	:	2/5/23

Signature	:	
Co-Supervisor	:	
Date	:	

ACKNOWLEDMENTS

I would like to express my sincerest gratitude to everyone who has supported me throughout this project. Firstly, I would like to thank my supervisor DR. Tey Jing Yuen for their valuable guidance, encouragement, and support throughout the project. His guidance has effectively steered me towards the correct direction throughout the duration of this project.

I am also grateful to my family and friends for their constant encouragement and support throughout this project. Their support and assistance have aided me in maintaining my motivation and focus throughout the entirety of this project.

Finally, I would like to extend my thanks to all those who have contributed to this project in one way or another, including the post graduate students in KB733 lab and peers who have provided valuable assistant. This project would not have been possible without their support and encouragement.

ABSTRACT

3D printing is a type of additive manufacturing that manufacture that creates a three-dimensional object by adding material layer by layer. In this study, the Fused Deposition Modeling (FDM) 3D printing is used. The purpose of this research is to improve the overall mechanical properties of 3D printed parts and eliminate the weakness by combining 2 different materials into 1 part. In traditional single-material printing, the choice of material used to create a part is limited to a single material. This limitation results in reduced mechanical properties and application limitations for the 3D printed parts. However, the introduction of multi-material 3D printing has overcome these limitations by combining different materials in one 3D printed parts. Multi-material printing is capable of printing composite materials, which can significantly improve the overall mechanical properties of printed parts. The composite materials are formed by combining two or more materials that complement each other, thus eliminating the weakness of individual materials and improving overall properties. The use of composite materials in printing also allows for the creation of parts with specific functions and purposes. Overall, multi-material printing has revolutionized the capabilities of 3D printing and expanded its potential applications, paving the way for new and innovative designs in various industries. There will be three main experiments in this study to determine the mechanical properties of 3D printing material, which is tensile test, flexural test and Izod impact test. All three experiments are done to determine the mechanical properties of mono material 3D printing. The experimental data are then inserted into Ansys simulation to simulate the mechanical properties of multi material 3D printing parts. Lasty, 2 sets of multi material 3D printed specimens are printed to validate the simulation data by doing those 3 experiments. The simulation shows that the combination of PLA and PETG specimens can provide the highest ultimate tensile strength and modulus with the moderate flexural strength and modulus. For the PLA and PETG combination 3D printing, the tensile test of this combination is 37.15 MPa and the flexural strength is 46.35MPa, the impact resistance is 294.64 J/m. The study also proves that most of the simulation model are accurate but there are still some improvements need to be done to increase the accuracy of the

simulation model. The differences between the simulation and experimental results are lesser than 20%.

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LIST OF SYMBOLS / ABBREVIATIONS

c_p	specific heat capacity, J/(kg·K)
h	height, m
K_d	discharge coefficient
M	mass flow rate, kg/s
P	pressure, kPa
P_b	back pressure, kPa
R	mass flow rate ratio
T	temperature, K
v	specific volume, m^3
α	homogeneous void fraction
η	pressure ratio
ρ	density, kg/m^3
ω	compressible flow parameter
ID	inner diameter, m
MAP	maximum allowable pressure, kPa
MAWP	maximum allowable working pressure, kPa
OD	outer diameter, m
RV	relief valve

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

3D printing is a type of additive manufacturing that is the process of creating and constructing a three-dimensional part by solidifying and building the material layer by layer. The common 3D printers only focus on printing thermoplastics due to its ease of materials handling and manufacturing. Thermoplastics are plastic polymers that can melt when it is heated to a certain temperature and solidified when it is cooled. The type of thermoplastics that are commonly used for 3D printing are ABS, PLA, PETG, and TPU. Different 3D printing materials provide different mechanical properties of the 3D printed parts.

Polylactic acid, PLA is the easiest 3D printing material for Fused Deposition Modeling (FDM) printer. PLA is rigid and strong but brittle. It has low heat and chemical resistance. PLA is also a biodegradable and odorless material. PLA parts are typically utilized for concept models and prototypes that do not require high strength 3D printed parts, whereas Acrylonitrile Butadiene Styrene (ABS) is a tougher and more durable material. It provides higher heat and impact resistance compared to PLA. The main application of ABS is functional parts that require better mechanical properties. Thermoplastic polyurethane (TPU) is a highly flexible and stretchable material. It also has extremely high impact resistance compared to other 3D printing material. The flexibility of TPU printed parts can vary by changing its infill density. The main application of TPU material is parts that require high flexible properties.

Many existing 3D printers only can print one material at a time back then. Single material printing has limited the application of printed parts because of the weakness of material's mechanical properties. Multi material printing can solve these problems by combining different materials in one printing process. Printing composite material can eliminate the weakness of the material and improve the overall mechanical properties. Composite material printing also can benefit parts with specific purposes. For example, printing TPU at the shell provides high impact resistance and printing ABS at the infill can increase the strength of the parts. Combining these two materials can increase the strength of the parts and reducing the chances of breaking it due to its low impact resistance.

1.2 Importance of the Study

Multi material 3D printing can achieve optimal mechanical properties such as impact resistance, tensile strength and flexural strength. In this study, there are few combinations of different material that can compensate the weakness of other material and increase the overall strength of the multi material 3D printed parts.

1.3 Problem Statement

3D printed parts are not widely used in industry mainly due to its weak mechanical properties of thermoplastics. Most of the thermoplastic's mechanical properties do not have enough strength, impact resistant or flexural modulus. Multi material printing can solve this problem by improving the mechanical properties and eliminating the weakness of thermoplastics. Composite material printing can improve the overall mechanical properties of 3D printed parts.

3D printed parts have many advantages such as flexible design, rapid prototyping, lightweight, minimum waste and cost effectiveness. But there is also a drawback of 3D printing that limits the application of 3D printed parts. The main disadvantage of 3d printing is the limited choice of materials. Most 3D printers are only capable of printing thermoplastics. Thermoplastics is a polymer plastics material with weak mechanical properties. The polymer chain is held by intermolecular forces which can be break by external forces. Mechanical properties of thermoplastics also may change drastically when the temperature changes.

Lastly, not all thermoplastics have good adhesion with other thermoplastics. This would also be the problem during composite material 3D printing. 3D printed parts with bad adhesion problems will cause the object to lose its mechanical properties. Adhesion problems would also increase the printing difficulties. Hence, the adhesion problem needs to be solved to further increase the mechanical properties for composite material printing.

1.4 Aim and Objectives

This study aims to investigate the mechanical properties changes for multi-material composite 3D Printing. The two objective of the project is:

1. Characterize the mechanical properties changes for multi material composite 3D printing (ASA/TPU/PETG/ABS/PC/PP)
2. Determine the best combination of the composite material which provides superior mechanical properties in term of flexural, tensile strength and impact resistance.
3. Develop the simulation model to predict the mechanical performance of the composite material.

1.5 Scope and Limitation of the Study

The scope of this study is to determine the best combination of composite material which provides superior mechanical properties in term of tensile, elongation and impact resistance. The design of contact surface of two composite material and the material adhesion must be studied. The simulation must be conducted to determine the best combination of composite material.

The limitation of the study is the printing parameter for the testing parts. All the testing parts must print with 100 percent infill. The layer height must be 0.2mm and the tensile pulling direction should be aligned with the layer. The condition of the filament should be maintained in perfect condition to avoid mechanical properties change due to moisture.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The chapter include the study of 3d printing technology in Section 2.2. The mechanical properties of multi material 3D printed parts is studied in Section 2.3. Next, the standard test method for mechanical properties test 3D printed parts is justified in Section 2.4.

2.2 3D Printing

3D printing can create physical objects from a geometrical representation by successive addition of material (Shahrubudin, Lee and Ramlan, 2019).3D printing consider as additive manufacturing (AM) method which build a 3 dimensions structure by solidifying material layer by layer with the help of computer numerical control. 3D printing or additive manufacturing has huge differences with the traditional ways of manufacturing which is removing the excess material from raw material.

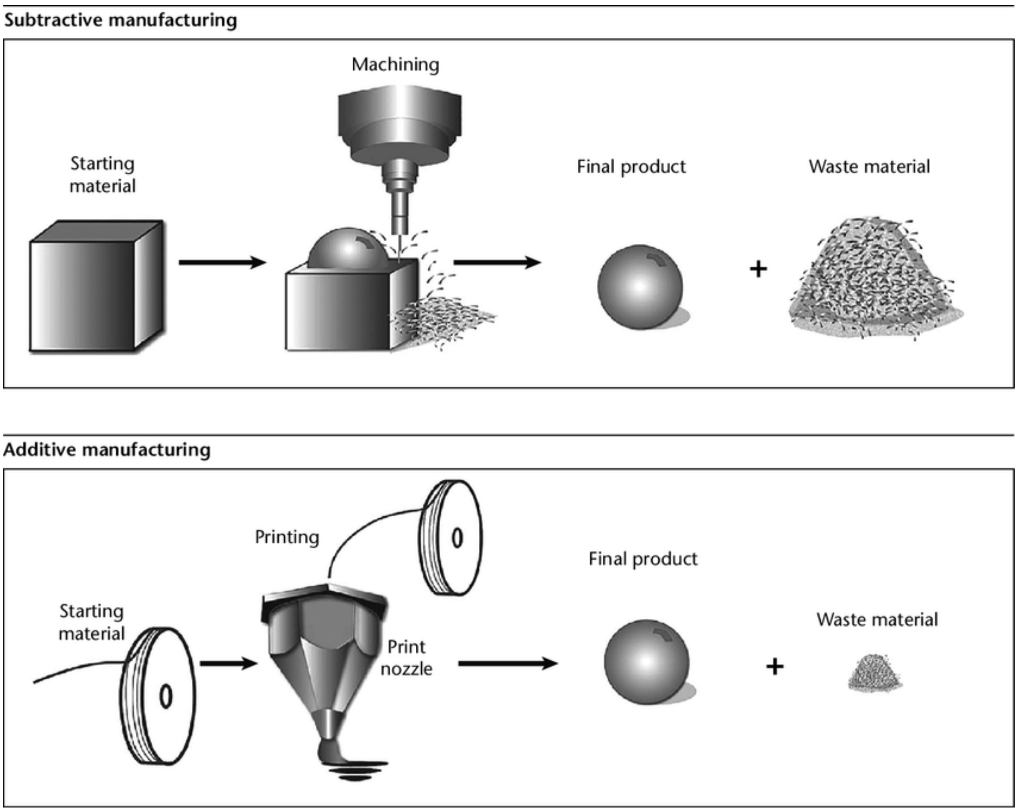


Figure 2-1: Differences between additive manufacturing and subtractive manufacturing (Levesque *et al.*, 2020)

As the 3D printing technology has been more and more advance, the cost of 3D printing has reduced significantly easy to operate and it became common and available in the market. The user base, composed of individuals and businesses operating in dozens of industries, has significantly increased in recent years (Brandon Miller, 2022). Therefore, 3D printing technology has become mainstream manufacturing technology in industrial revolution 4.0.

3D printing technology has many advantages and disadvantages. The advantages of 3D printing compared to traditional was of manufacturing are:

- 3D printing allows rapid prototyping where it has flexibility for object fabrication.
- 3D printing produces significantly less waste compared to subtractive manufacturing.
- The starting cost for parts fabrication is less because it uses less tools than subtractive manufacturing.

However, 3D printing technology also has disadvantages and limitations. The disadvantages of 3d printing technology are:

- The consistency of 3D printed parts are still the main problems for 3D printing. The quality of parts such as surface finishing, mechanical properties and dimensions is not always consistent and have high accuracy.
- There are still many materials that cannot be fabricated by using 3D printing technology such as stainless steel, cloth and others.

2.2.1 Types of 3D printing technology

There are several types of 3D printing technologies that provide different functions and have relative advantages and disadvantages. According to ASTM Standard F2792, ASTM catalogued 3D printing technologies into seven groups, including the binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization (Shahrubudin, Lee and Ramlan, 2019). Each 3D printing technology has strengths and weaknesses, and the users can choose based on requirement and parts expectation. The main example of 3D printing type is Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Digital Light Process (DLP), Multi Jet Fusion (MJF), PolyJet, Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM).

2.2.1.1 Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) will be the main 3D printing technology used in this report. FDM is considered as the material-extrusion based 3D printing technology. FDM is also known as Fused Filament Fabrication (FFF) has been patented by Stratasys.

FDM has 3 different variants of 3D printing process which are hot extrusion of rod, cold extrusion of slurries and hot extrusion of pallets. Hot extrusion of rod is pushing in the rod feedstock to hot end by using piston or roller. Slurries cold extrusion is feeding clay or paste in slurry form. The feedstock is normally pushed to the hot end by piston. Pallets hot extrusion is extruding the feedstock material in form of pallets. The material of feedstock is thermoplastics, but it is in the form of small granules. The feedstock is pushed by using rotating screw which is similar to injection molding.

FDM 3D printing works by heating the thermoplastics filament to it melting point and let the material achieve semi-liquid state. The extruder will extrude the material and construct the shape on the printing bed. A wide variety of thermoplastics filament materials to can be print by FDM 3D printer such as polylactic acid (PLA), polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU), nylon, Poly Cyclohexylenedimethylene Terephthalate glycol (PCTG), Polypropylene (PP) and Polybutylene Terephthalate (PBT).

Other than printing one material, some FDM printers are capable to print multi-material. There are different designs of 3D printers to print multi material. The first design of multi material 3D printer is single nozzle design. In order to extrude multi material in a single nozzle, different types of materials are combined in the single nozzle before or during the melting phase in the print head. One of the ways to combine multiple materials can be melt and mix into one single mixed material filament. The other way to print multi material with single nozzle is install an additional filament selector on the 3D printer. The filament selector uses Bowden extrusion system with a filament cutter and selector to automatically load different materials into the nozzle. There is a significant drawback of this concept where there will be many impurities in the 3D printed parts. The printer might have to print a tower at the side to clear out all the impurities after changing material. To prevent material wasting, some developers program the printer to wipe all the impurities into infill. Pursa3d has released a multi material upgrade with this concept.

Figure 2-2: Original Prusa i3 MMU2S upgrade kit

The other type of FDM 3D printer that is capable to print multi material is multi nozzle 3D printer. There are 2 types of multi nozzle 3D printers which are multiple nozzles are mounted on the same print head and printer with multiple print head. The multi nozzle printer works by changing different print head to change to different material during printing.

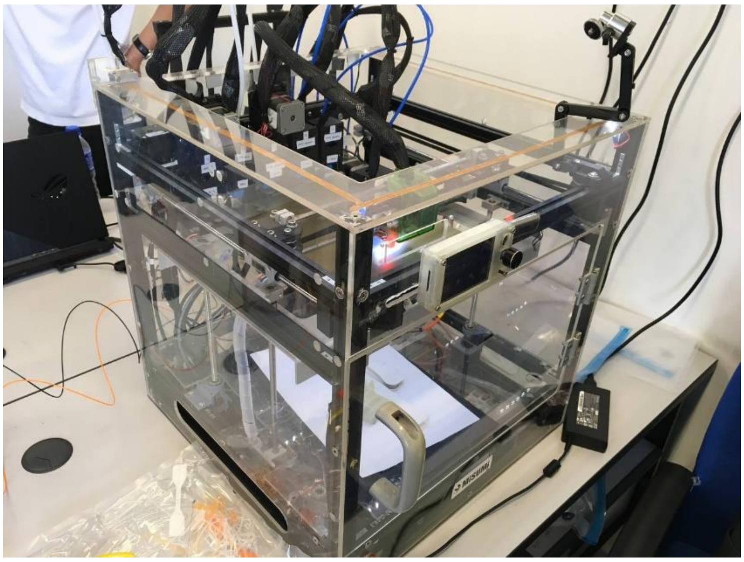


Figure 2-3: Multitool printer at UTAR

2.2.2 Stereolithography

Stereolithography (SL) is an additive manufacturing that works by using UV laser to solidify the photopolymer resin. Ultraviolet light can solidify photopolymers resin in short amount of time and form a layer of 3D object with desired shape. The 3D object is completed after the Ultraviolet light solidifies the photopolymers resin layer by layer. There are some post processing processes that need to be done to remove excessive photopolymer resin on the 3D printed object.

Stereolithography technology can be applied to multi material 3D printing. The SL multi material printing works by using multiple reservoirs that contain different types of photopolymers resins. The mechanical properties of different photopolymer resins might be varied significantly, they are typically more brittle and have lower heat distortion temperature. There are also many engineering grade photopolymers resins such as pp-like resin and ABS-like resin. These photopolymer resins can be used to compare the mechanical properties of multi material 3D printing object with multi material FDM 3D printed parts.

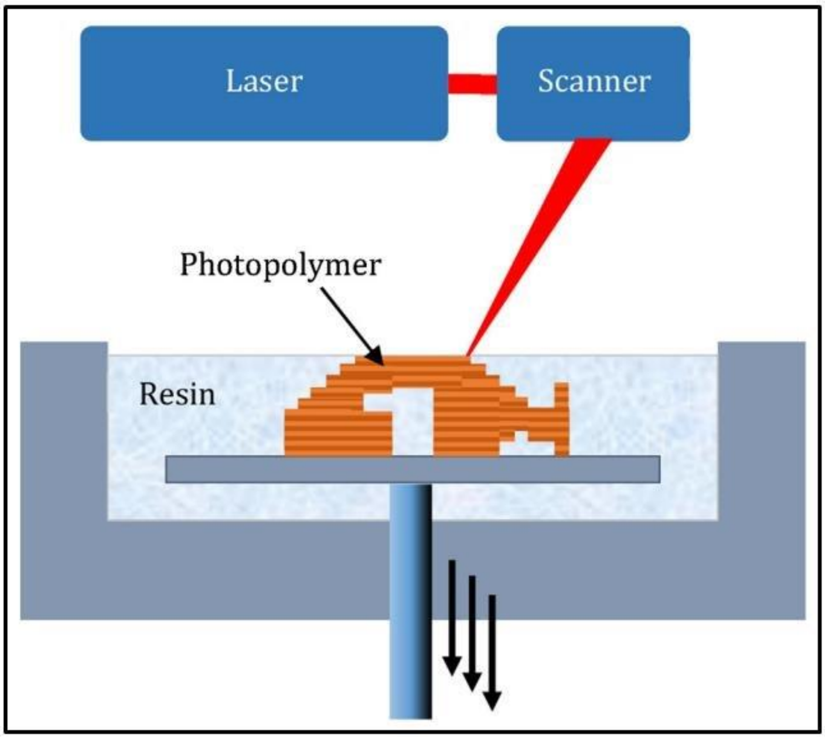


Figure 2-4: Schematic diagram of stereolithography (SL) technology (Stansbury, 2016)

2.2.3 Material Jetting

Material jetting is known as inkjet 3D printing. Material jetting works by extruding small droplets of photopolymer resins such as ink onto the build surface. The ultraviolet light will quickly solidify the ink and create a desired 3D printed object.

Material jetting technology also can be used to print multi material parts. In order to print multi material using this technology, the print head of the 3D printer has multiple nozzles. Different material can be extruded through different nozzles onto the print bed. The ultraviolet (UV) light can cure the droplets of the resins and convert it into solid form. The UV light source can be mounted on the print head to cure the resin immediately after extruding onto the print bed. The material that can be printed using material jetting technology is similar to stereolithography (SL). Hence, the material properties of both 3D printed parts should be similar.

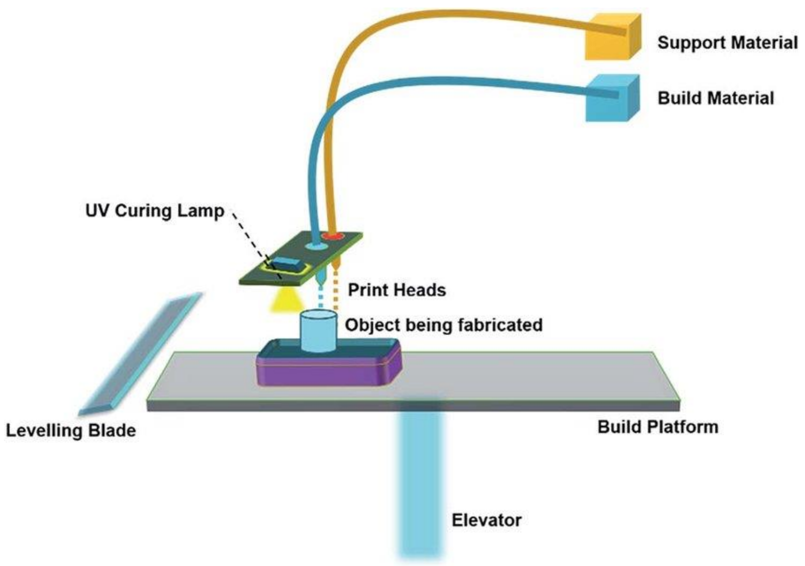


Figure 2-5: Schematic diagram of material jetting technology (Sireesha, 2018)

2.3 Mechanical Properties of Multi Material 3D Printing Parts

The multi material 3D printing that will discuss in this chapter is extrusion based which is FDM 3D printing. There are many factors that can affect the mechanical properties of the multi material 3D printed object. Firstly, there will be boundary interface occurred when the extrusion print head change every time. Boundary interface is formed between different materials of the printed parts at boundary of object that printing process is discontinuous (Lopes, Silva and Carneiro, 2018) . Therefore, the boundary interface will affect the mechanical performance of multi material 3D printing parts. The design of the 3D printed part shall consider this issue to overcome the boundary interface between different material.

Another problem that might affect the mechanical properties of multi material 3D printing is the chemical bonding or the material adhesion issue. Some material combinations are chemical incompatible or low adhesion between different materials. If the adhesion between layers or different material is not perfect, the mechanical properties performance might drop significantly due to layer delamination. Adding adhesive agent might solve this issue but the adhesive agent also will cause some different in the mechanical properties of the 3D printed parts. Lastly, different material having different thermal expansion coefficient. The shrinkage of 3D printed parts will be different if the 3D printed parts having different material. Therefore, this issue might cause the adhesion issue between different material that affect the mechanical properties of multi material 3D printing parts.

According to the Lopes, Silva and Carneiro (2018), the mechanical properties of multi material 3D printing is obtained in the article. The article used the combination of PLA, TPU, and PET as the material for 3D printing. The standard of test method is according to DIN 53504-S2a. The tensile properties such as Young’s Modulus and tensile strength of the specimen is obtained through the experiment. The material combination of the test specimen is show in the Figure 2-6, Figure 2-7 and Figure 2-9 below:

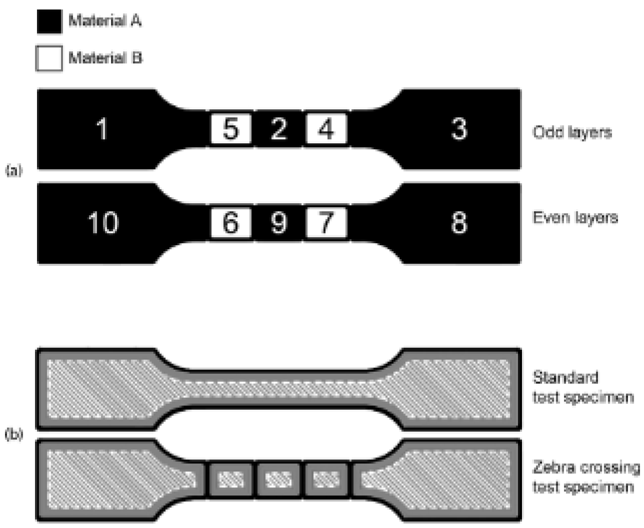


Figure 2-6: Material orientation of the test specimen (Lopes, Silva and Carneiro, 2018)

The Young modulus and the tensile strength obtained from the experiment are also show in the figure below.

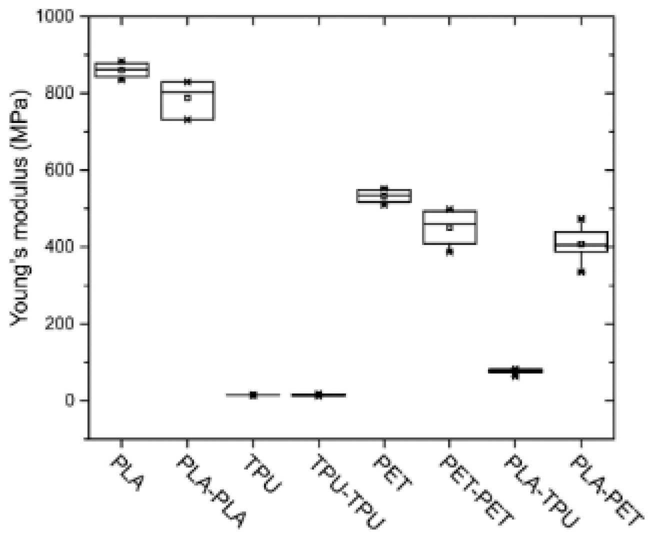


Figure 2-7: Young modulus of test specimen (Lopes, Silva and Carneiro, 2018)

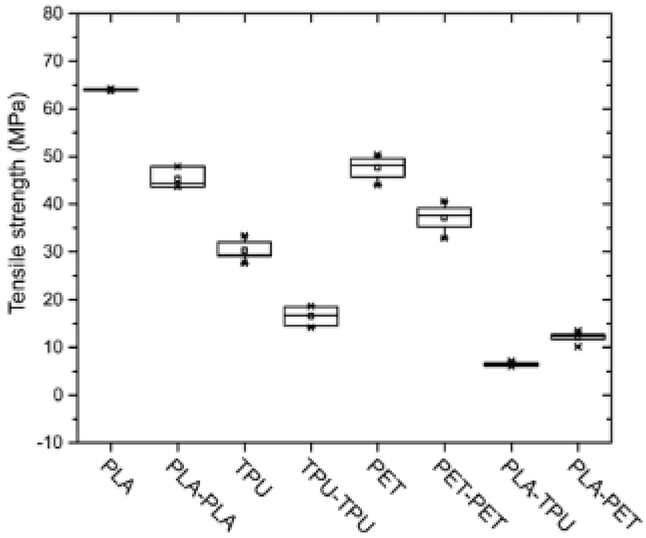


Figure 2-8: Tensile strength of test specimen (Lopes, Silva and Carneiro, 2018)

Table 2-1: Tensile properties of test specimen(Lopes, Silva and Carneiro, 2018)

Specimen type	Material	E (MPa)		σ(Mpa)	
		Average	StfDev	Average	StdDev
A	PLA	860.2	21.9	64.0	0.2
	TPU	14.4	0.5	30.3	2.4
	PET	523.1	19.4	47.7	2.7
B	PLA-PLA	787.6	51.0	45.3	2.3
	TPU-TPU	14.9	2.6	16.6	2.3
	PET-PET	450.2	52.4	37.2	3.2
C	PLA-TPU	76.9	6.6	6.5	0.4
	PLA-PET	407.1	47.3	12.2	1.1

Specimen type A is the test specimen printed with 1 material with the same extruder print head. Specimen type B is the test specimen printed with 1 material with two different extruder print heads. Specimen type C is the test specimen printed with two different materials by using 2 different extruder print heads.

Type A specimens can demonstrate the expected mechanical properties of each material, where PLA and PET exhibit high tensile strength and Young's Modulus, while TPU has a lower tensile strength and Young's Modulus.

By comparing type A and type B specimens, the effect of the boundary interface can be observed. Both tensile strength and Young's Modulus of the type B specimen have decreased. The TPU type B specimen has a similar Young's Modulus but lower tensile strength, as the tensile strength is more influenced by the material than the design. However, the Young's Modulus is more influenced by the material than the design.

Comparison of type B and type C specimen can show the chemical affinity of the material. For the type C PLA-TPU specimen, it has lower Young's Modulus compared to Type B PLA but higher than Type B TPU specimen. The tensile strength is lower than type B TPU specimen and type B PLA specimen. This result show that the affinity of both materials is slightly weak.

For PLA-PET type C specimen, the Young's Modulus is slightly lower than type B PET specimen. But the specimen is significantly weaker in tensile strength where the tensile strength is lower than type A and type B PLA specimen. The result shows that both materials are not chemical compatible.

2.4 Mechanical Properties Test of 3D Printed Material

2.4.1 Test Method for Tensile Properties of Plastics Material

The standard of testing for tensile properties is ASTM D3039M - 14. This test method can use to determine the tensile strength of polymer composite material. The composite material that can be tested using this method is limited to discontinuous fiber composites and continuous fiber. The test specimen uses for this test is stated in the Table 2-2 below:

Table 2-2: Tensile test specimen dimension

Fiber orientation	Width (mm)	Length (mm)	Thickness (mm)	Tab length (mm)	Tab thickness (mm)	Tab angle (mm)
0°	15	250	1	56	1.5	7 or 90
90°	25	175	2	25	1.5	90
Symmetric	25	250	2.5	-	-	-
Random	25	250	2.5	-	-	-

Select the correct width and thickness dimension for the test specimen to make sure that the failure happens in the gage section. The number of fibers in the test specimen's cross section also must be sufficient to represent the mechanical properties of bulk material. The length of the specimen should be longer than the requirement to reduce the bending stress from the grip. The gage section should be as far as possible from the grip to obtain a more accurate test result. The recommendation dimensions of test specimen are stated in Table 2-2. These dimensions are obtained after undergoing many testing laboratories to get acceptable failure mode with different materials.

There are many materials such as fabric material, sheet molding compound and multidirectional laminates that can be tested successfully without tabs. Nevertheless, adding tabs to specimens are highly recommended especially when testing unidirectional materials. Tabs can ensure that the failure to happen in fiber direction. Another main reason to add tab is to ensure that the failure does not happen in the gripping area. The recommended dimension of tab is shown in Table 2-2. The tab material that is recommended to use for this test is fiber-reinforced polymer matrix materials. The material of tab must have higher strength compared to the test specimen. There is also a simple equation to calculate the minimum bonded tab length. The tab length should be increased to reduce the chance of failure happening in gripping area. The equation is stated below:

$$L_{min} = F^t h / 2F^{su} \tag{2.1}$$

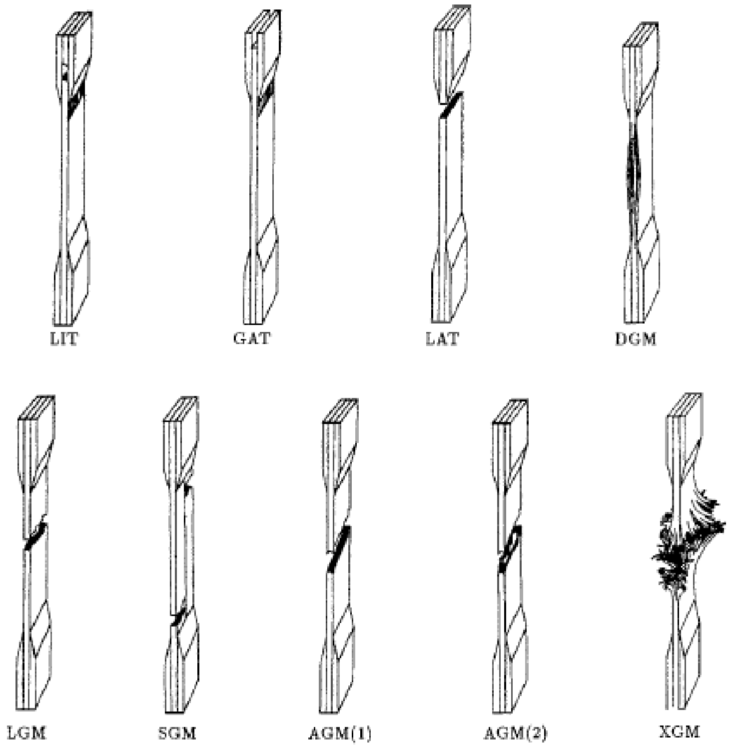
L_{min} = minimum length of bonded tab, mm

F^t = ultimate tensile strength of specimen material. MPa

h = specimen thickness, mm

F^s = ultimate shear strength of specimen material or tab material (whichever is lower), MPa

The procedure of testing starts with placing the specimen into the grips of the tensile test machine. Tighten the grip properly. Record the grip pressure if it is used on a controllable pressure grip such as hydraulic and pneumatic grips. The speed of testing should be set to a constant strain rate occur in gage section. The strain rate used should obtain failure within 1 to 10 minutes. A standard displacement of pulling should be 2 mm per minute. After the failure happens, collect the force vs displacement or force vs strain data. The failure mode of the specimens should be recorded for analyzing purpose.



First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xys)
long. Splitting	S
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

Figure 2-9: Failure code of tensile test (ASTM D3039 M -14)

2.4.2 Test Method for Flexural Strength of Plastics Material

The standard of flexural test method of plastics materials is ASTM D790 – 10. This test method can determine the flexural properties of plastics. Both rigid and semirigid materials can be used for this test. The material that cannot be break at the outer layer within 5 percent strain limit of test methods. This test method uses 3-point loading system apply to the specimen. The loading support and loading nose should have cylindrical shape. The radius of the cylinder should be 5 mm.

The specimen dimension is 127mm in length, 12.7mm in width and 3.2mm in depth. The length of the specimen shall be 10 percent longer than the support span and at least 6.4mm longer at each end of the support. The main purpose of overhanging is to prevent the test specimen to slip during the test.

The procedure of the test start with ensure the width and depth of the test specimen nearest to 0.03 mm. Place the test specimen on to the support to the nearest 0.1 mm when the span is lesser than 63mm and to 0.3mm if the spans is larger or equal 63 mm. The crosshead motion speed can be calculated with the simple equation given below:

$$R = ZL^2 / 6d \tag{2.2}$$

$R = rate\ of\ crosshead\ motion\ speed, mm/min$

$L = support\ span, mm$

$d = depth\ of\ beam, mm$

$Z = rate\ of\ straining\ of\ outer\ fiber, mm/mm/min$

Make sure that the cylindrical surfaces of supports and loading nose are parallel. The loading nose should be at the centre of both supports. The load is applied with the calculated crosshead rate. Record the load deflection data. Plot the load deflection curve to obtain flexural strength of the test specimen. The test should be stop when the maximum strain reaches 0.05 mm/mm in the outer layer of the specimen or the specimen break before reaching maximum strain. The deflection is calculated with the equation:

$$D = rL^2 / 6d \tag{2.3}$$

$D = midspan\ deflection, mm$

$r = strain, mm/mm$

$L = support\ span, mm$

$d = depth\ of\ beam, mm$

Flexural stress is the elasticity of a material is tested as a beam loaded at midpoint of two supports point. The maximum stress applied is located at the midpoint of the test specimen. The stress at any point of the load deflection curve can be calculated with the equation below:

$$\sigma_f = 3PL/2bd^2 \tag{2.4}$$

$\sigma = stress\ in\ outer\ fibre\ at\ midpoint, Mpa$

$P = load\ in\ rhe\ load\ deflection\ curve, N$

$L = support\ span, mm$

$b = width\ of\ specimen, mm$

$d = depth\ of\ specimen, mm$

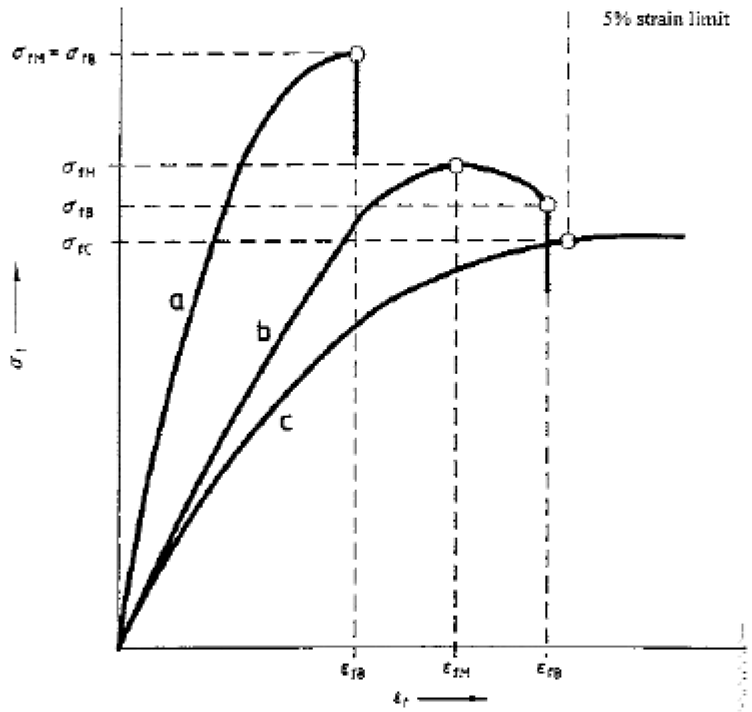
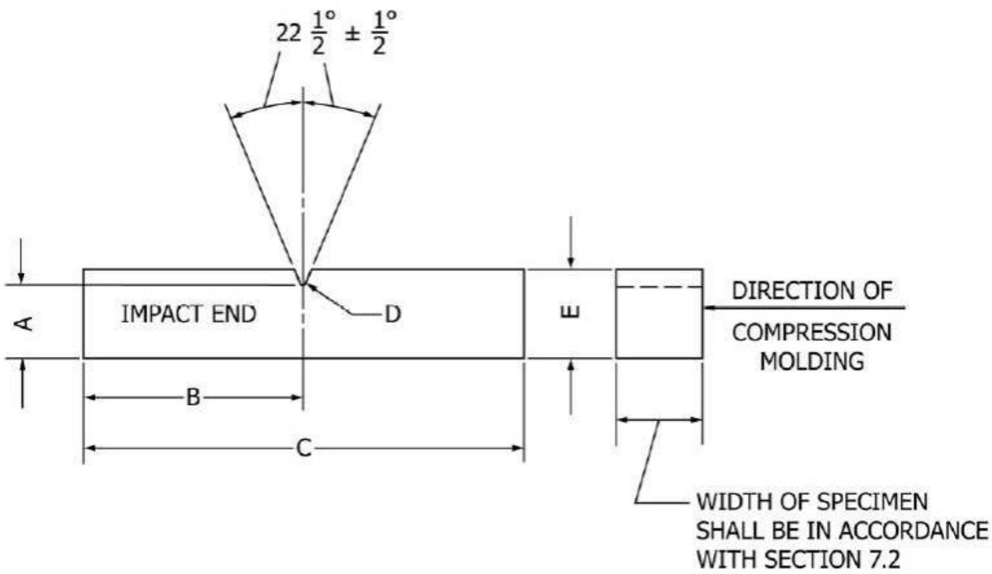


Figure 2-10: Flexural stress Vs strain graph (ASTM D790 – 10)

The graph presented above illustrates various curves representing the flexural test results. Curve A indicates that the test specimen fractures before reaching the yield point. Curve B shows that the specimen fractures after reaching the yield point but before reaching the 5 percent strain limit. On the other hand, curve C indicates that the specimen does not fracture even after reaching the 5 percent strain limit.

2.4.3 Test Method Impact Resistance of Plastics Material

The standard for this test methods to determine impact resistance of plastics material is ASTM D256 – 10. This testing method can determine the impact resistance of plastics material with a Izod pendulum hammer. The impact resistance of the test specimen can be determined by the amount of energy needed to break the test specimen in 1 pendulum swing. The standard test specimen needs to have a milled notch. The notch can focus the stress concentration that can increase chance of brittle fracture, reduce the chance to get ductile facture. The notch of the test specimen can reduce the plastic deformation and let the facture happen behind the notch.



	mm	in.
A	10.16 ± 0.05	0.400 ± 0.002
B	31.8 ± 1.0	1.25 ± 0.04
C	63.5 ± 2.0	2.50 ± 0.08
D	0.25R ± 0.05	0.010R ± 0.002
E	12.70 ± 0.20	0.500 ± 0.008

Figure 2-11: Dimension of Izod Impact Test Specimen (ASTM D256 – 10, 2015)

The dimension of the test specimen shall follow the dimension show in Figure 2-7. The width of specimen should be within 3.0 mm and 12.7 mm. if the specimen is lesser than 12.7 mm, the notch should be at the shorter side. The angle of the notch should be 45° and have a depth of 2.54 mm. The length of the test specimen is 63.5 mm, and the notch is located at the midpoint of the length.

There are 4 similar test methods that are presented in the test methods. For the test method A, the test specimen is placed as a vertical beam between two vise jaw. The test specimen is broken with one pendulum swing. The contact surface of the pendulum and specimen is always on the notch surface and the specimen is clamped at the centreline of the notch. For test method C, it has similar setup as the test method A. Test method C has an additional step to obtain the expanded energy to toss portion of test specimen. Test method C is suitable for the material that have Izod impact resistance that are lesser than 27 J/m. Test method D can test the sensitivity of the test specimen's notch. The test method will decrease the notch radius to increase the stress concentration on the notch. The test method E has similar setup with test method A, the specimen also places vertically but its orientation is 180° reverse. This test method can test the impact resistance of unnotched specimen.

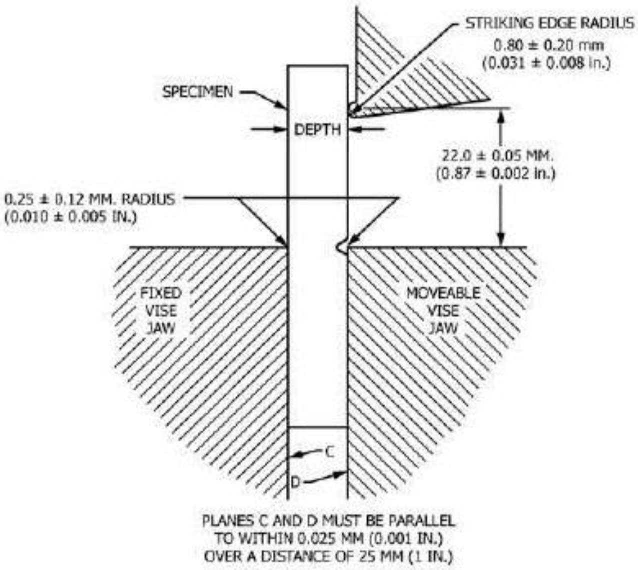


Figure 2-12: Izod Impact Resistance Test Method A and C (ASTM D256 – 10, 2015)

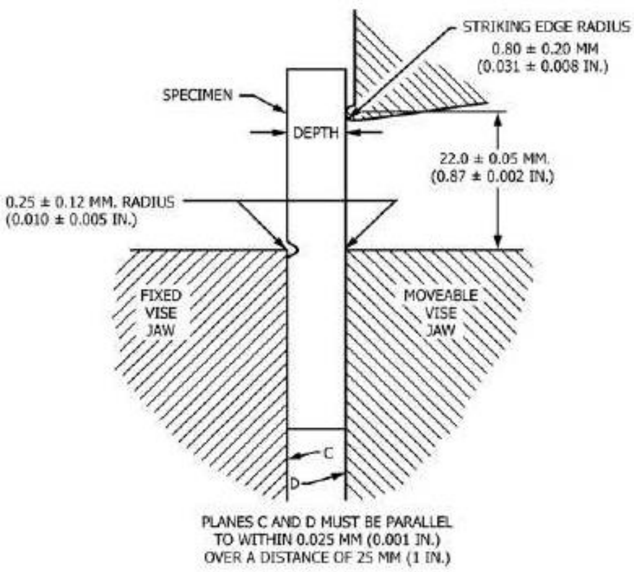


Figure 2-13: Izod Impact Resistance Test Method E (ASTM D256 – 10, 2015)

Prepare 5 to 10 specimen for each material that going to do the Izod Impact resistance test. The breaking energy of the test specimen shall be estimated to choose the suitable energy for the pendulum. Use the standard pendulum with lightest weight that expected to break test specimen with the lost less than 85 percent of the energy. Record the width of test specimen after breaking. The length of the remaining specimen under the notch should also be recorded.

2.5 Summary

The literature review has shown various type of 3D printing technology that can print multi material parts. The mechanical properties of multi material objects that has been found in other research are also shown in literature review. Lastly, the standard test method

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this chapter, the detailed methodology and work plan to investigate the mechanical properties for 3d printed parts and determine the mechanical properties changes for multi-material composite 3D Printing are listed and discussed.

3.2 3D print specimen for mechanical properties test

The main 3D printed materials for this research are PLA, PETG, TPU, ASA, PCTG and PETG-CF. All of the specimens are printed with the multitool 3D printer located at UTAR. The multitool 3D printer not only capable of printing single material specimen but it can also print multi material specimen but changing its print head whenever it is needed to print other material on the same piece of specimen. The print setting of all specimens is set as similar as possible to reduce the factors that might affect the experiment result. The print setting for all the specimens is shown in the Table 3-1, Table 3-2 and Table 3-3 below:

The dimension of test specimens are printed according to the ASTM standard. The drawings that show the dimension of test specimens are shown in the appendix below.

Table 3-1: 3D print setting for Izod Impact Test Specimens

Specimen material		PLA	PETG	ASA	TPU	PCTG	PETG-CF
Shell thickness (mm)	Vertical shell	1.26	1.26	1.26	1.26	1.26	1.26
	Horizontal shell	1.2-1.3	1.2-1.3	1.2-1.3	1.2-1.3	1.2-1.3	1.2-1.3
Infill	Infill pattern	Rectilinear	Rectilinear	Rectilinear	Rectilinear	Rectilinear	Rectilinear
	Infill density	100	100	100	100	100	100
	Infill angle	45	45	45	45	45	45
Layer height (mm)	First layer	0.3	0.3	0.3	0.3	0.3	0.3
	Subsequent layers	0.2	0.2	0.2	0.2	0.2	0.2
Temperature (°C)	Nozzle	222	235	235	230	235	235
	Bed	70	80	105	50	95	90
Print speed (mm/s)	First layer	20	20	20	20	20	20
	Infill	60	60	60	60	60	60
	Perimeters	60	60	60	60	60	60

Table 3-2: 3D print setting for Flexural Test Specimens

Specimen material		PLA	PETG	ASA	TPU	PCTG	PETG-CF
Shell thickness (mm)	Vertical shell	1.26	1.26	1.26	1.26	1.26	1.26
	Horizontal shell	1.2	1.2	1.2	1.2	1.2	1.2
Infill	Infill pattern	Rectilinear	Rectilinear	Rectilinear	Rectilinear	Rectilinear	Rectilinear
	Infill density	100	100	100	100	100	100
	Infill angle	45	45	45	45	45	45
Layer height (mm)	First layer	0.2	0.2	0.2	0.2	0.2	0.2
	Subsequent layers	0.2	0.2	0.2	0.2	0.2	0.2
Temperature (°C)	Nozzle	222	235	235	230	235	235
	Bed	70	80	105	50	95	90
Print speed (mm/s)	First layer	20	20	20	10	20	20
	Infill	60	60	60	30	60	60
	Perimeters	60	60	60	30	60	60

Table 3-3: 3D print setting for tensile test specimens

Specimen material		PLA	PETG	ASA	TPU	PCTG	PETG-CF
Shell thickness (mm)	Vertical shell	1.26	1.26	1.26	1.26	1.26	1.26
	Horizontal shell	1.2-1.3	1.2-1.3	1.2-1.3	1.2-1.3	1.2-1.3	1.2-1.3
Infill	Infill pattern	Rectilinear	Rectilinear	Rectilinear	Rectilinear	Rectilinear	Rectilinear
	Infill density	100	100	100	100	100	100
	Infill angle	45	45	45	45	45	45
Layer height (mm)	First layer	0.3	0.3	0.3	0.3	0.3	0.3
	Subsequent layers	0.2	0.2	0.2	0.2	0.2	0.2
Temperature (°C)	Nozzle	222	235	235	230	235	235
	Bed	70	80	105	50	95	90
Print speed (mm/s)	First layer	20	20	20	10	20	20
	Infill	60	60	60	30	60	60
	Perimeters	60	60	60	30	60	60

3.3 Mechanical properties experiment setup

3.3.1 ASTM D3039 M – 08 Test Method for Tensile Properties of Plastics

The machine that will be using for this test is Shimadzu universal testing machine. The tab is cut out using band saw into 55 mm in length, 25 mm width. The material of the tab is FR4 plate. Stick the tab and the material using superglue as adhesive agent. The upper and the lower clamp of the machine clamps tab. Set the displacement rate 5 mm / min and insert the gage length of the specimen into the Shimadzu software. Set the force and displacement to zero before starting the experiment. Stop the test after the failure happen. Obtain the final result in the Shimadzu software.

3.3.2 ASTM D790 – 10 Test Method for Flexural Properties of Plastics

This test method uses Shimadzu servo-hydraulic dynamic universal testing machine. Adjust the support of the machine to the distance of 51.2 mm between each other. Place the test specimen at the centre of both support and move down the loading nose until it touches the test specimen. The rate of crosshead speed should set at 1.365 mm /min and control the rate of strain at 0.01 mm/mm/min. Stop the test if the specimen is break or the specimen outer surface reached 0.05 mm/min. All the final result can be obtained from the software.

3.3.3 ASTM D256 – 10 Test Method for Izod Impact Resistance of Plastics

Setting up the Izod Impact test machine by calculate the friction and windage correction to reduce the effect of the Izod Impact resistance of the test specimen. The test method used in this experiment is test method A where the pendulum will hit the notch surface. The specimen is clamped where the centreline of the notch is parallel to the jaw. The pendulum shall break the test specimen with a single swing. Raise the hammer to 151°. Released and let the pendulum fall freely to break specimen. After breaking the specimen, hold the pendulum to avoid damaging the specimen again. Record the final reading and the calculate the impact resistance of the material.

3.4 MATLAB software

In order to validate the model of simulation in Ansys software, the data gotten from experiment are required to input into Ansys. However, datasets are often noisy or contain unwanted variations. Graph smoothening is the process of removing noise or other unwanted variations from a dataset, in order to produce a smoother, more accurate representation of the underlying trend or pattern.

In this report, there are 3 different sets of data for each material which are the stress-strain data from tensile and flexural test and the Izod impact test. There are always some noises in the experimental data due to vibration and the measuring equipment issues. So, it is critical to use data processing software to reduce the noise while remaining the graph trend for all the stress strain curve.

For this simulation, all the material data are defined by inserting experimental data. For thermoplastic material definition, multilinear isotropic hardening is used to define the stress and strain in the strain hardening zone. A negative slope of True Stress vs Plastic Strain curve is not permitted in a multilinear plasticity material model.

3.5 ANSYS software

ANSYS software can simulate and validate all the experiment data. Mechanical properties can be obtained by the simulation in Ansys software. To ensure that the simulation is similar to the experiment data that got from the standard test method above, it is very important to import data and create material model in the ANSYS software. In creating material model, the true stress and strain will be calculated with the equation. The elastic strain can also be calculated with the true stress.

After creating the material model in ANSYS software, analyse and validate all the experiment data that got from the standard test method. If all the data is valid proceed to simulate multi material specimen. The mechanical properties of multi material 3D printed specimen can obtained from ANSYS simulation. The optimal 2 set of material combination are chosen out to test with the standard test method.

3.5.1 Material model

After collecting all the experimental data for 3 test which are tensile test, flexural test and Izod impact test. The mechanical properties data of PLA, PETG, ASA, TPU, PCTG and PETG-CF are post processed and calculated the true stress and strain. For this simulation, multilinear isotropic hardening is used. Multilinear isotropic hardening requires plastic strain and stress. The true stress, strain and plastic strain is calculated with the formula below. The Young’s modulus and poison ratio are inserted in the material model. Lastly, ultimate tensile strength and yield strength are defined in material model.

$$\sigma_{true} = \sigma_{engineering} \times (1 + \varepsilon_{engineering}) \quad (3.1)$$

$$\varepsilon_{true} = \ln (1 + \varepsilon_{engineering}) \quad (3.2)$$

$$\varepsilon_{elastic} = \frac{\sigma_{true}}{E} \quad (3.3)$$

$$\varepsilon_{plastic} = \varepsilon_{total} - \varepsilon_{elastic} \quad (3.4)$$

$\sigma_{engineering} = Engineering\ stress, MPa$

$\varepsilon_{engineering} = Engineering\ strain, MPa$

$\sigma_{true} = True\ stress, Mpa$

$\varepsilon_{true} = True\ strain, \frac{mm}{mm}$

$E = Young's modulus, MPa$

$\varepsilon_{elastic} = Elastic\ strain$

$\varepsilon_{plastic} = Plastic\ stain$

$\varepsilon_{total} = Total\ strain$

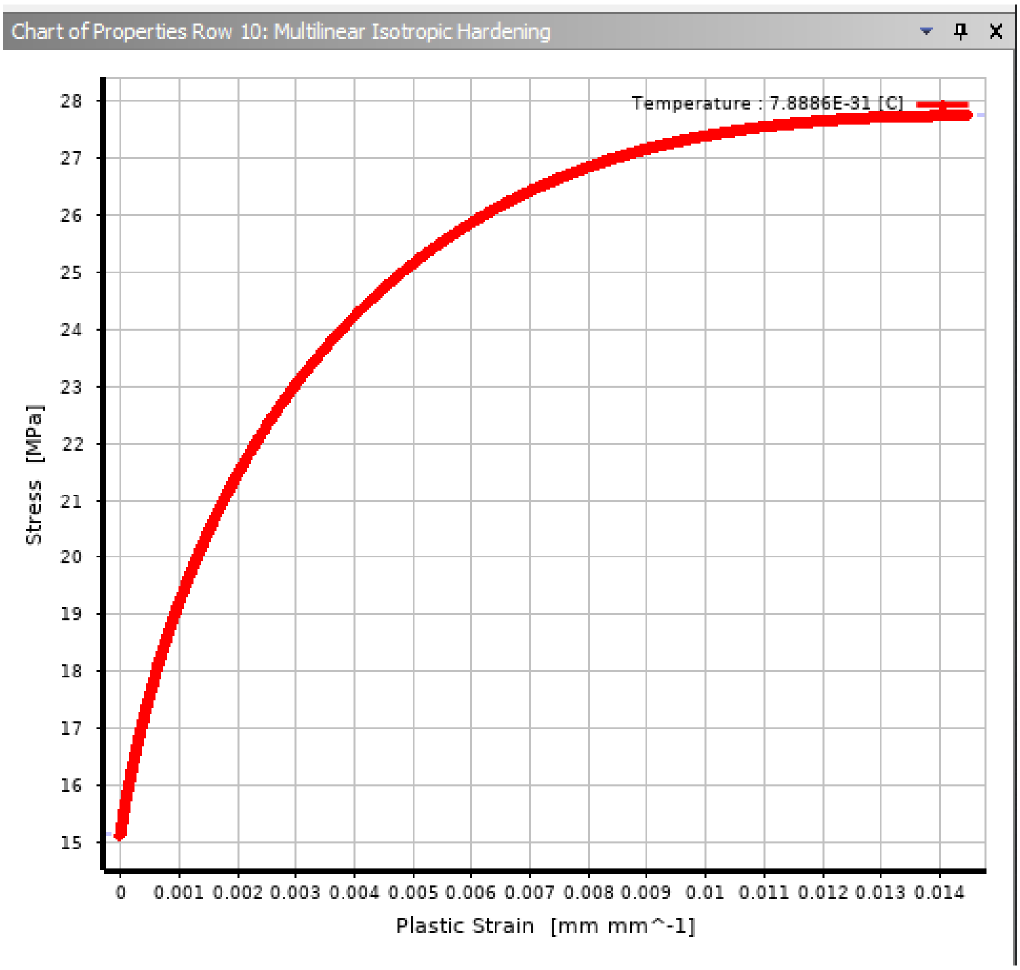


Figure 3-1: Multilinear isotropic hardening graph

Properties of Outline Row 4: PETG-CF

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	1340	kg m^-3		
4	Isotropic Elasticity				
5	Derive from	Young's Modulus and Poisson's...			
6	Young's Modulus	1235.8	MPa		
7	Poisson's Ratio	0.3			
8	Bulk Modulus	1.0298E+09	Pa		
9	Shear Modulus	4.7531E+08	Pa		
10	Multilinear Isotropic Hardening	Tabular			
11	Scale	1			
12	Offset	0	MPa		
13	Tensile Ultimate Strength	27.528	MPa		

Figure 3-2: Material model definition

3.5.2 Creation of Model Geometry

Figures below show that the specimens flexural test and tensile test model in Ansys mechanical. The models are created by SpaceClaim. The simulation setups are also shown below.

3.5.2.1 Flexural test

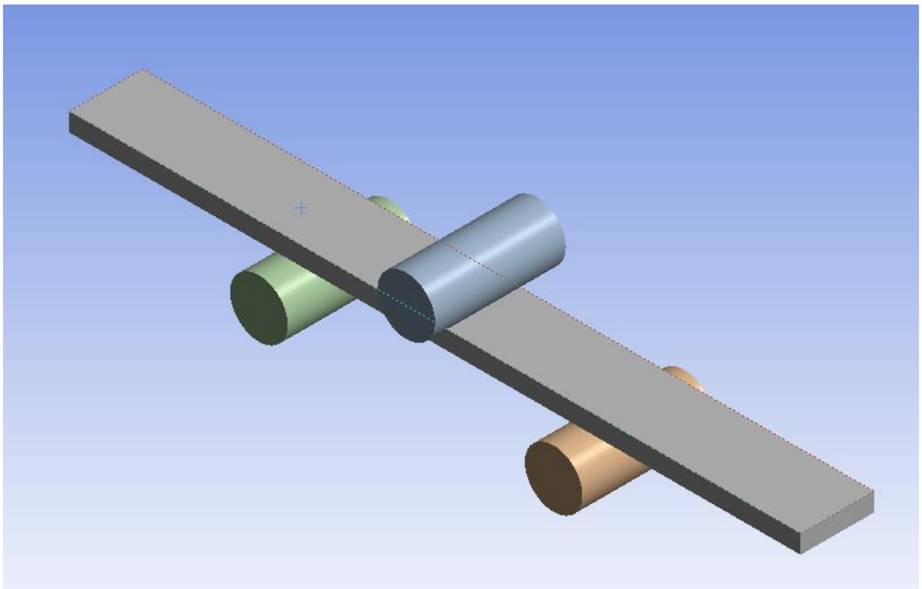


Figure 3-3: Flexural test in ANSYS simulations

The simulation flexural test specimen's dimensions are same with the experimental dimensions. The support also placed in the same positions as the experiment setup. The contact of the support and specimens are set as frictionless contact. The element size of the meshing of specimens are set at 0.002m

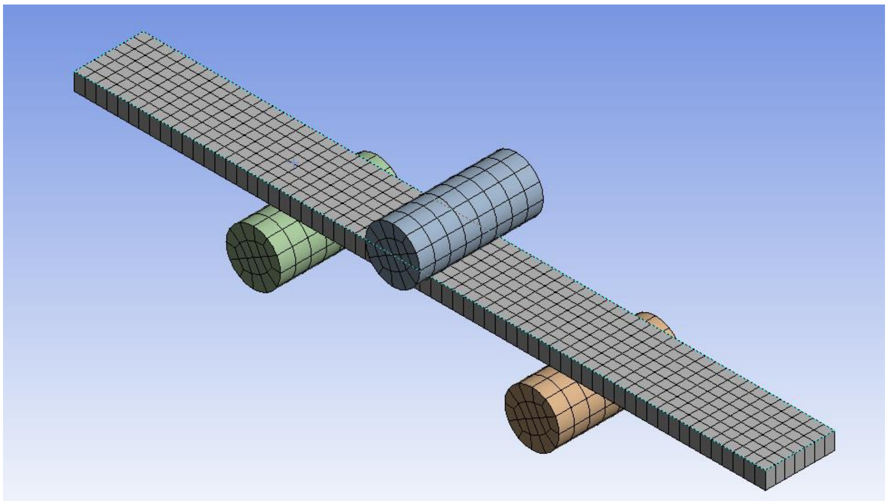


Figure 3-4: Meshing of the flexural test simulations specimens

Static structural system is chosen to simulate the flexural test. In this simulation the specimen is assigned to the material that is defined in the step earlier. All the support is assigned as structural steel.

The simulation is set with 100 sub steps to collect 100 data points. All the data points are used to plot the stress-strain graph. The displacement of the top head is set at 1.365 mm/min. The speed is set according to ASTM D790 standard. The top support is set to move 6.825 mm downwards. The displacement is set for the specimen to reach the strain in the outer surface of 0.05 mm/mm. Lastly, the equivalent total strain, equivalent stress and stress intensity are recorded as the simulation results.

3.5.2.2 Tensile test

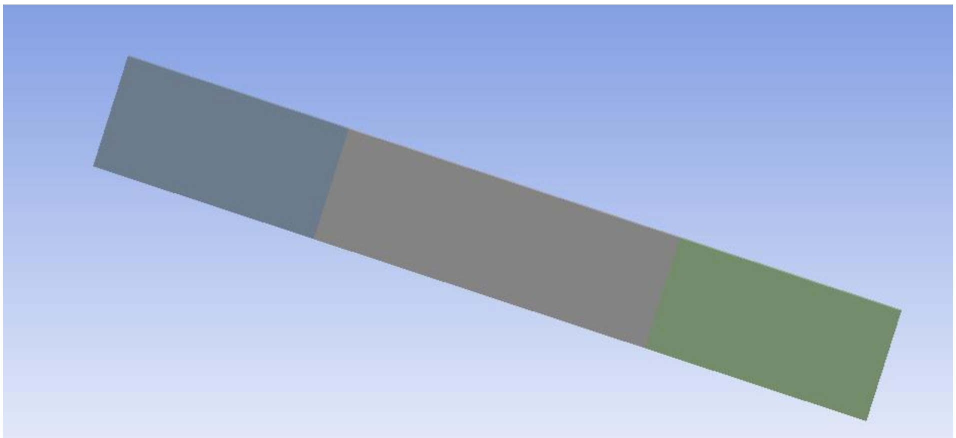


Figure 3-5: Tensile test in ANSYS simulation

Figure 3-5 above show the specimens for tensile test simulation. The dimensions of the specimens is same with the experiment. The specimen model is split into

3 sections which are the top and bottom clamp section and the middle area of interest.

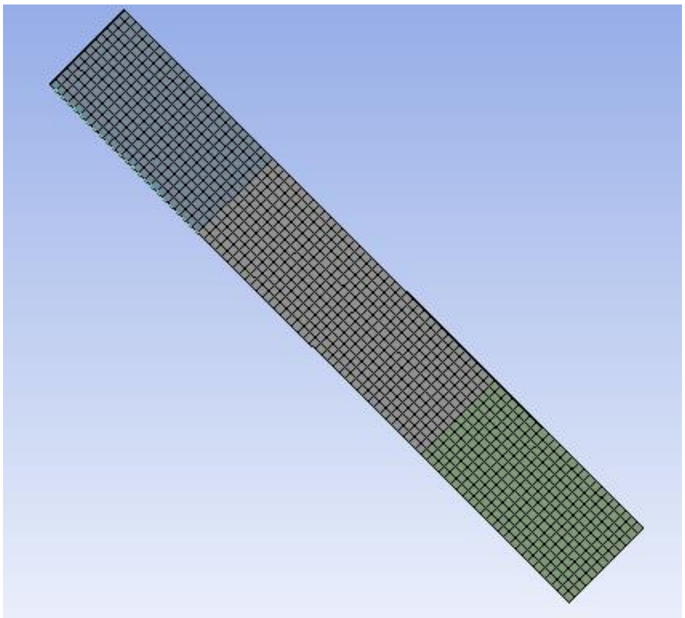


Figure 3-6: Meshing of tensile test specimen for simulation

Figure 3-6 above shows the meshing of the specimen’s model. The element meshing size is 0.002 mm.

Static structural system is chosen to simulate the tensile test. The bottom section of the specimen is set to be fixed support. The top section is set to have constant speed to 2mm/min. Lastly, the equivalent total strain, equivalent stress and maximum principal stress data are recorded.

3.6 Mechanical Interlocking Design for Multi Material Specimen

In this study, mechanical interlocking has been introduced as a solution to improve material bonding in multi-material 3D printing. Material adhesive problems have always caused issues to the mechanical properties of composite 3D printed parts, and if they fail due to material delamination problems, it can significantly affect the mechanical properties. Therefore, the use of mechanical interlocking is aimed at enhancing the bonding between the materials and improving the overall mechanical properties of the 3D printed parts. The idea behind this method is to design a mechanical interlocking structure between the different materials in the composite, such that the interlocking structure provides a strong mechanical bond between the materials. This method can be used to enhance the mechanical properties of the 3D printed part and make it more durable and reliable. The Figure 3-7 below shows the proposed mechanical interlocking design for composite material 3D printing.

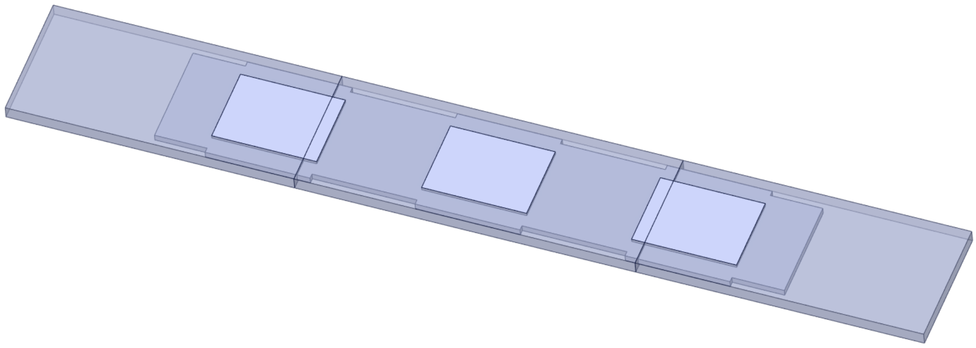


Figure 3-7: Mechanical interlocking design for composite material 3D printing

3.7 Summary

First, single material test specimens are 3D printed. The material that are going to do test such as PLA, PETG, ASA, TPU, PETG-CF and PCTG. Then, the specimen will undergo several tests such as tensile test, impact resistance test and flexural test to obtain the mechanical properties of each material. After that, insert all the mechanical properties data into ANSYS software. Validate the experiment data with ANSYS simulation. Simulate the multi material test specimen and obtain the mechanical properties of each combination in the ANSYS software. Lastly, 5 combinations of multi material 3D printed objects are chosen to undergo mechanical properties test in order to validate the ANSYS simulation result.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter show and analyse the simulation result and experimental results of mono material and multi material 3D printed specimens in term of tensile strength, flexural strength and impact resistance. Highlighting of key data, validating the simulation results and the experimental results, determination of the best combination of multi material 3D printing, and proving the simulation model are accurate can be found in this chapter. This chapter is divided into few main parts:

4.2 Experimental data of 3D printed Mono-Material Specimens

In this report, there are 3 main experiment to determine the mechanical properties of 3D printing material. The 3 experiments are ASTM D3039 Tensile Test, ASTM D790 Flexural Test and ASTM D256 Izod Impact test. All these experimental data will be used to define the material model in Ansys simulation in order to obtain accurate simulation data for multi-material specimen. Figure 4-1 show that the Ultimate tensile strength and the flexural strength of each material.

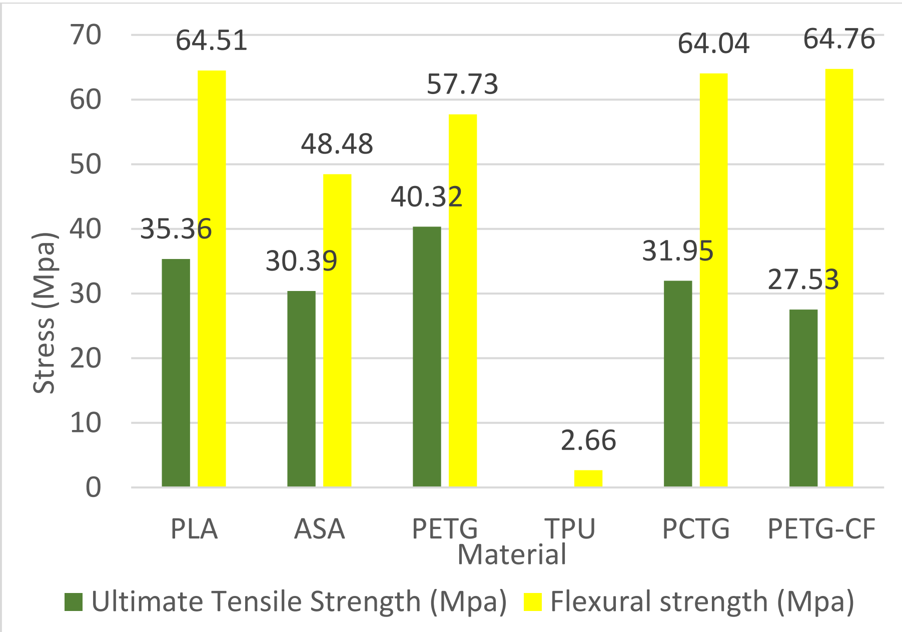


Figure 4-1: Experiment data of Mono-material specimen

Figure 4-1 indicate that PETG exhibits the highest ultimate tensile strength among the materials tested, albeit relatively lower flexural strength. In contrast, PLA and PCTG display lower ultimate tensile strength, but they possess the highest flexural strength. These results are indicative of differing mechanical properties of the materials under evaluation. Ultimate tensile strength refers to the maximum stress a material can withstand under tensile loading, while flexural strength represents the maximum stress a material can endure under bending. Higher ultimate tensile strength implies that the material can withstand greater tensile forces, whereas higher flexural strength indicates greater resistance to deformation, specifically bending.

The Figure 4-2 shown below provides a visual representation of the impact resistances of various materials. It can be observed that ASA and TPU display the highest impact resistance among the materials tested. This implies that these two materials can withstand high impact forces without fracturing or breaking. Having high impact resistance means that these materials can absorb energy from an impact, reducing the likelihood of fracture or damage. This is important for the durability and reliability of the components made from these materials, as they will be able to withstand high impact forces without failure.

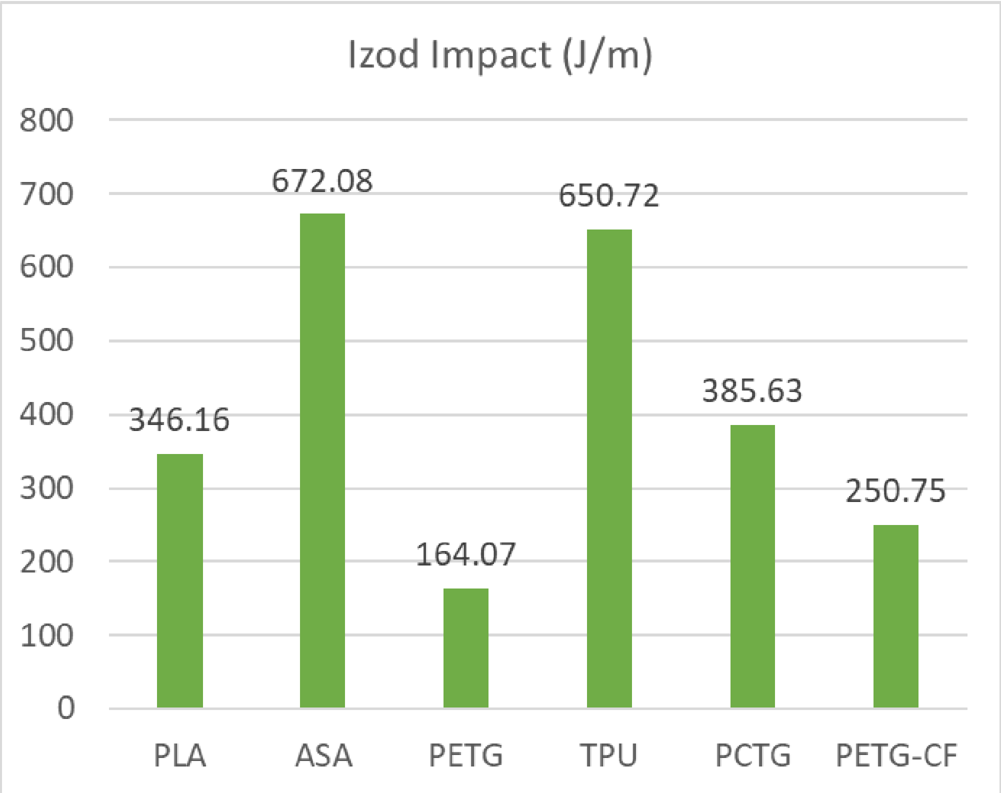


Figure 4-2: Impact resistance of mono material specimen

4.2.1 Stress-Strain curve of ASTM D3039 Tensile Test

Other than the ultimate tensile strength and flexural strength, the stress strain curve are also important to indicate the material behaviour. The stress strain curve can provide much information of the material such as young's modulus, yield strength, ultimate strength, strain hardening zone and necking zone. Engineering stress and strain, and the true stress and strain also can be calculated by using the data given from the experiment. Other than that, the stress-strain curve is also very important to validate the simulation data by comparing the curve pattern. The Figure 4-3 below will show the stress strain curve obtain from ASTM D3039 Tensile Test.

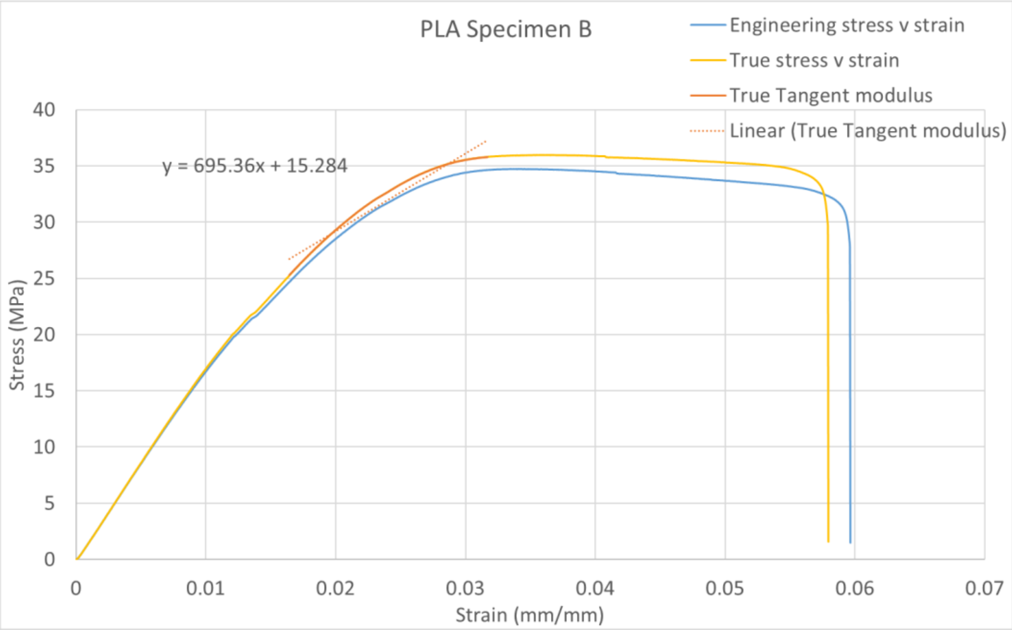


Figure 4-3: Stress strain curve of PLA specimen

4.3 Simulation Validation and Verification

All the experimental data will input into the simulation material model to simulation the Tensile and flexural test. Before simulation the multi material specimen, it is very important to ensure that the accuracy of simulation and experimental data. In this case, the simulation of single material is done, and the stress strain curve is obtained to compare with the experimental data. The comparison between experimental data and simulation data will show in the table and figure below. The simulation data are validated because the percentage error is relatively small, and the stress strain curves pattern are quite similar.

4.3.1 Tensile test

The models created in this study assume that the 3D printed specimens exhibit multi linear plastics behaviours. According to the Figure 4-3, the stress-strain curve obtain from the tensile test and simulation is similar. The percentage different of the tensile properties such as ultimate tensile strength and tensile modulus are relatively small. All the stress strain curve of other material will be shown in the appendix below.

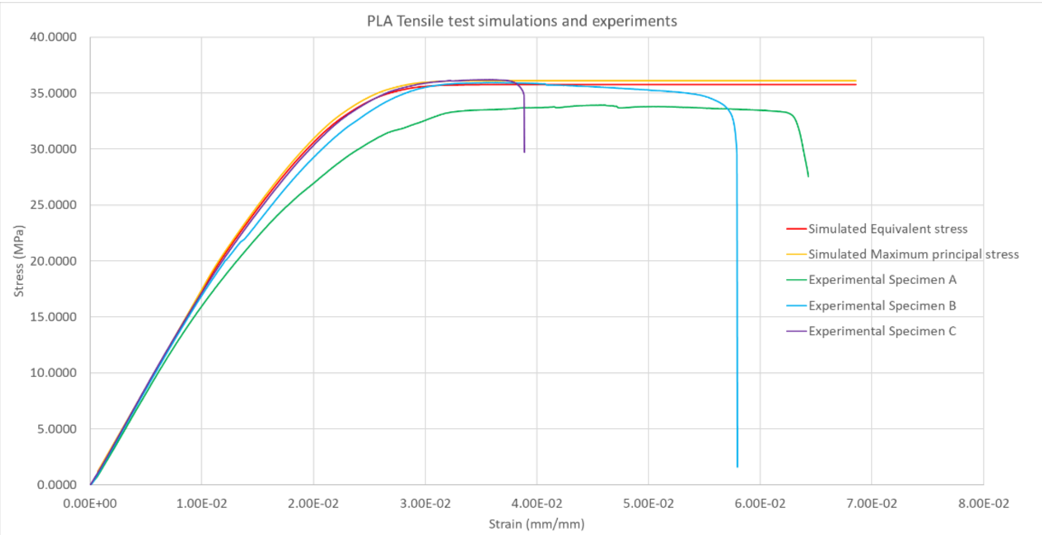


Figure 4-4: Tensile test simulation and experimental data for PLA specimens

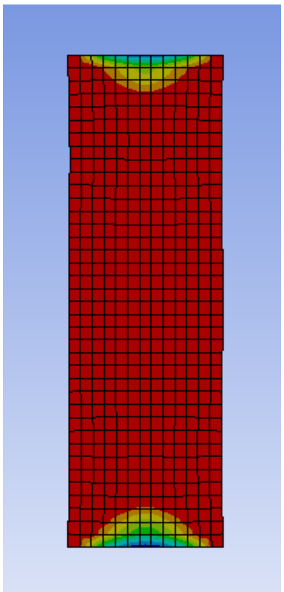


Figure 4-5: Stress intensity of tensile test simulation for PETG specimens

Figure 4-4 displays stress concentration results obtained from simulations. The data reveals that most of the stress concentration occurs at the middle of the specimens, which is the critical location. Furthermore, the results suggest that the simulation model employed is accurate and closely resembles the behaviour observed in the experimental specimens. This agreement between the simulation and experimental results lends confidence to the accuracy of the simulation model and reinforces the usefulness of such models in predicting the behaviour of materials under different loading conditions.

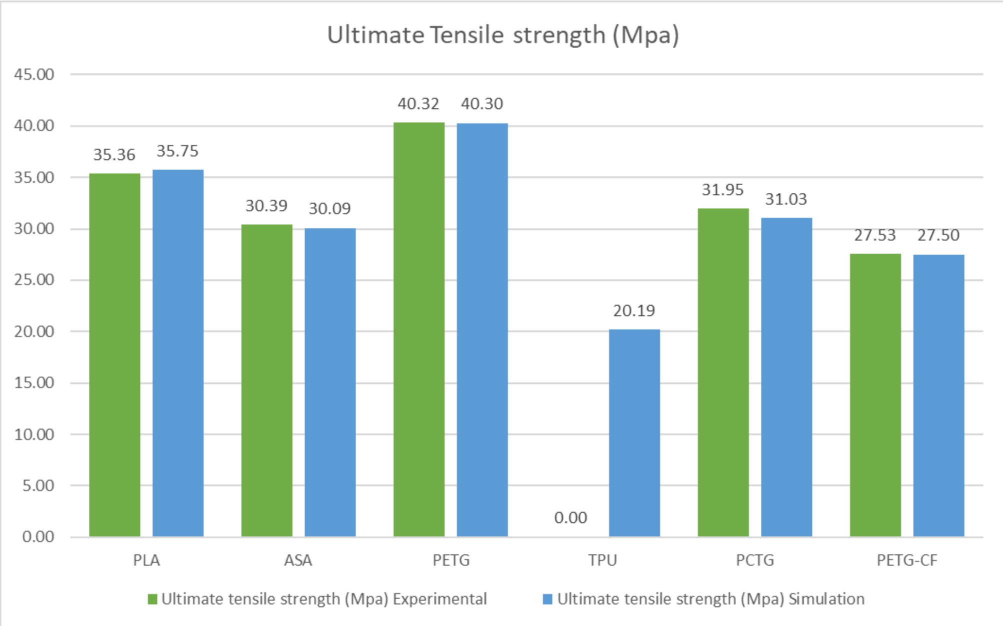


Figure 4-6: Experimental and simulation Ultimate tensile strength

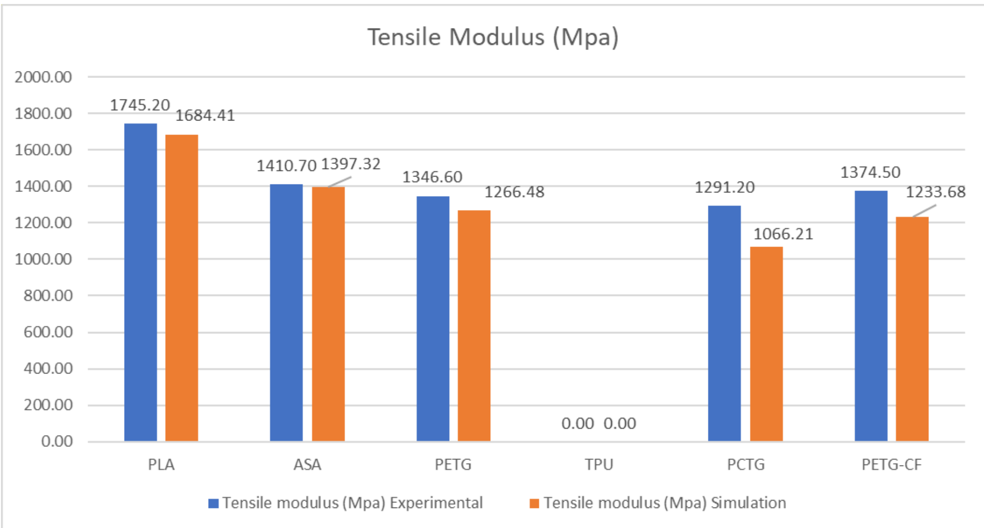


Figure 4-7: Experimental and simulation Tensile Modulus

Table 4-1: Tensile properties of mono material specimens

Material	Ultimate tensile strength (MPa)		Percentage differences	Tensile modulus (MPa)		Percentage differences
	Experimental	Simulation		Experimental	Simulation	
PLA	35.36	35.75	-1.11	1745.20	1684.41	3.48
ASA	30.39	30.09	0.99	1410.70	1397.32	0.95
PETG	40.32	40.30	0.06	1346.60	1266.48	5.95
TPU	-	20.19		-	-	
PCTG	31.95	31.03	2.88	1291.20	1066.21	17.43
PETG-CF	27.53	27.50	0.09	1374.50	1233.68	10.24

Table 4-1 presents data on the ultimate tensile strength and tensile modulus for both experimental and simulated specimens, along with the percentage differences between the two. The data reveals that the simulation results are in close agreement with the experimental results, with minimal differences observed. This suggests that the simulation model employed in this study is reliable and can accurately predict the mechanical behaviour of materials under tensile loading. Furthermore, the results highlight the potential usefulness of simulations in predicting the behaviour of multi-material 3D-printed specimens. By accurately predicting material behaviour, simulations can aid in the optimization of design parameters and material selection, thereby improving the overall performance of the printed structures.

4.3.2 Flexural test

The results of the simulation study indicate that the flexural stress-strain behaviour of most parts is similar to the experimental data. However, the simulated stress-strain curves exhibit slightly lower values compared to the experimental data. Furthermore, most of the stress-strain curves exhibit lower stress values after the yield point. These observations show that the materials may not behave isotopically as defined in the simulation, but rather may exhibit orthotropic or even anisotropic behaviour. Figure 4-9 show that the flexural stress strain behaviour of PLA and PETG specimens. The stress strain curves of other materials are shown in the appendix.

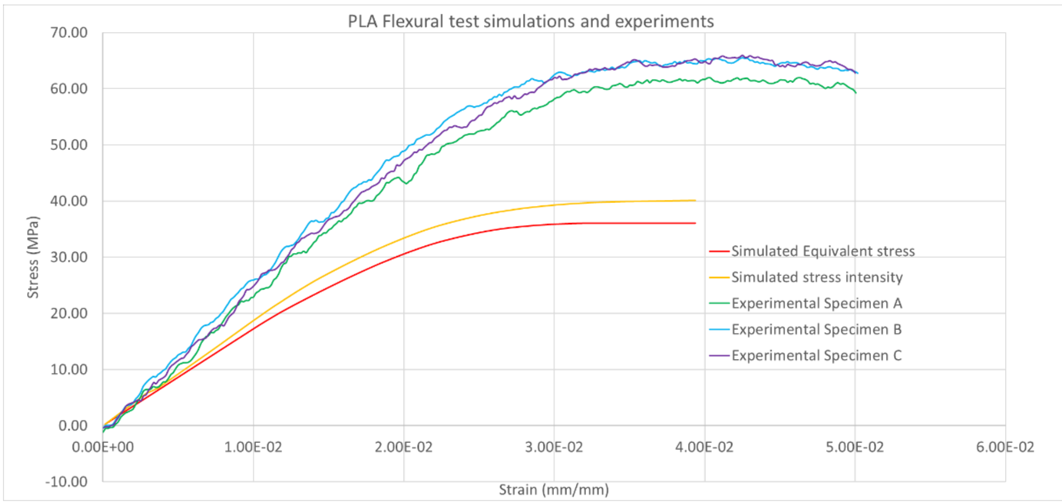


Figure 4-8: Flexural simulation and experimental data for PLA specimens

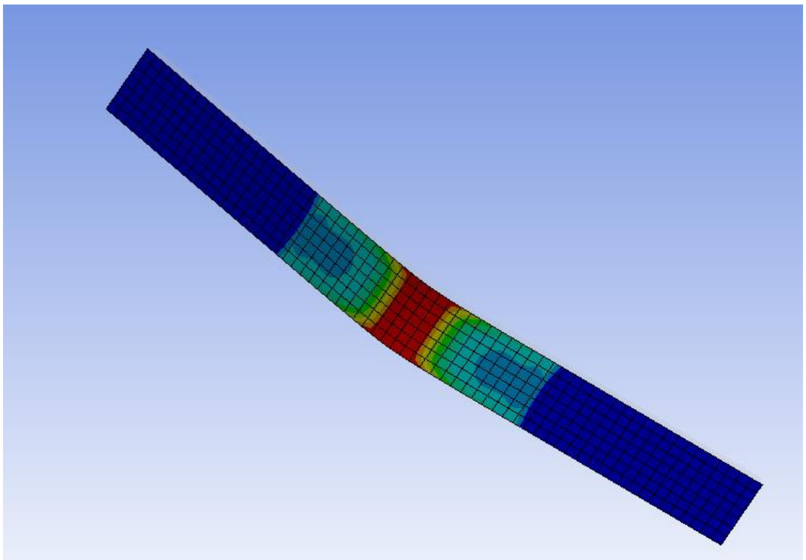


Figure 4-9: Stress intensity of flexural simulation for PLA specimens

The simulation model for the 3-point bending test is presented in Figure 4-11. The results of the simulation show that the stress intensity, equivalent total strain, and equivalent stress are concentrated in the middle of the specimens, which is the critical region. These indicate that the simulations are mostly accurate.

In the Figure 4-10 below show that the comparison of experimental flexural strength and simulation flexural strength. The simulations for flexural strength are considered as not very accurate due to the differences between the experimental and simulation results. The percentage differences are show in the Table 4-2 below.

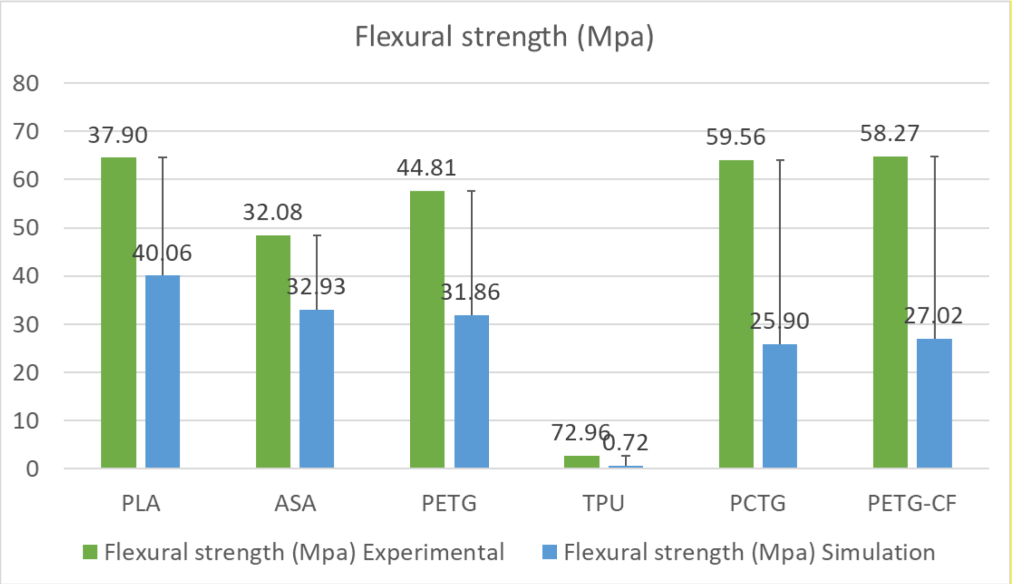


Figure 4-10: Experimental and simulation Flexural strength

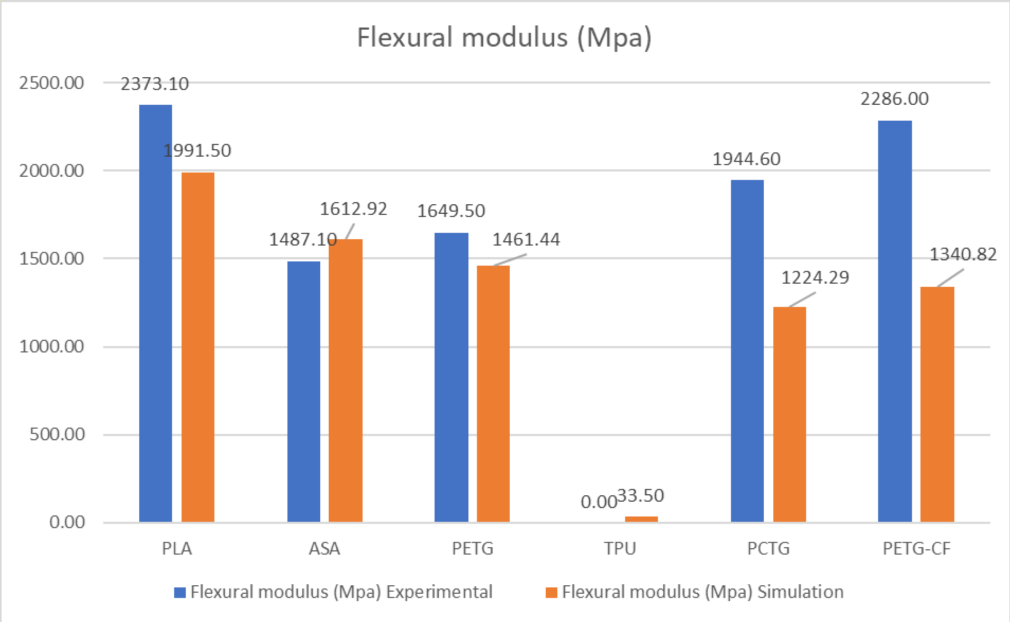


Figure 4-11: Experimental and simulation Flexural modulus

Table 4-2: Flexural properties of Mono material specimens

Material	Flexural strength (MPa)		Percentage differences	Flexural modulus (MPa)		Percentage differences
	Experimental	Simulation		Experimental	Simulation	
PLA	64.51	40.06	37.90	2373.10	1991.50	16.08
ASA	48.48	32.93	32.08	1487.10	1612.92	-8.46
PETG	57.73	31.86	44.81	1649.50	1461.44	11.40
TPU	2.66	0.72	72.96	-	33.50	
PCTG	64.04	25.90	59.56	1944.60	1224.29	37.04
PETG-CF	64.76	27.02	58.27	2286.00	1340.82	41.35

In Table 4-2, the flexural strength and flexural modulus for both experimental and simulated specimens, along with the percentage differences between the two. There are 6 materials in the table which are PLA, ASA, PETG, TPU, PCTG and PETG-CF. The percentage differences for all the materials are relatively on the higher side. These results show that the flexural simulation might be not very accurate. There could be some error in defining the material properties and model setup in the simulation.

4.3.3 Izod Impact test

Table 4-3 presents a comparison between the simulated impact resistance and the experimental impact resistance. The findings indicate a significant percentage difference between the two, suggesting that the simulation was inaccurate in predicting the impact resistance of the tested specimens. It is important to note that while the simulation results were mostly consistent with the experimental data for other mechanical properties, the Izod impact test appears to be an exception, and further research may be needed to improve its accuracy.

Table 4-3: Experimental and simulation data of Impact resistances

Material	Izod Impact (J/m)		Percentage differences (%)
	Experimental	Simulation	
PLA	346.16	1320.45	-73.78
ASA	672.08	1731.18	-61.18
PETG	164.07	1731.18	-90.52
TPU	650.72	161.34	-
PCTG	385.63	1485.35	-74.04
PETG-CF	250.75	1273.82	-80.32

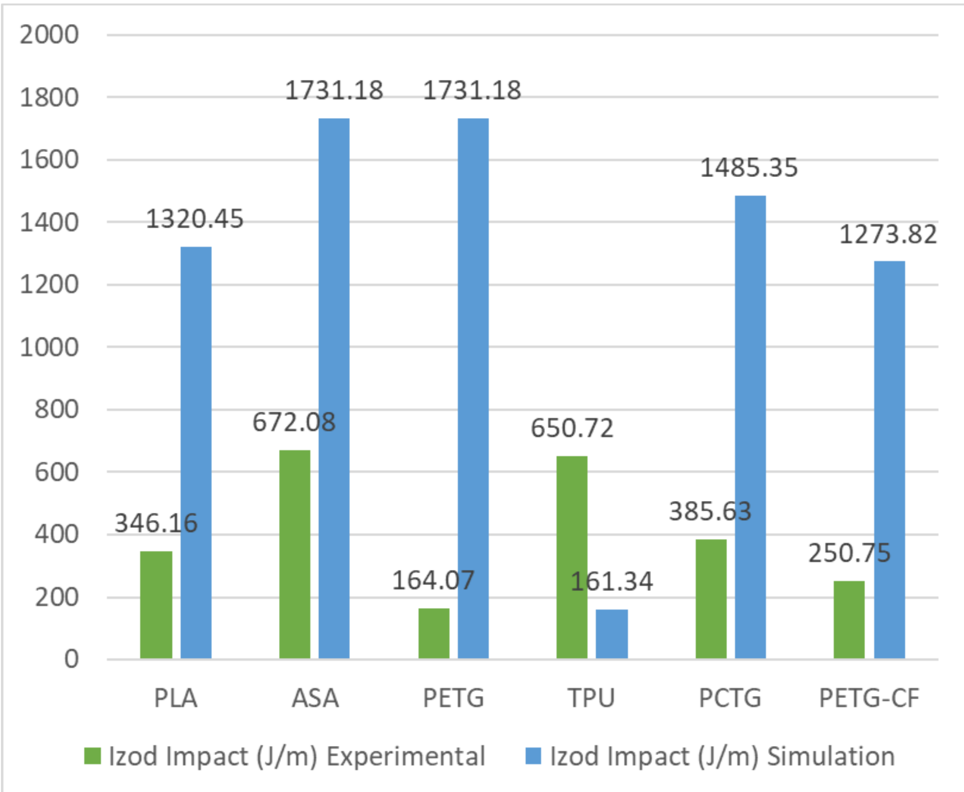


Figure 4-12: Experimental and simulation Impact resistance

4.3.4 Conclusion of Comparison of Experimental and Simulation Results

For the tensile test, the simulation results are closely similar to the experimental results. The percentage differences for both tensile modulus and ultimate tensile stress are lesser than 5%. However, foe the flexural test, the percentage differences are relatively larger. Most of the differences occur after the yield stress of the material. For the flexural strength, the percentages differences are ranging for 30% to 58%. The percentage differences of flexural modulus are ranging for 8% to 41%. Lastly, the percentages differences for Izod impact test are ranging for 70% to 90%. These results show that the simulation model for Izod impact is not accurate.

4.4 Simulation of Multi Material 3D printed Specimen

After validating and verified the mono material simulation results. The multi material specimens' simulation is done to identify the mechanical properties change to the 3D printed specimens. There are many combinations of material that can be printed. In order to save time, simulation can get the mechanical properties of each combination. The best combinations are chosen to be 3D printed and do the experiment again to validate the multi material 3D printed specimens. Below show that the summary of mechanical properties of multi material 3D printed specimens.

4.4.1 Simulation of Multi material Tensile Properties

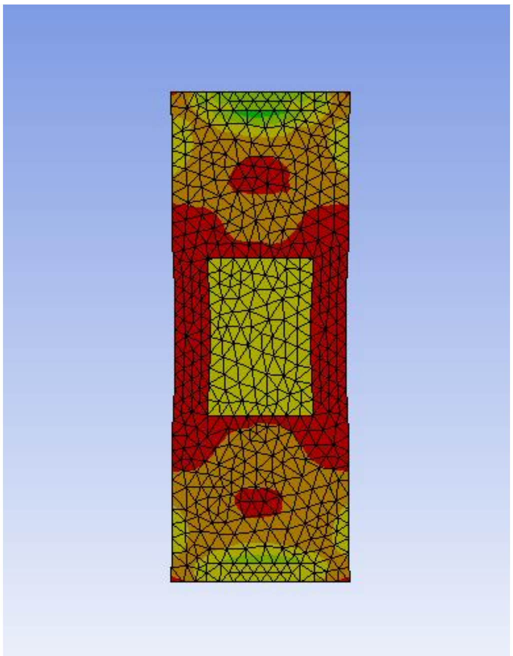


Figure 4-13: Stress intensity of tensile simulation of PLA/PETG composite material 3D printing

Table 4-4: Tensile properties of each material combination

Concept	Material combination	Ultimate tensile strength (MPa)	Tensile modulus (MPa)
1	Shell - ASA Infill - PLA	31.66	1522.58
2	Shell – PLA Infill - ASA	32.43	1566.73
3	Shell – TPU Infill - PLA	13.05	627.82
4	Shell - PLA Infill - TPU	15.89	798.11
5	Shell - PETG Infill - PLA	37.147	1441.99
6	Shell - PLA Infill - PETG	37.014	1535.67
7	Shell - PCTG Infill – PETG-CF	28.613	1131.54
8	Shell – PETG-CF Infill - PCTG	28.532	1165.62
9	Shell - PLA Infill – PETG-CF	30.75	1521.51
10	Shell – PETG-CF Infill - PLA	29.906	1422.97

In Table 4-4 above show that the Tensile properties of each combination. The two tensile properties are Ultimate tensile strength and tensile modulus. Ultimate tensile strength show that the maximum stress withstands by the specimens in tensile direction while the tensile modulus shows that the stiffness of specimens before yield. From the table above, the highest tensile strength is PLA and PETG combination. This combination also has a relatively higher tensile modulus. Besides that, the PCTG and PETG-CF combination is chosen to proof the simulation results. Figure 4-14 show the ultimate tensile strength in bar chart form.

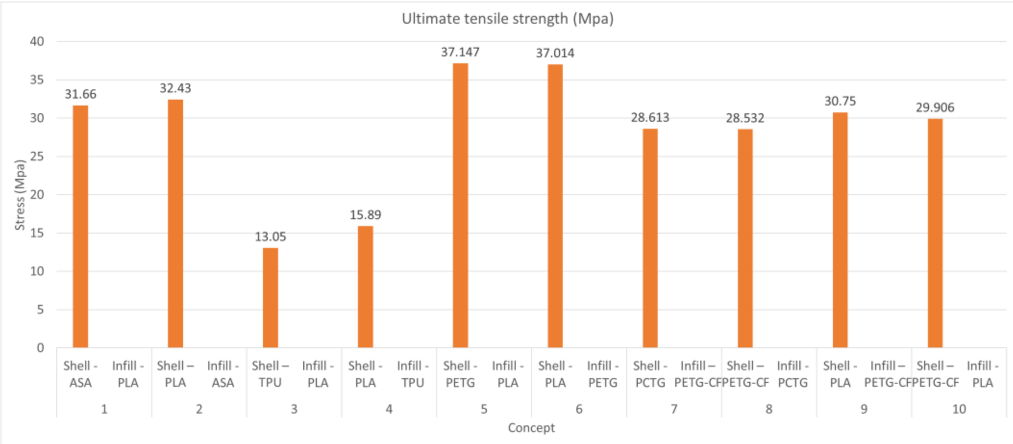


Figure 4-14: Ultimate Tensile Strength of Multi Material 3D printed Specimens

4.4.2 Simulation of Multi Material Flexural Properties

Other than tensile properties, there are also other mechanical properties to determine the strength of the 3D printed specimens. Flexural strength is the maximum bending stress before yield, while the flexural modulus is the tendency to bend certain material or can be define as flexural deformation. Higher flexural modulus means the specimens are more resist to bend. All the combinations are simulated in Ansys to determine the flexural properties. The summary of flexural properties of each combination are shown in the Figure 4-15 and the Table 4-5.

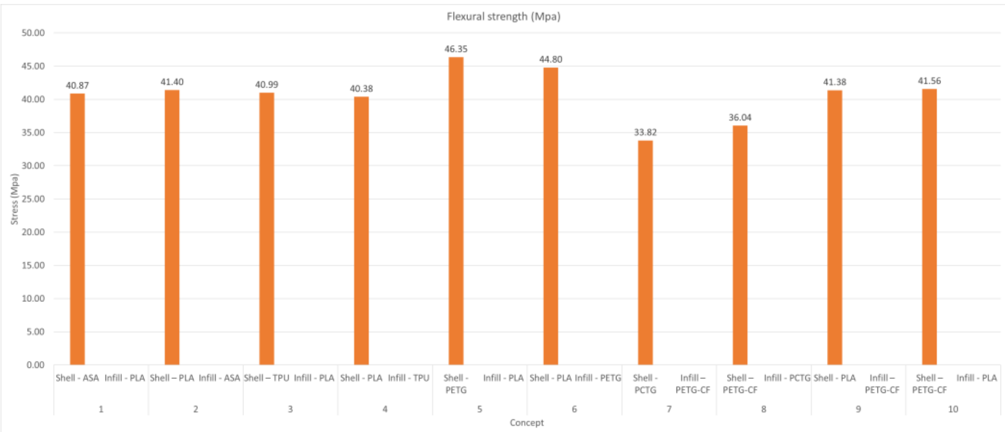


Figure 4-15: Flexural strength of Multi material 3D printed Specimens

Table 4-5: Flexural properties of Multi material specimens

Concept	Material combination	Flexural strength (MPa)	Flexural modulus (MPa)
1	Shell - ASA Infill - PLA	40.87	1761.28
2	Shell – PLA Infill - ASA	41.40	1691.52
3	Shell – TPU Infill - PLA	40.99	400.44
4	Shell - PLA Infill - TPU	40.38	1498.07
5	Shell - PETG Infill - PLA	46.35	1747.49
6	Shell - PLA Infill - PETG	44.80	1833.61
7	Shell - PCTG Infill – PETG-CF	33.82	1171.30
8	Shell – PETG-CF Infill - PCTG	36.04	1172.28
9	Shell - PLA Infill – PETG-CF	41.38	1603.88
10	Shell – PETG-CF Infill - PLA	41.56	1750.40

Table 4-5 above show that the PLA and PETG combination has highest Flexural strength and Flexural modulus. The PLA and PETG combinations can consider as one of the best combinations of multi material 3D printing. The simulation data above indicate that the PLA PETG combination are more resist to bend. Other than that, the PCTG and PETG-CF combination is chosen to proof the simulation results. The Figure 4-16 below show that the stress concentration of multi material flexural simulation. Section 4.5 will show the experimental results of multi material specimens.

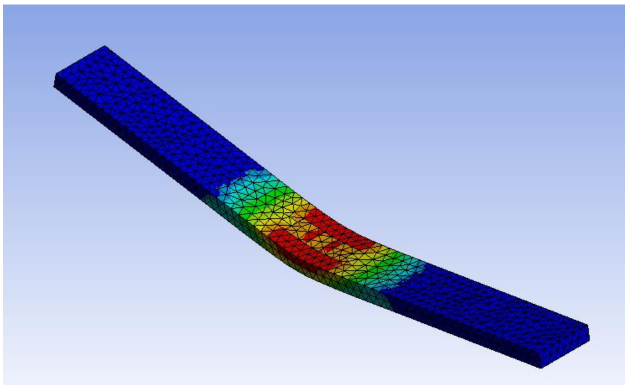


Figure 4-16: Multi material specimens flexural test simulation

4.5 Mechanical Properties of Multi Material 3D Printed Specimens

In this chapter, the chosen combinations of multi material 3D printing are printed out and undergo a series of experiment to determine the mechanical changes. The simulations of multi material specimens also can be validated by comparing the experimental data and the simulation data. Before printing the multi material specimens, there are some small multi material parts are printed to ensure the adhesion of the multi material specimens. Figure 4-17 below show each combination has good adhesion. The part on the left is PLA-PETG; parts on the right is PCTG-PETGCF combination.

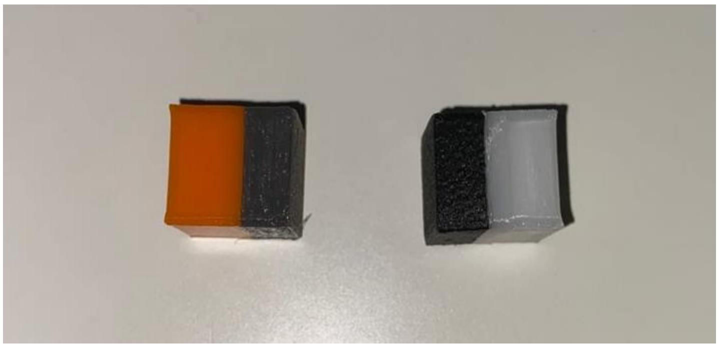


Figure 4-17: Material adhesion test parts (PLA-PETG left; PCTG-PETGCF right)

4.5.1 Mechanical Properties of PCTG/PETG-CF Combinations

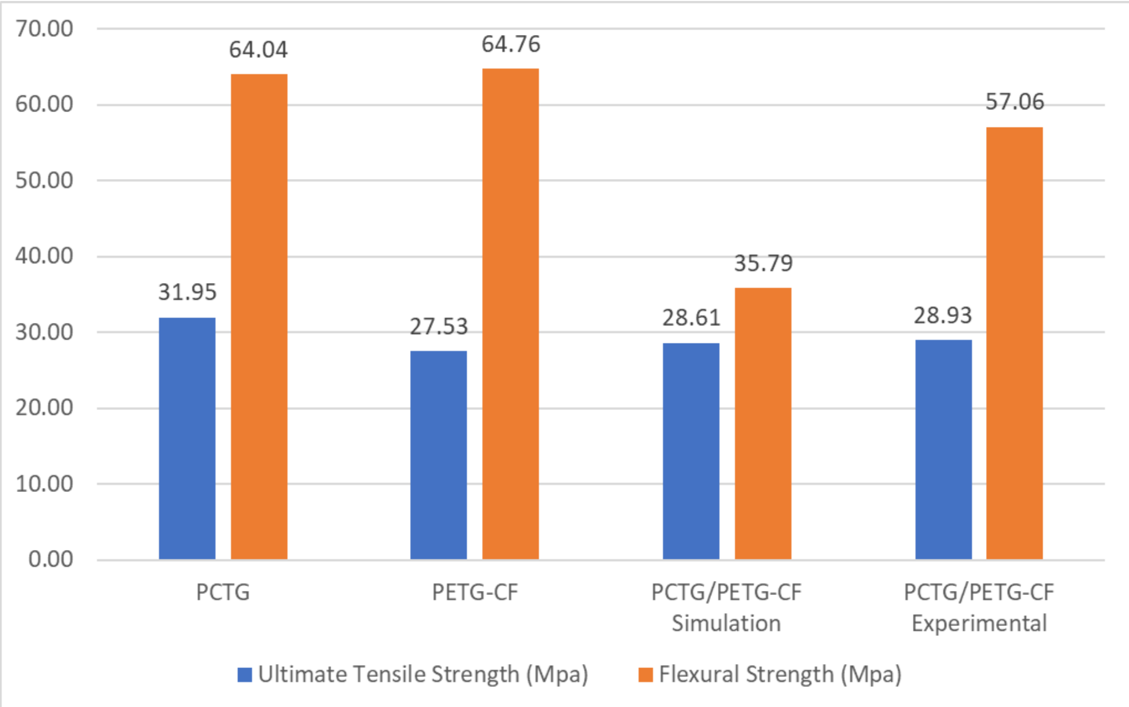


Figure 4-18: Ultimate Tensile strength and Flexural strength of PCTG and PETG-CF combinations

Table 4-6: Mechanical properties of PCTG/PETG-CF combinations

	Ultimate Tensile Strength (Mpa)	Flexural Strength (Mpa)	Izod Impact (J/m)
PCTG	31.95	64.04	385.63
PETG-CF	27.53	64.76	250.75
PCTG/PETG-CF Simulation	28.61	35.79	
PCTG/PETG-CF Experimental	28.93	57.06	341.85

In the Figure 4-18 above, combination chosen for this study is PCTG for the shell and PETG-CF for the infill. While this combination may not provide the highest tensile strength, but it has the highest flexural strength. This combination of PCTG shell and PETG-CF infill has higher flexural strength indicates the specimen is more resistance to bending forces without deformation or failure. The tensile strength of multi material the average of the two mono-material specimens. Combining of two different materials can enhance the tensile strength of the weaker material while maintaining good flexural strength. Composite 3D printing can improve overall mechanical properties. In the bar chart also can show that the simulated tensile strength is similar to the experimental data while the simulated flexural strength is slightly lower. This can prove that the simulation model is accurate in most of the parts.

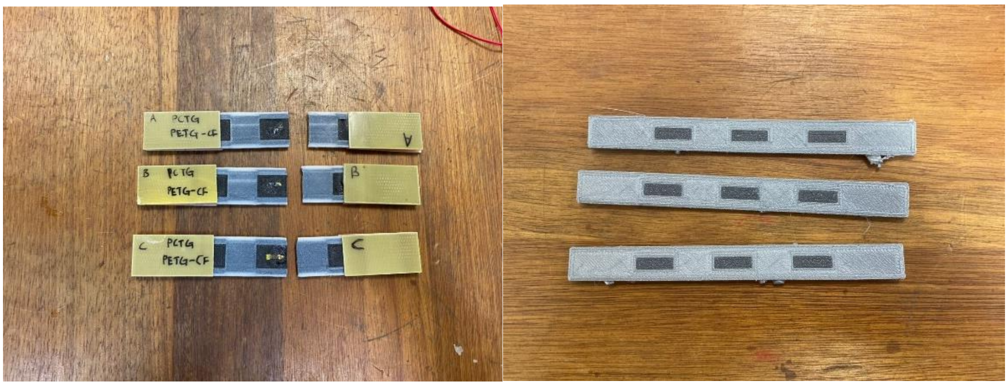


Figure 4-19: PCTG/PETG-CF specimens after tensile test

The Figure 4-19 above shows that the fracture point of PCTG and PETG-CG combination multi material 3D printing. All the specimens break at the same position on the specimens. These happened mostly due to the weak point of mechanical interlocking design. The weak point of the mechanical interlocking design might also affect the mechanical properties of the specimens. It is possible that the tensile and flexural strength of the multi-material specimens could be increased if the weak point in the mechanical interlocking design is solve with a better design. In this study, there is no delamination due to material adhesion happened. Both of the materials are well bonded throughout the whole experiment.

4.5.2 Mechanical Properties of PLA/PETG specimens

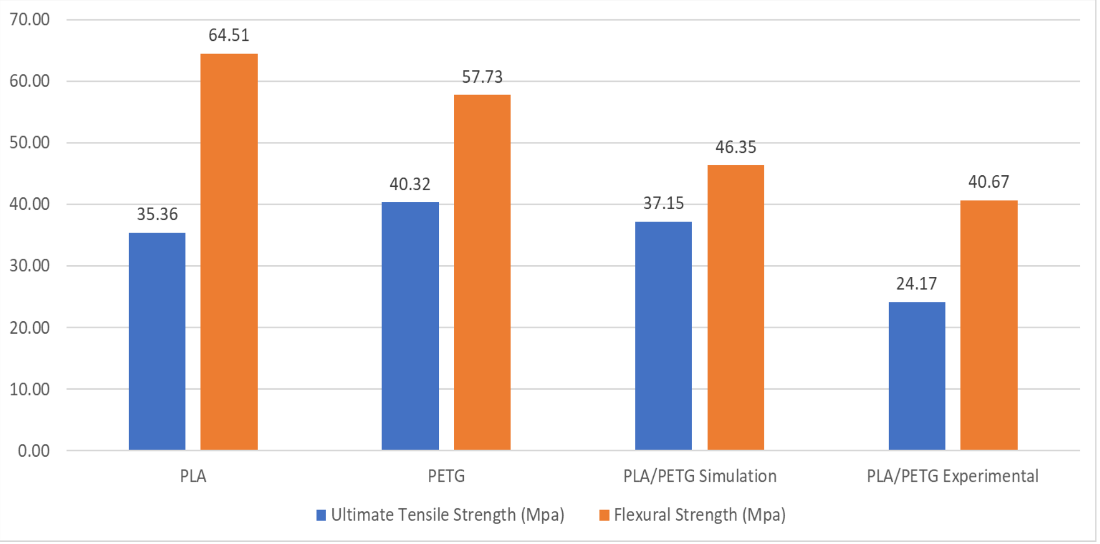


Figure 4-20: Mechanical properties of PLA/PETG combinations

Table 4-7: Mechanical properties of PLA/PETG combinations

	Ultimate Tensile Strength (MPa)	Flexural Strength (MPa)	Izod impact (J/m)
PLA	35.36	64.51	346.16
PETG	40.32	57.73	164.07
PLA/PETG Simulation	37.15	46.35	
PLA/PETG Experimental	24.17	40.67	294.64

Figure 4-20 above show the mechanical properties change of the PLA/PETG combinations. The experimental data show that the Ultimate tensile strength and the flexural strength are lower than the simulation and the mona material specimens. The main reason of these is the PLA filament used is not the same brand as the single material specimens. Additionally, it is believed that the PLA specimens used in the multi-material specimens may have degraded over time due to long-term storage, which could have further contributed to the observed differences in mechanical properties. The experimental results may not be entirely accurate due to the use of PLA in the multi-material specimens.

However, the combination of PCTG/PETG-CF in Section 4.5.1 has demonstrated that the simulation results are quite accurate. As a result, the simulation model developed in this study could be used as a reliable tool for predicting the mechanical behaviour of other multi-material structures.

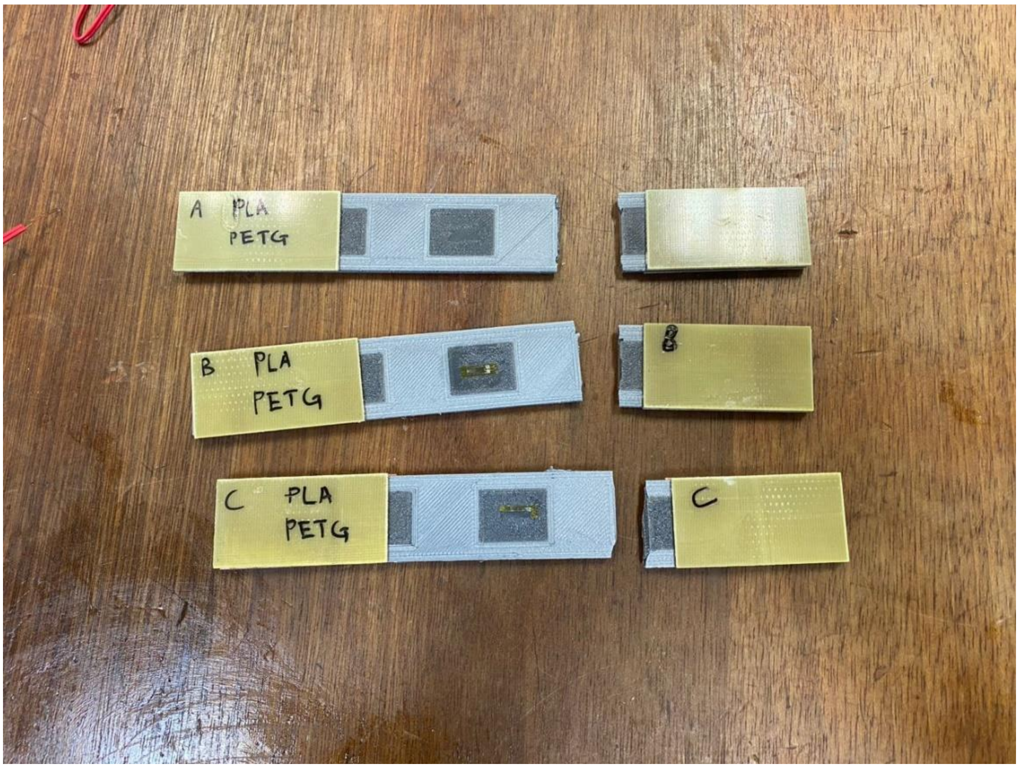


Figure 4-21: PLA/PETG specimens after tensile test

Figure 4-22: PLA/PETG flexural specimens

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research has shown that the best combination of multi material 3D printing in term of tensile strength, flexural strength and impact resistance. The best combination should be PLA and PETG combinations as it provides superior overall mechanical properties in terms of tensile strength and flexural strength. The simulation in this study shows that the improvement of mechanical properties of multi material 3D printing is around 5% compared to its mono material 3D printed parts. The PLA/PETG combination provide 37.15 MPa of Ultimate Tensile strength and 46.35MPa of Flexural strength. Improved mechanical properties in composite material 3D printing can lead to increased structural integrity, greater design flexibility, and expanded application possibilities.

The simulation model used in this study has shown that the simulated results closely match the experimental results, indicating that other materials can also be added to simulate changes in the mechanical properties of composite material 3D printing. The combination of PCTG/PETG-CF in Section 4.5.1 has demonstrated that the simulation results are quite accurate. Nevertheless, these results were able to present an insight into improving the mechanical properties of 3D printed parts by utilizing multi-material printing.

Besides that, the simulation model also can be validated. The accuracy of the simulation is quite high in term of tensile properties which is Ultimate tensile strength and tensile modulus. However, the simulated flexural properties and impact resistance are not very accurate due to define of material and model setup. There are some future improvements that can be done to improve the simulation accuracy.

5.2 Recommendation for Future Work

This study has observed that while most of the Ansys simulation results are similar to the experimental data, there is still room for improvement in the Ansys simulation. Specifically, the Izod impact test shows differences that require further investigation. Upon analysis, it is believed that the differences may be affected by material model definition and the need for proper definition of the failure mode for the material. Improving the accuracy of the Ansys simulation will lead to a better simulation of the mechanical properties of multi material 3D printed parts.

Furthermore, the mechanical interlocking design has some weak point. These might cause the mechanical properties of the composite parts to be lower. Therefore, further research is required to explore and evaluate various design alternatives in order to determine the best mechanical interlocking design that can effectively enhance the material bonding and improve the overall mechanical properties of multi material 3D printed parts. Such efforts could potentially lead to the development of stronger and more reliable composite 3D printed parts with wider applications and increased functionality.

In multi-material 3D printing, achieving proper material adhesion is crucial for successful printing. When materials cannot bond with each other, printing becomes impossible. However, even when adhesion is achieved, the resulting bond may not be strong enough to withstand mechanical stresses. This can lead to delamination of the printed part and decreased mechanical properties. As such, material adhesion is a significant challenge in multi-material 3D printing that requires careful consideration and optimization.

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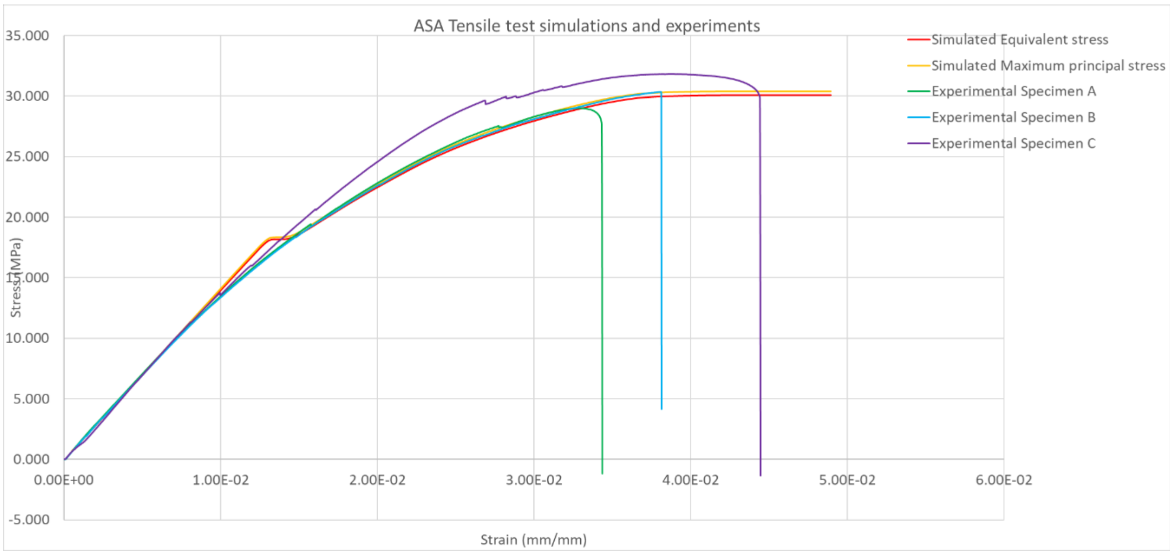
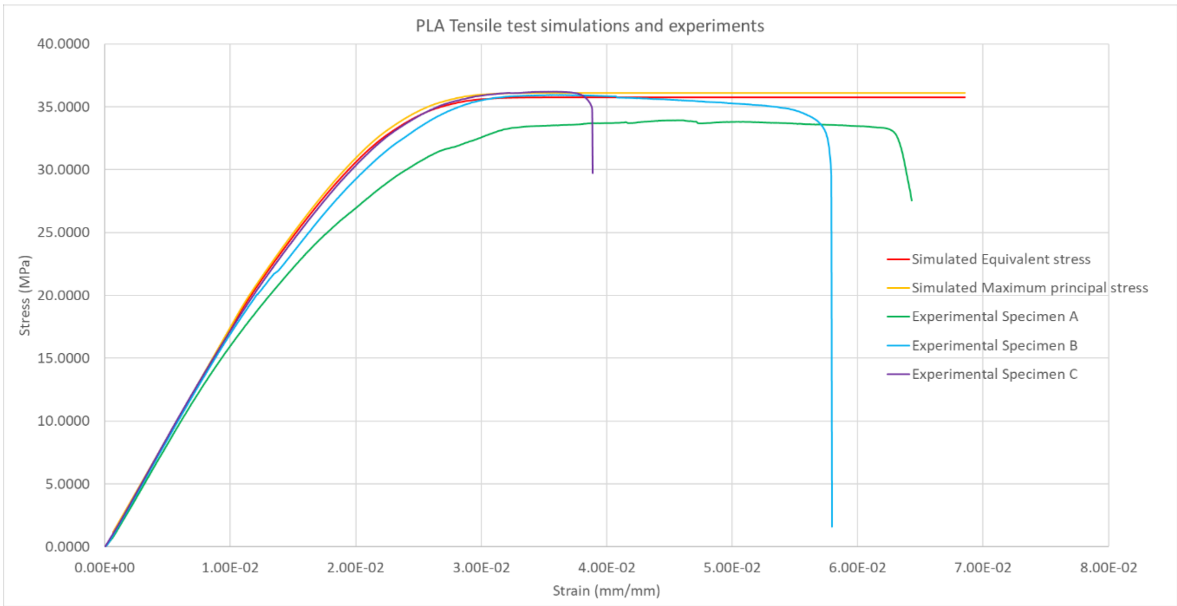
APPENDIX

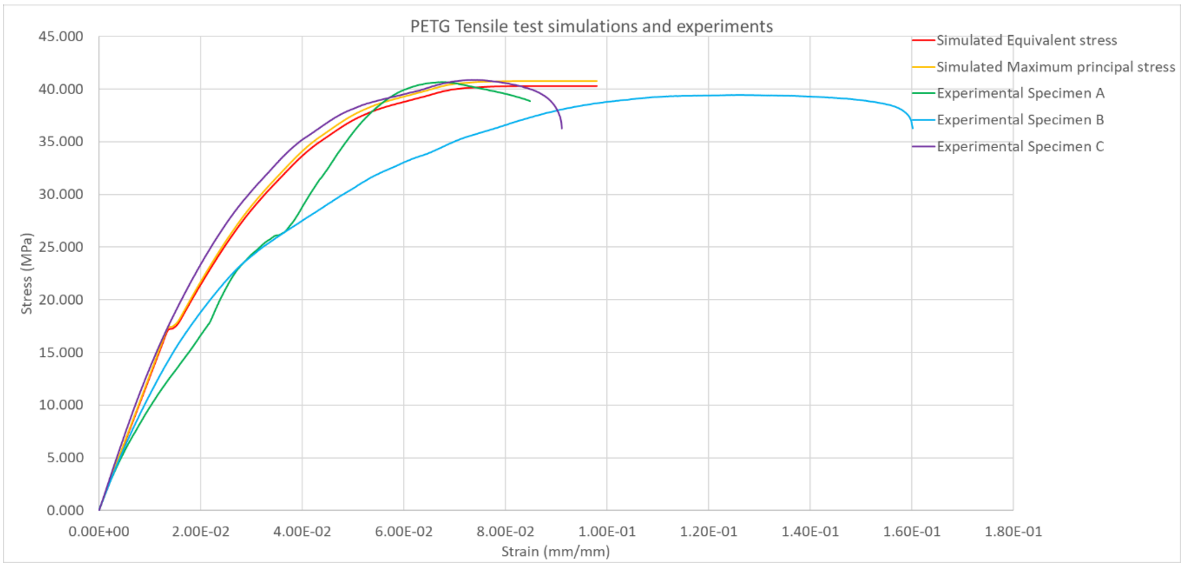
Appendix A: Tensile test stress-strain curve of ASA specimens (Simulation and experimental)



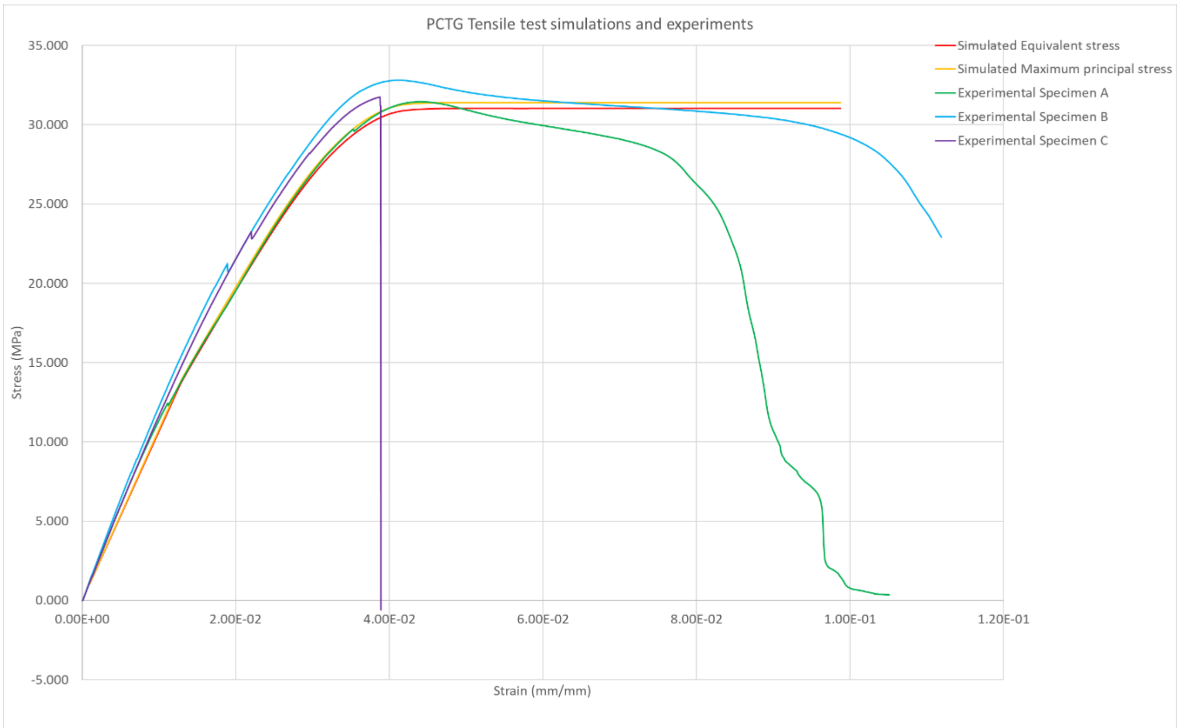
Appendix B: Tensile test stress-strain curve of PLA specimens (Simulation and experimental)



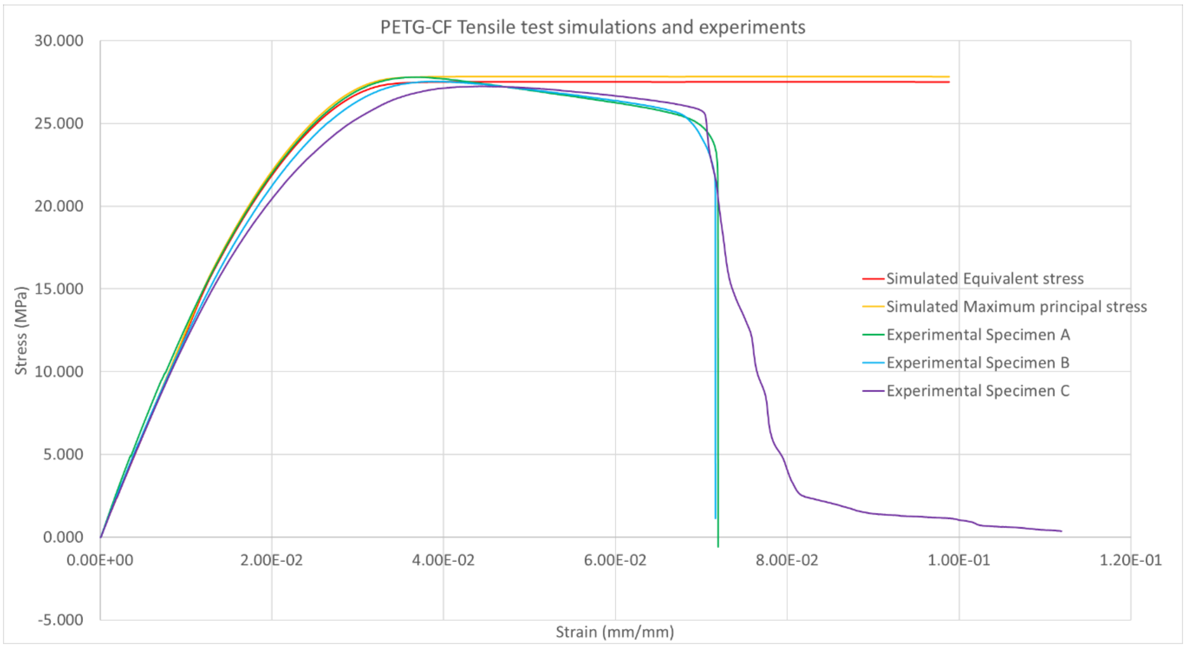
Appendix C: Tensile test stress-strain curve of PETG specimens (Simulation and experimental)



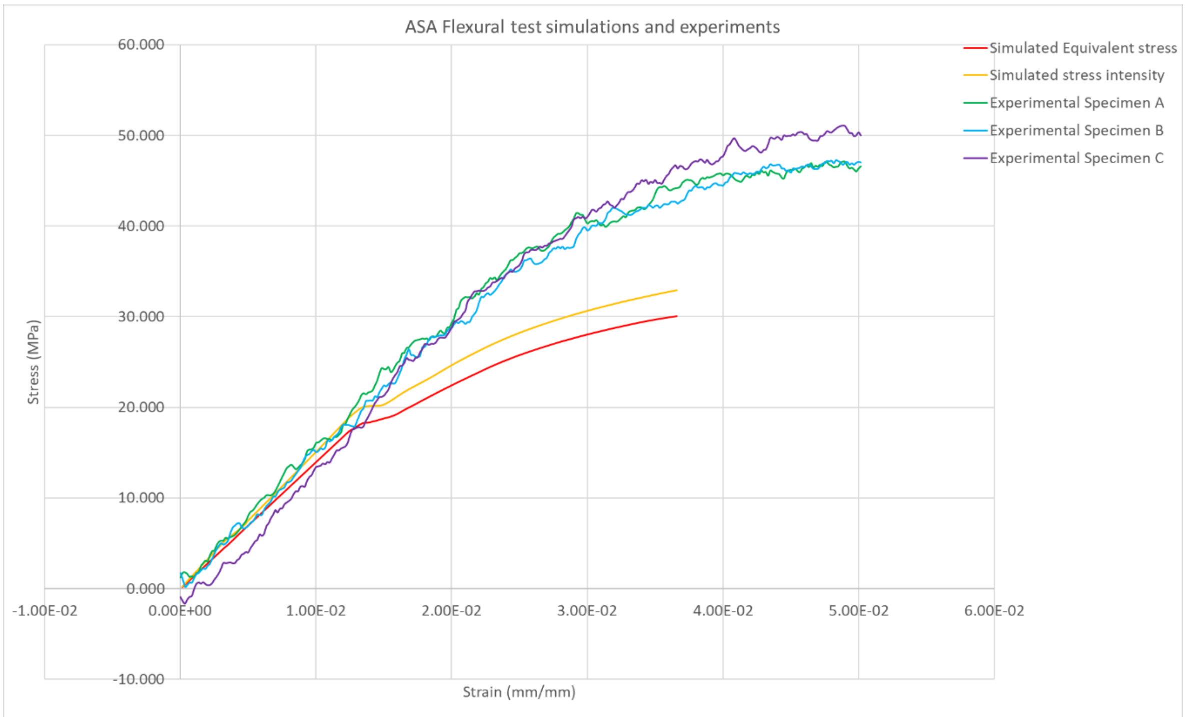
Appendix D: Tensile test stress-strain curve of PCTG specimens (Simulation and experimental)



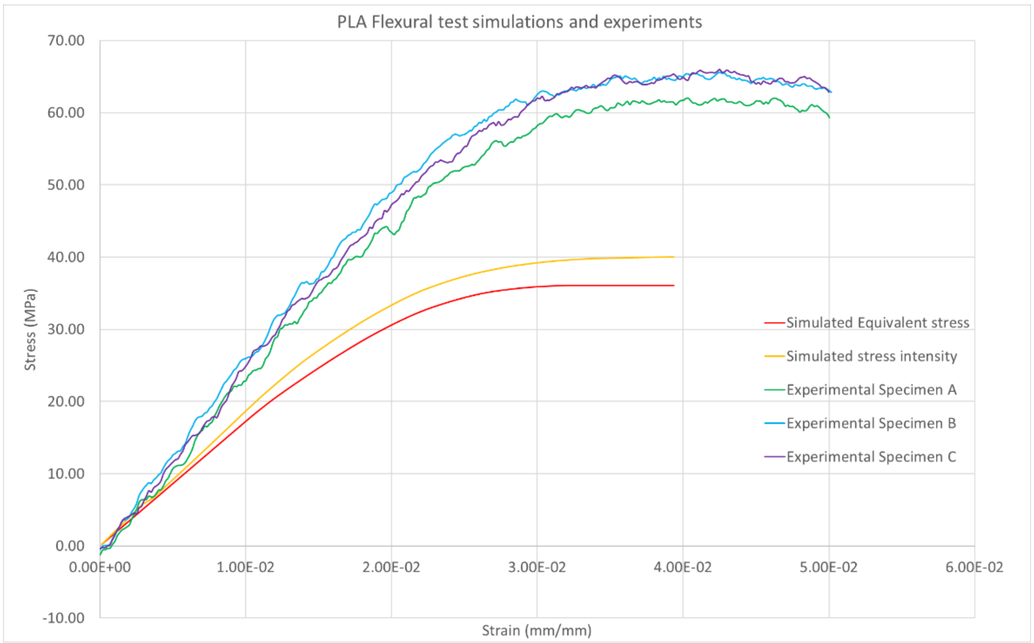
Appendix E: Tensile test stress-strain curve of PETG-CF specimens (Simulation and experimental)



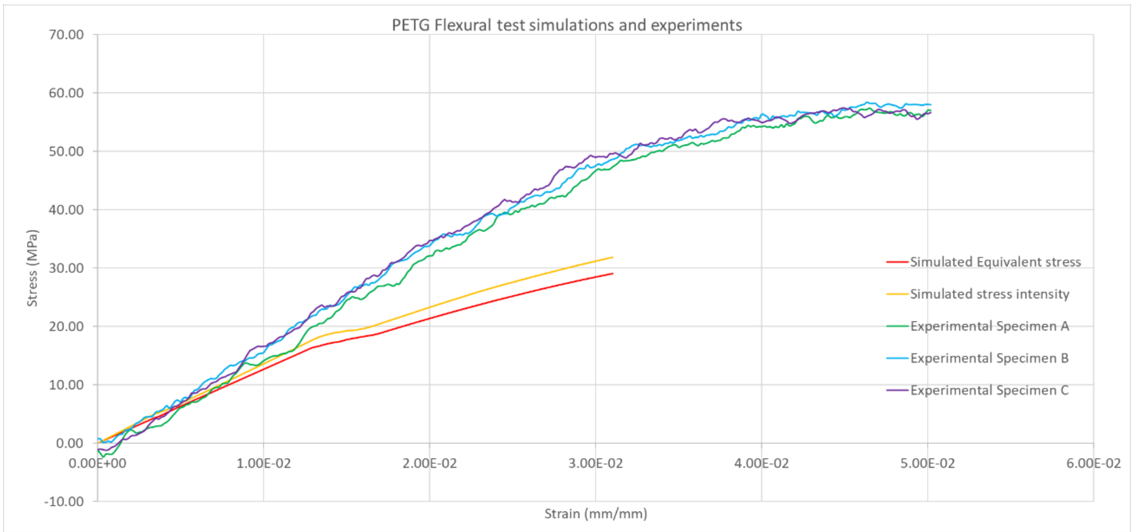
Appendix F: Flexural test stress-strain curve of ASA specimens (Simulation and experimental)



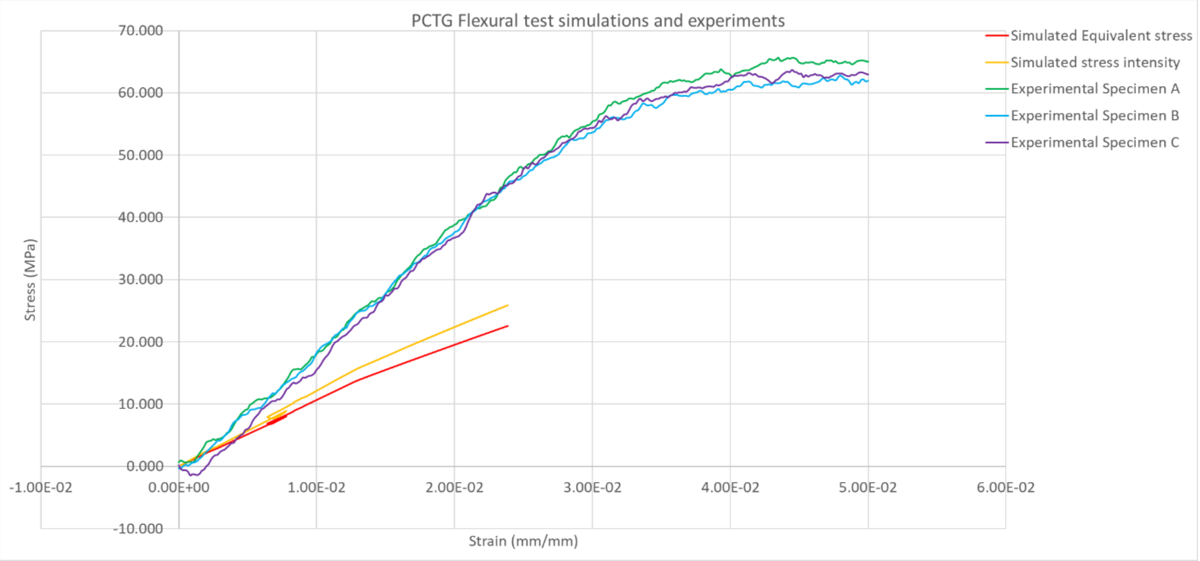
Appendix G: Flexural test stress-strain curve of PLA specimens (Simulation and experimental)



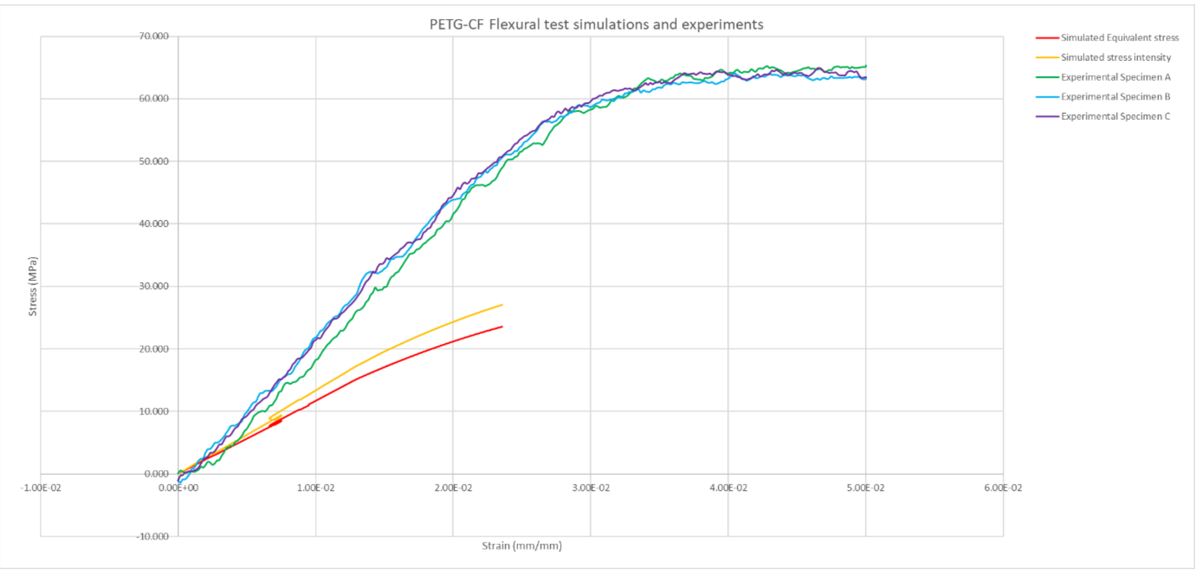
Appendix H: Flexural test stress-strain curve of PETG specimens (Simulation and experimental)



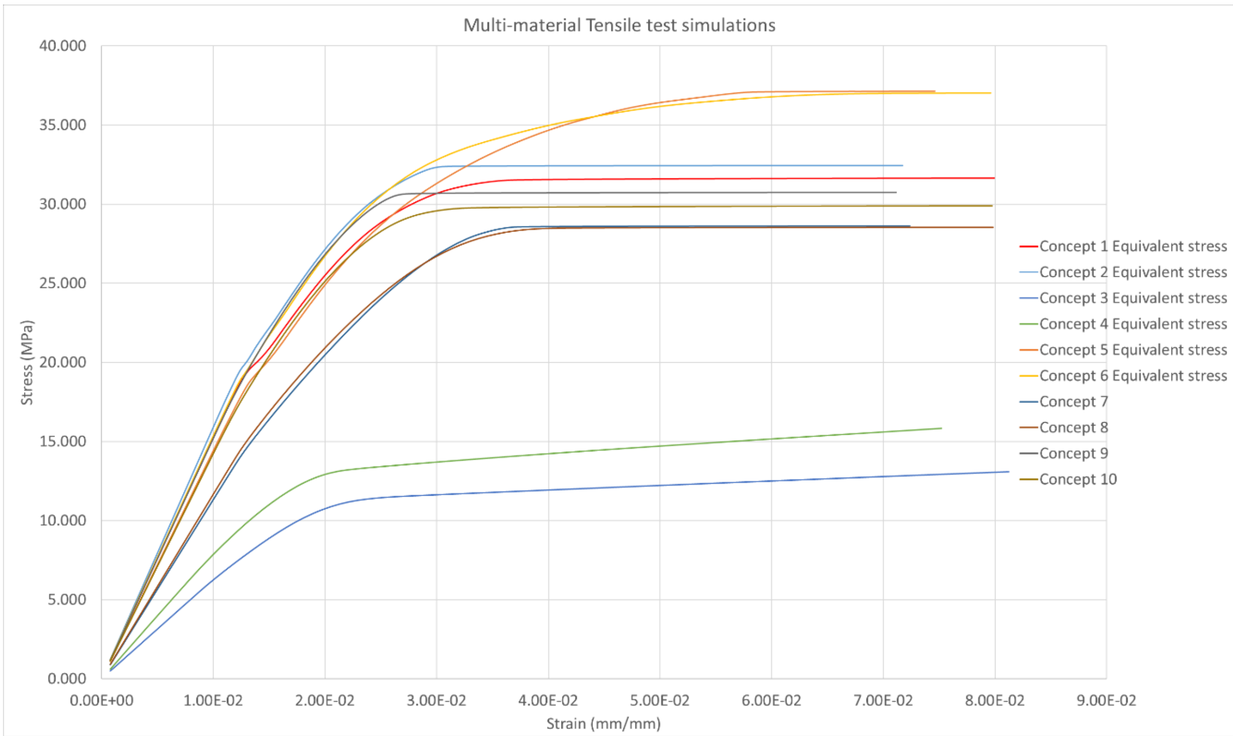
Appendix I: Flexural test stress-strain curve of PCTG specimens (Simulation and experimental)



Appendix J: Flexural test stress-strain curve of PETG-CF specimens (Simulation and experimental)



Appendix K: Tensile Stress-Strain curve of Multi material 3D printed Specimens



Appendix L: Flexural Stress-Strain curve of Multi material 3D printed Specimens