STUDY ON STRENGTH COMPARISON OF FDM PRINTED ABS MANUFACTURED BY DIFFERENT COMPANIES

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This report is submitted in fulfillment of the requirement for the degree of Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JANUARY 2022

DECLARATION

I declare that this project report entitled “Strength Comparison of FDM Printed ABS Manufactured by Different Companies” is the result of my own work except as cited in the references

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature : ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved mother and father

ABSTRACT

Additive Manufacturing (AM) is a technology for printing three-dimensional objects from three-dimensional model data. It has been enhanced to minimise production costs. The most widely used additive manufacturing process is fused deposition modelling, which extrudes models layer by layer using a thermoplastic filament. It is becoming increasingly important and plays a significant role in the manufacturing of multifunctional product nowadays. When selecting the proper material for 3D printing, it is necessary to consider the intended usage of the material. The appropriate material selection is critical to ensuring the product's durability and strength. The goal of this study was to assess the strength of a thermoplastic material chosen for comparison, which is Acrylonitrile Butadiene Styrene (ABS) that is made by various companies. Specimens were manufactured using thermoplastic filament and submitted to tensile and compression tests to see whether different manufacturers have an effect on the strength. All printed specimens were ensured to have the same parameters for printing process to avoid interfering with the testing results. The ABS material's strength was determined by the way each specimen reacted and the highest load that the specimen could withstand during compression and tensile tests. The data indicate that different manufacturers have an effect on the ABS material's strength. The methodologies used in this study are sufficient to demonstrate the strength comparison of ABS material manufactured by various manufacturers.

ABSTRAK

Pembuatan aditif ialah teknologi untuk mencetak objek tiga dimensi daripada data model tiga dimensi. Ia telah dipertingkatkan untuk meminimumkan kos pengeluaran. Proses pembuatan aditif yang paling banyak digunakan ialah pemodelan pemendapan bersatu, yang mencetak model lapisan demi lapisan menggunakan filamen termoplastik. Ia menjadi semakin penting dan memainkan peranan penting dalam pembuatan produk pelbagai fungsi pada masa kini. Apabila memilih bahan yang sesuai untuk percetakan 3D, adalah perlu untuk mempertimbangkan penggunaan bahan yang tepat. Pemilihan bahan yang sesuai adalah penting untuk memastikan ketahanan dan kekuatan produk. Matlamat kajian ini adalah untuk menilai kekuatan bahan termoplastik yang dipilih untuk perbandingan, iaitu Acrylonitrile Butadiene Styrene (ABS) yang dibuat oleh pelbagai syarikat. Spesimen telah dicetak menggunakan filamen termoplastik dan diserahkan kepada ujian tegangan dan mampatan untuk melihat sama ada pengeluar berbeza mempunyai kesan ke atas kekuatan. Spesimen yang dicetak dipastikan mempunyai parameter yang sama bagi setiap spesimen eksperimen untuk mengelakkan gangguan dengan keputusan ujian. Kekuatan bahan ABS ditentukan oleh cara setiap spesimen bertindak balas dan beban tertinggi yang boleh ditahan oleh spesimen semasa ujian mampatan dan tegangan. Data menunjukkan bahawa pengeluar yang berbeza mempunyai kesan ke atas kekuatan bahan ABS. Metodologi yang digunakan dalam kajian ini adalah mencukupi untuk menunjukkan perbandingan kekuatan bahan ABS yang dikeluarkan oleh pelbagai pengeluar.

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LIST OF ABBREVIATIONS

AM	Additive Manufacturing
CAD	Computer-aided Design
FDM	Fused Deposition Modeling
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic Acid
3DP	3-Dimensional Printing
LMD	Laser Metal Deposition
ASTM	American Society for Testing and Material
CAM	Computer-aided Manufacturing
DOE	Design of Experiment
NCDS	Nano Composite Deposition
RP	Rapid Prototyping
PP	Polypropylene
PE	Polyethylene
PEEK	Polyether Ether Ketone
PMMA	Poly(methyl methacrylate)
SMP	Shape Memory Polymer
ASCII	American Standard Code for Information Interchange
DCP	Digital Light Processing
CI	Confidence Interval
ISO	International Organization for Standardization
PN-EN	European Standards
FD	Fused Deposition
SFF	Solid Freeform Fabrication
STL	Stereolithography

LIST OF SYMBOLS

α	=	Angle
w	=	Width
mm	=	Millimeters
$°C$	=	Celcius
P	=	Facet vertices
n	=	Floating numbers
v	=	Floating numbers
z	=	Facet’s height
T_g	=	Transition temperature
T_m	=	Melting point
T_e	=	Extrusion temperature
in	=	Inches
L_3	=	Total length
L_1	=	Length of parallel edges narrow zone
R	=	Radius
b_2	=	Width of ends
b_1	=	Width of narrow zones
h	=	Thickness
L_0	=	Reference Length
L	=	Length between clamps

CHAPTER 1

INTRODUCTION

1.1 Background

Additive Manufacturing (AM) is the process of printing 3D products out of 3D model data. Additive Manufacturing processes take the information from a computer-aided design (CAD) file that is later translated to a stereolithography (STL) file. Each layer that will be printed containing the information of the CAD drawing that is approximated by triangles and sliced in this process. The Additive Manufacturing (AM) has been advanced for reducing production costs.

Amongst the numerous 3D printing methods, the utmost prominent AM technology in today's global is Fused Deposition Modeling (FDM). It has a wider array of people who are interested in it because of its reliability, wide variety of useable materials, safety, and production simplicity, as well as cheaper equipment costs and lower process temperatures. For polymer processing, FDM is the most widely used method. It may be used with a wide range of thermoplastic materials. Many different materials have been utilised or produced as a result of investigating materials for additive technologies, including countless types of thermoplastics, metals, ceramics, composites, biodegradable polymers, short fibre composites, polymer-metal mixture materials, and so on. On the market, there are many different materials to choose from, as well as a significant figure of different FDM substance company brands. In choosing the material, it is crucial because it contributes to the accomplishment of an excellent 3D printing outcome. This is especially important when evaluating price disparities for the same commodity.

Acrylonitrile butadiene styrene (ABS) is a well-known selection for filament in 3D printing, it is a three-monomer amorphous polymer consisting of acrylonitrile, butadiene, and styrene. ABS model components are very robust, have great dimensional stability, are simple to manufacture, are chemical resistant, and are inexpensive. It also has fascinating modelling characteristics and a broad range of colours. ABS filaments are available in 1.75 mm or 3 mm diameters and a variety of colours in FDM.

According to Adi Pandžić et al. (2020), although every single one PLA specimens were 3D printed in the similar settings, contrast in the mechanical behaviour content from different manufacturers can be seen. The strength values stated by manufacturers also vary from the findings shown in the paper. There is a possibility that this may happen for other materials. Hence, the objective of this project is to study the strength comparison of FDM printed ABS manufactured by multiple companies.

1.2 Problem Statement

There are currently many different manufacturers for the identical FDM material where the price difference could go up to 50%. According to Adi Pandžić et al. (2020) study, PLA materials from different companies may have different tensile strengths. The findings revealed that even though the material is the same, the tensile properties of the same material vary between manufacturers. This could happen with other similar materials. This project will focus on strength comparison of FDM printed ABS from different manufacturers. The results of the research will be beneficial for consumers to choose best ABS material with low cost and offering the greatest strength.

1.3 Objective

The objective of this project are as follows:

1. To compare the difference in tensile strength properties of ABS FDM printed material from different manufacturers (maximum force, tensile strength, yield strength, Young Modulus, stress strain diagram).
2. To analyse the compressive strength of ABS FDM printed material from various manufacturers.

1.4 Scope of Project

The scopes of this project are:

1. Only results of the strength of ABS materials are presented in this report.
2. Design the test specimen using CATIA V5.
3. The strength comparison of the specimens is measured by tensile test and compressive test only.
4. Creating the specimen using Creality Ender-6 FDM 3D Printer.

1.5 General Methodology

The actions that need to be carried out to achieve the objectives in this project are listed below.

1. Literature review

   Journals, articles or any materials related to this will be analysed.

2. Measurement

Surveying the correct measurement and dimension for cylinder specimen required to test compressive strength. Making sure all specimen for different manufacturers is the same in size and dimensions.

3. Design

   Designing the shape of the specimens using CATIA V5. Ensuring all the dimensions are correct and identical for each specimen.

4. Create

   Build the cylinder specimen using Creality Ender-6 FDM 3D Printer. Ensuring all the specimen using the same printer and the same printing parameters to avoid the possible interferences with the result.

5. Testing

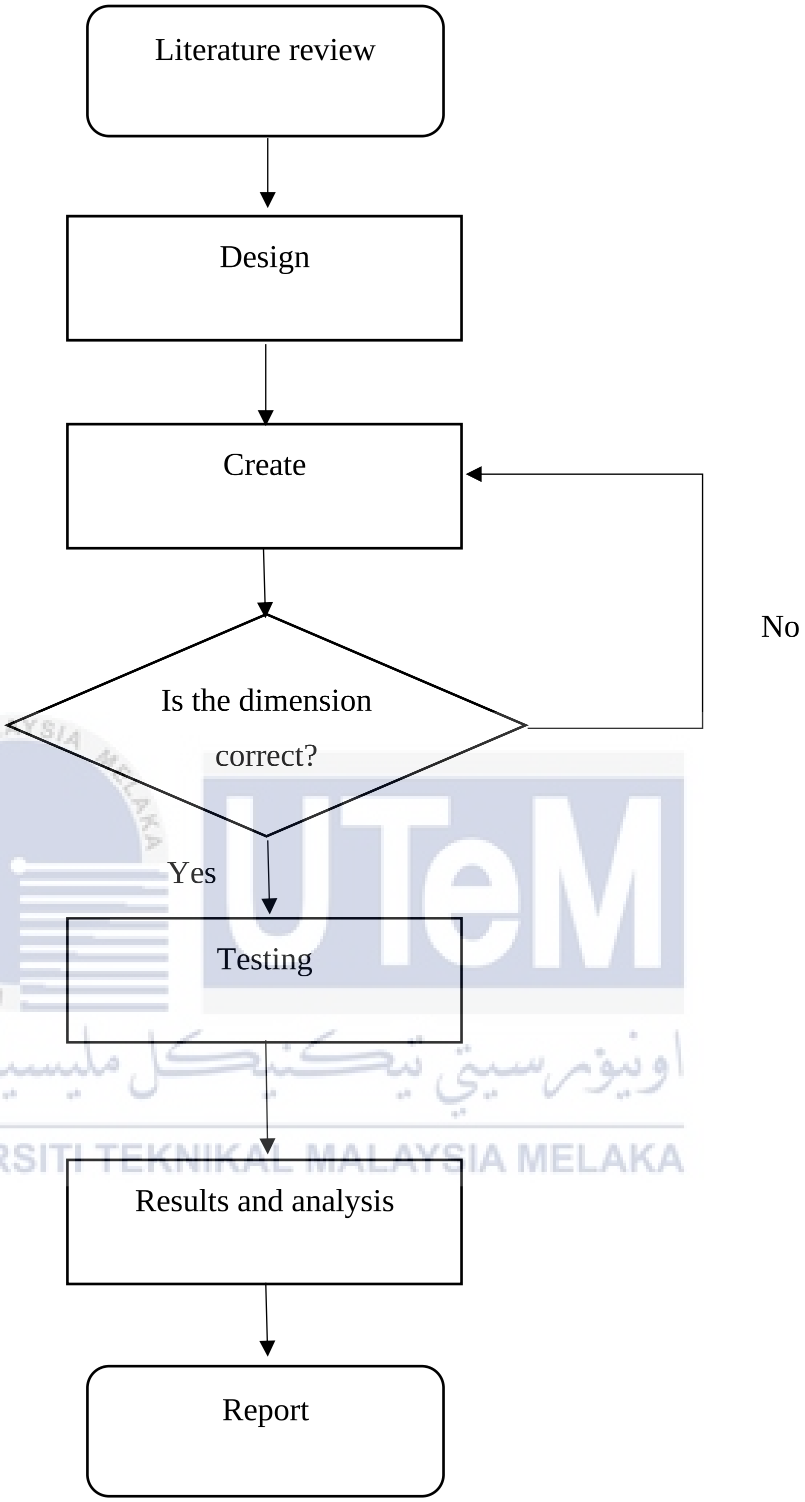
   Experimental study of the compressive strength with the specimens.

6. Results and analysis

   All results are collected in a suitable manner. Analysis will be presented on how every specimen from particular manufacturer withstand the compressive testing until failure to determine their strength.

7. Report writing

   A report on this study will be written at the end of the project.



Flowchart of the methodology

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter goes over a few key components that involve with Fused Deposition Modelling (FDM) and materials used for 3D printing. PLA, PETG, and ABS are just a few of the various materials available for FDM printing. ABS is one of the most often utilised materials in the industry for 3D printing these days due to a lot of advantages such as great heat resistance and lightweight. Given the large number of companies out there making the same material and each claiming to have the best product, consumers are having difficulty deciding which brand is the most durable. The goal of the project is for studying the strength comparison of FDM printed ABS manufactured by different companies. Several ABS specimens from a manufacturer will be printed and their strength will be tested using compressive test and tensile strength test. At the end of this project, the ABS material strength from various manufacturers can be compared to determine which brand is the best and provides the most value for money.

The failure of each specimen from each manufacturer can be detected by the strength testing. The point of failure, as well as the amount of compression and tension that a specimen can bear, will be determined. To eliminate errors and interference with the test findings, each specimen prepared for the test must have the same dimension. ABS material strength from various manufacturers will be compared and analysed.

2.2 Additive Manufacturing

Additive manufacturing (AM) is manufacture producing name for 3D printing, a computer-controlled process that produces three dimensional objects by deposition of substance, commonly in layers. AM processes also have been studied, and some have even been commercialised. Stereolithography (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Laminated Objective Manufacturing (LOM), Three-Dimensional Printing (3DP), and Laser Metal Deposition (LMD) are just a few examples of AM [2]. Information is taken from a computer-aided design (CAD) file and translated to a stereolithography (STL) file in additive manufacturing processes. The drawing created in CAD software is approximated by triangles and sliced to include the details for each layer that will be printed in this process. AM technologies have the advantage of being able to create items with geometric and material complexities that would be impossible to achieve with subtractive manufacturing methods.

The ASTM F42 committee grouped the AM processes into seven categories in an effort to standardise terminology. The method of material deposition, the energy source used, and the state of the construction material used all differ from one another (wire feedstock, liquid, powder or sheets). The following is a list of these processes:

1) Binder jetting: To combine powder materials, a liquid bonding agent is placed selectively.
2) Directed energy deposition: Focused thermal energy (e.g., laser, electron beam, or plasma arc) is used to fuse materials by melting as they are being deposited
3) Material extrusion: Material is selectively dispensed through a nozzle or orifice.
4) Material jetting: Droplets of build material are selectively deposited.
5) Powder bed fusion: Thermal energy selectively fuses regions of a powder bed.
6) Sheet lamination: Sheet materials are bonded to form an object.

7) Vat photopolymerization: Liquid photopolymer in a vat is selectively cured by light-activated polymerization.

2.3 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is 3D printing process that uses a continuous filament of a thermoplastic material. Software that processes an STL file (stereolithography file format) is needed for FDM technology. A model must then be sliced with another programme for the build operation. Support systems can be created if necessary. The model is created by extruding thermoplastic material that solidifies upon exiting the nozzle in layers. A coil of plastic filament is unwound, and the flow is controlled by an extrusion nozzle. Worm-drive regulates the pace of filament insertion into the nozzle. To melt the material, the nozzle is heated. A numerically operated mechanism allows it to travel in both horizontal and vertical directions. A computer-aided manufacturing (CAM) software programme controls the nozzle, and the component is shaped from the bottom up, one layer at a time. Extrusion head movement is regulated by stepper motors. The mechanism employs an X-Y-Z rectilinear movement.

FDM process is extremely versatile because it allows minor overhangs on the lower layers. One of certain limitations of FDM is it cannot manufacture undercuts without the use of support content. Variety of FDM materials available, including ABS and PLA, that have various difference that can be comparable between strength and temperature properties [9].

2.4 FDM Parameter

The qualities of produced items are determined by numerous printing conditions that are set during fabrication process. From a research done, FDM process parameters affect the tensile strength of a built part. A study from Lee et al. (2007) concludes that printing parameters such as layer thickness, raster angle and air gap have a major impact on the ABS prototype. Three rapid prototyping processes which are FDM, 3D printer and Nanocomposite Deposition (NCDS) were used to produce prototype parts to study the effect of build direction on the compressive strength. The tested prototypes were found to be extremely influenced by the build direction when using NCDS. Printed parts are sensitive to processing parameters as it influences the meso-structure and fibre-to-fibre bond strength. Furthermore, due to the FDM build technique, uneven heating and cooling cycles cause stress accumulation in the constructed component, resulting in distortion, which is the primary cause of poor bonding and hence affects the strength.

A test was also conducted by Lee et al. (2007) to see how component orientation and raster angle differences influence tensile strength. Both method parameters were discovered to have an impact on the tensile strength. In the test, crucial printing parameters including raster width, part orientation, raster angle and air gaps were analysed to see their impacts on the tensile strength of test prototypes. The following are the meaning of the parameters:

:

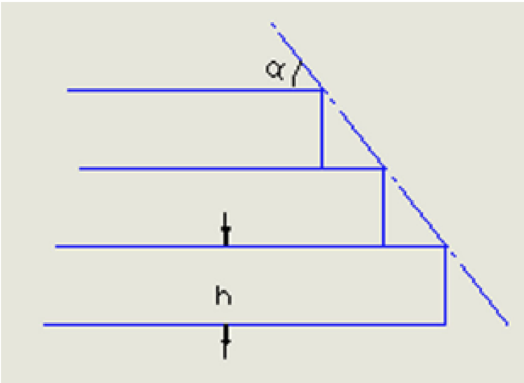


Figure 2.1: Height of slices or layout of layer thickness

1) The layer thickness, as seen in Fig. 2.1, is the deposited slice height of the FDM nozzle. This parameter is to see how thicker or thinner layers affect the consistency of the final product.

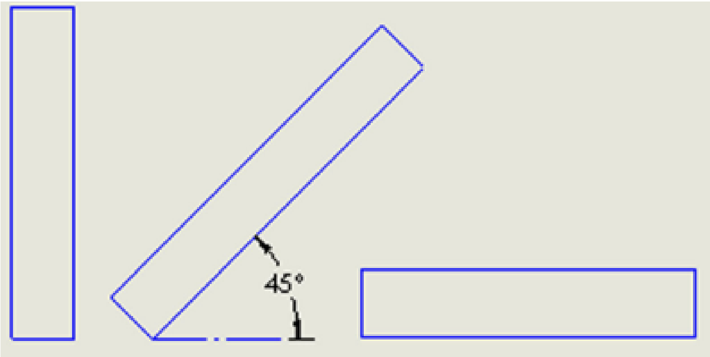


Figure 2.2: Orientation of part

2) The part's orientation is described as how it should be oriented during production, as seen in Fig. 2.2.

Figure 2.3: Raster angle parameter

3) The raster is measured from the X-axis on the bottom layer as seen in Figure 2.3. It also describes the orientation of the material beads (roads) in relation to the part's loading.

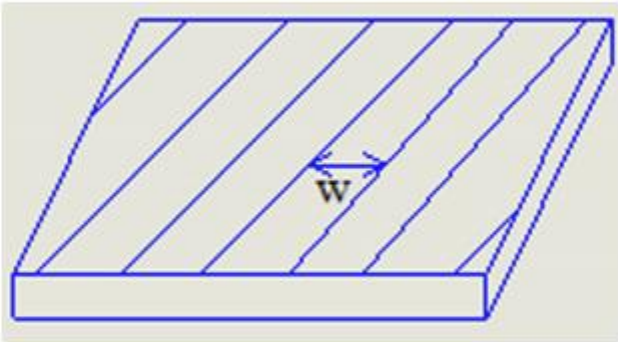


Figure 2.4: Raster width parameter

4) The raster width, also known as road width, is the breadth of the deposition path in relation to size of the tip. As demonstrated in Fig. 2.4, Raster width relates with the width of the tool path of the raster pattern that is used to fill the interior portions of the curve parts.

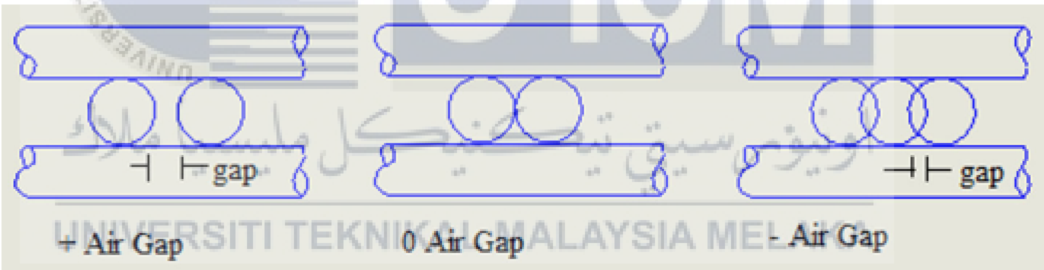


Figure 2.5: Air gap application

5) The air gap parameter, as shown in Fig. 2.5, is the distance between the beads of deposited FDM material.

A total of 32 parts were produced to test out the tensile strength. The specimens were fabricated in a build direction with different part orientation (0°, 39°, 90°) and different raster angle (0°, 30°, 45°). All specimens are from ABS material. From Table 2.1, a clear difference of strength values could be seen when there is a variation of process parameters. The maximum tensile strength is collected in run 5 with detailed processing parameters shown in Table 2.1.

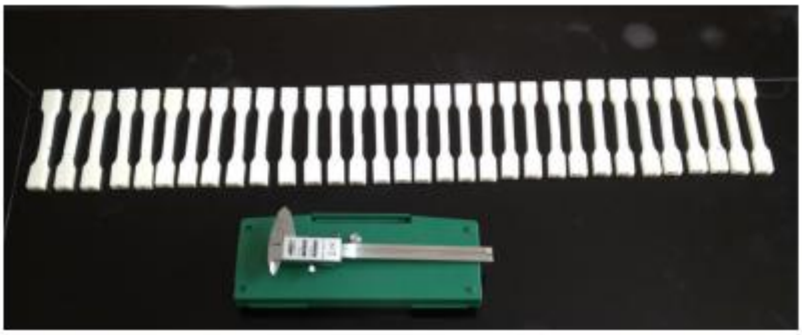


Figure 2.6: Thirty-two dogbone ABS specimens for tensile test

Table 2.1: The input process parameters

Run	A [part orientation]	B [raster angle]	C [raster width]	D [air gap]	Measured (MPa) UTS
1	0	0	0.2032	−0.00254	34.07
2	0	0	0.2032	0.5588	6.14
3	0	0	0.5588	−0.00254	29.83
4	0	0	0.5588	0.5588	10
5	0	45	0.2032	−0.00254	38.9
6	0	45	0.2032	0.5588	4.44
7	0	45	0.5588	−0.00254	36.03
8	0	45	0.5588	0.5588	8.59
9	90	0	0.2032	−0.00254	23.94
10	90	0	0.2032	0.5588	4.29
11	90	0	0.5588	−0.00254	23.8
12	90	0	0.5588	0.5588	9.45
13	90	45	0.2032	−0.00254	21.51
14	90	45	0.2032	0.5588	3.95
15	90	45	0.5588	−0.00254	18.37
16	90	45	0.5588	0.5588	7.77

2.5 Materials for FDM

To produce high-quality components on a constant basis, 3D printing, like any other manufacturing process, requires materials of excellent grade that adhere to strict guidelines. 3D printing technology can create fully functional parts out of a variety of materials, including ceramics, metals, and polymers, as well as their hybrids, composites, and functionally graded materials.

2.5.1 Metals

Metal 3D printing technology has sparked a lot of interest in the aerospace, automotive, medical, and manufacturing industries due to the benefits it provides. Metal materials offer great physical qualities and can be employed in a variety of applications, including printing human organs and aerospace components. These materials include aluminium alloys, cobalt-based alloys, nickel-based alloys, stainless steels, and titanium alloys, to name a few. In dental applications, a cobalt-based alloy is suitable because of its heat-treated conditions, high stiffness, robustness, high recovery capacity, and elongation. Furthermore, 3D printing technology can use nickel base alloys to produce aerospace parts. In dangerous environments, 3D-printed objects made of nickel base alloys can be used because of its strong resistance to corrosion and hot temperature tolerance of up to 1200 °C. Finally, titanium alloys can be used to build the thing utilising 3D printing technology. Titanium alloys feature a number of unique qualities, including resistance to corrosive substance, malleable, oxidation resistance, and low density.

2.5.2 Polymers

Polymeric components, ranging from first model until practical constructions plus complex geometry, are frequently produced using 3D printing technology. Utilising FDM, 3D printed model may be built by depositing successive layers of extruded thermoplastic filament like PLA, ABS, PP and PE. 3D print materials within state of liquid or low melting point is extremely put to use in the manufacturing industry because of the benefit the materials offer which are inexpensive and lightweight. Polymers have played an essential role as inert materials within medical field where it offers produce of device that can implanted into human body through surgery to restore body parts function.

2.5.3 Ceramics

3D print technologies may now generate objects utilising ceramic and concretes with not having significant pore or crack thanks to parameter optimization and establishment of good mechanical qualities. Ceramic is a strong, long-lasting, and fire-resistant material. Ceramic materials may be applied in nearly all geometries and shapes because of before setup, the condition is fluid, making them excellent for forthcoming construction and building projects. Ceramic materials are helpful in a variety of applications, including dentistry and aircraft. Alumina, bioactive glasses, and zirconia are examples of these materials.

2.5.4 Composites

Composites have revolutionised high-performance industries with their great adaptability, light weight, and customizability. Carbon fibre reinforced polymer composites and glass fibre reinforced polymer composites are two examples of composite materials. Carbon fibre reinforced polymer composite structures are commonly used in the aerospace industry due to their high specific stiffness, strength, corrosion resistance, and fatigue performance. Glass fibre reinforced polymer composites are widely used in 3D printing for a variety of applications and have a wide range of possible application because of their low-cost and great efficiency. Fibreglass has low coefficient of heat expansion with a strong thermal conductivity. Furthermore, because fibreglass does not burn and is unaffected by manufacturing process curing temperatures, it is a great option for 3D printing applications.

2.5.5 Smart materials

Smart materials are described as materials that can change the form and structure of an item in response to outward conditions including temperature and liquids. Self-evolution structures and robotic systems are two examples of 3D printed objects created with smart materials. 4D printing materials can also be classified as smart materials. Shape memory alloys and shape memory polymers are two examples smart materials. Some shape-memory alloys, such as nickel-titanium, have applications in biomedical implants and micro-electromechanical devices. Shape memory polymer (SMP) is a type of practical parts which respond towards stimuli such as brightness, electric conductivity, temperature, and certain varieties of chemicals. The complex shape of SMP could be produced using 3D printing technology.

2.5.6 Special materials

Food materials can be processed and produced using 3D print technology to create a certain desired figure and geometry. 3D-food printing can generate nutritious food since it let consumers to change the contents of the material without compromising the nutrient and flavor of the parts.

The 3D printing process also has the ability to produce multi-layered parts directly from lunar dust, which could be useful for future moon colonisation.

The development of 3D-textile printing will shine with the use of 3D printing technology in the jewellery and clothing industries. Shorter product processing times, lower packaging costs, and lower supply chain costs are some of benefits of the 3D print technologies in fashion industry.

2.6 Slicing software

In 3D printing, CAD files such as STereoLithography (STL) are regarded in practice. However, before the contour projection procedure can begin, the 2D contours layers must be made from slicing the STL file (Figure 2.7). Researchers have suggested numerous solutions for the before printing phase of STL in the past, including uniform slicing and adaptive slicing.

Figure 2.7: Process of generating shape: (a) Model with slice plane located at desired point (b) Shape after slicing

The STL format has established itself as the industry standard for RP. Binary STL and ASCII STL are two types of STL formats. The study was restricted to the ASCII STL file type. In ASCII STL file type, the solid name syntax is always followed by facet syntax with its standard vector, which is optional and frequently omitted with spaces. The outside loops represent its start of the vertex input, where P_1, P_2, and P_3 techniques are utilised, respectively. The floating numbers n and v are represented by the letters n and v.

```
solid name
facet normal ni nj nk
   outer loop
      vertex v1x v1y v1z
      vertex v2x v2y v2z
      vertex v3x v3y v3z
   endloop
endfacet
endsolid name
```

The *endfacet* syntax indicates that the facet has come to an end. Depending on the geometry's complexity, an STL file may include several facets, generally thousands. There is a newly found facets syntax following the preceding ending facets syntax if there is another facet. As the file's terminator, the STL file will make use of the *endsolid* name syntax.

Each facet was stored in a list of aspect classes that the slicing algorithm could read. The facet vertices, for example, were kept by the class (P_1, P_2,P_3), and also the facets highest and lowest Z-point. By comparing $z_{min} \leq z_{slice} \leq z_{max}$ for each facet in the list, the highest/lowest Z values are afterwards utilised for removing all other facets excepting those that intersecting upon slice plane.

All triangle part is converted into its own line segment using the slicing algorithm. Using the contour generation technique, these line segments may be joined to form contour lines. Facets in the STL format can be orientated in any direction and are completely arbitrary. Each potential connection between slice plane with all facet is depicted in Figure 2.8 and Table 2.2.

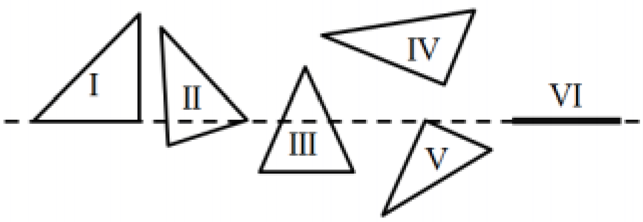


Figure 2. 8: Possible orientation and facets position

Table 2.2: Facet plane intersection definition

Case	Interaction of facet and plane	Possible Point
I	Line through one side of the facet	4
II	Line bisecting the facet through one vertex	3
III	Line bisecting the facet through two sides	2
IV	No intersection	0
V	Vertex intersection	2
VI	Parallel intersection	6

When each example of interaction indicated above is sliced, Table 2.2 classifies the probable number of points that would be created. Cases I, II, and III are the only ones that will produce the right line segment. The remaining cases are dismissed. Case V will have the same produced point while in Case VI, it was believed to be an advantage since in the real models, there will be other aspects of Case I in exactly same point yet it is vertical to those in Case VI. As a result, Case VI should been avoided for evading overlap lines of segment. Finally, there is no intersection in Case IV, therefore the algorithm will disregard it and go on to the next overlapping facet.

As a result of the facet edges with the same vertex yield two intersection points, intersections at the vertex will create two intersection points. Cases I, II, V, and VI all have this problem. As a result, these circumstances must be handled correctly. To isolate Case VI, the proposed algorithm first examines if the edges are paralleled or intersected upon the plane, then removes the corresponding edge in Case I. By removing a repeating intersection point, case II can be solved.

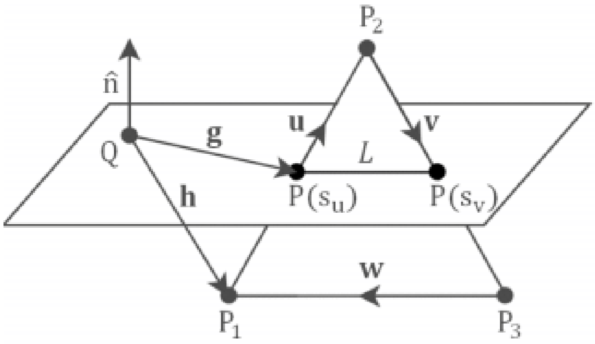
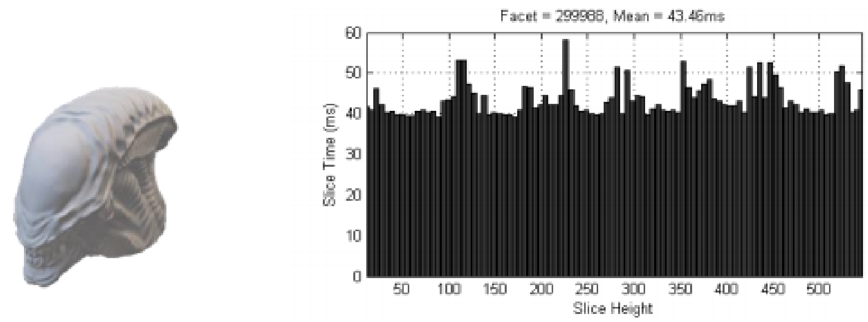
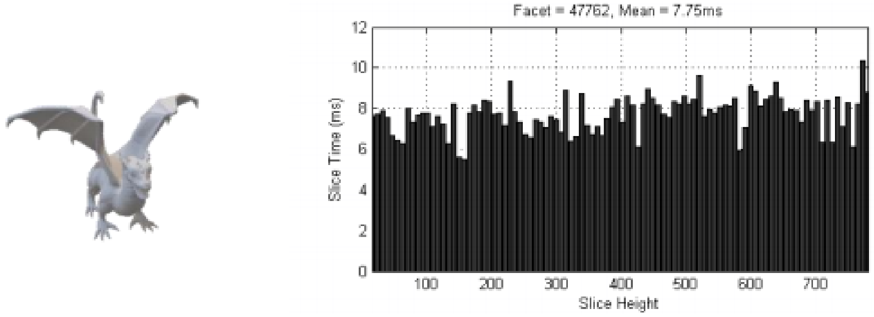


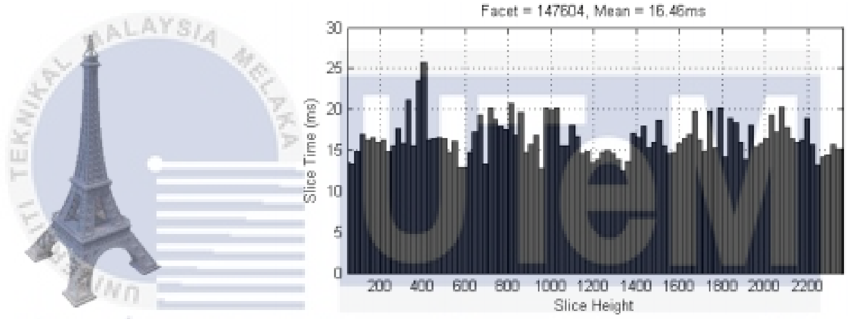
Figure 2.9: Facet-plane intersection diagram

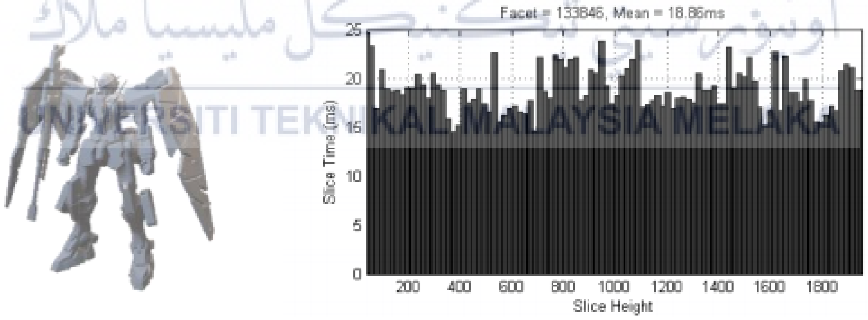
The line-plane intersecting calculation is the foundation to the suggested slicing algorithm. Consider the facet's one side as a line connecting two vertices. The line in three dimensions is either collateral or crosses the surface within one spot according to Figure 2.9.

Table 2.3: Sliced algorithm results


Facet = 299988, Mean = 43.46ms
Slice Time (ms)
Slice Height


Facet = 47762, Mean = 7.75ms
Slice Time (ms)
Slice Height


Facet = 147604, Mean = 16.46ms
Slice Time (ms)
Slice Height


Facet = 133846, Mean = 18.86ms
Slice Time (ms)
Slice Height

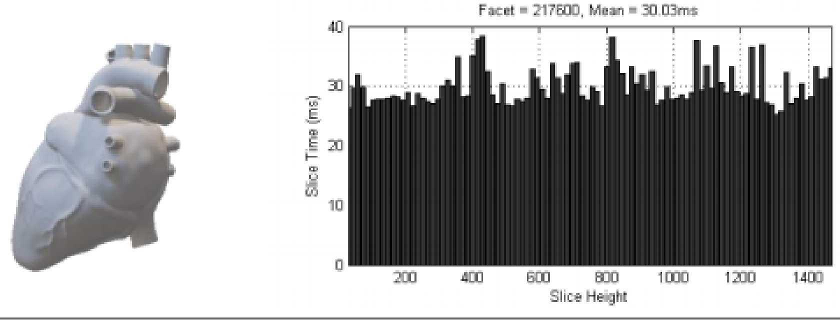

Facet = 217600, Mean = 30.03ms
Slice Time (ms)
Slice Height

Table 2.3 shows the results of slice timing with various slice heights, beginning from lowest point of the structure and progressing until highest point of all parts. The constancy of each slicing height's performance is obvious. As a result, the performance might be expressed with the average slicing time, as presented in the graph adjacent with 3 dimensional parts. Each part has a distinctive aspect number, which indicates the model's complexity. The contour slices in the graphs above are limited to 100. However, depending on the resolution of the DLP 3D printing equipment, this can be modified to any value. As displayed in Figure 2.10, a data demonstrated in graph of the facets number against the mean can be used to examine the relationship between each number unique facet and the mean number.

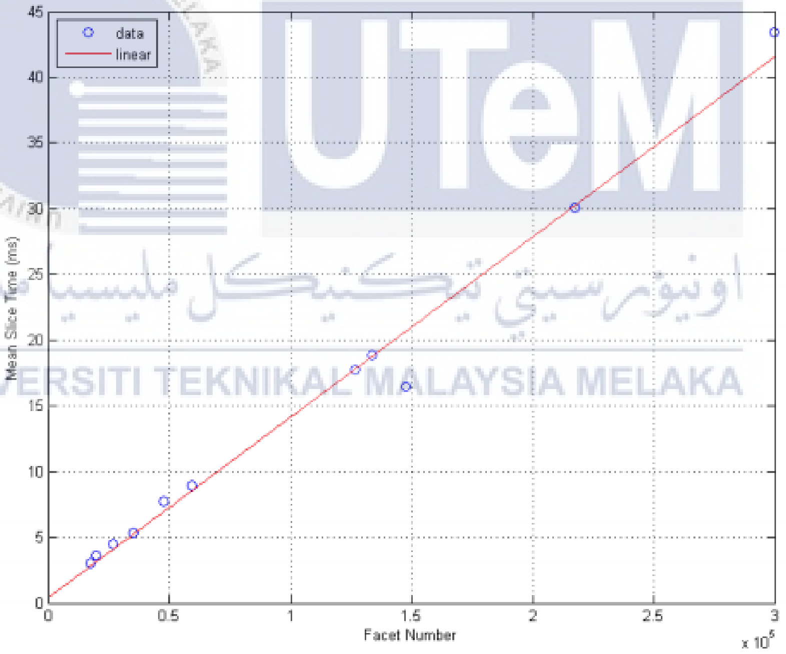


Figure 2.10: Facet Number vs. Mean Graph

Figure 2.10 has shown the average slicing time increases linearly in respect to the amount of facets. Slicing time will increase as the geometry becomes more complex. From ‘O’ notation, where it is a typical measure of algorithm difficulty, the slicing method given runs on O(n), which informs us that as the number of elements increases, so does the algorithm execution time. The results show that regardless of the slicing height, the slicing time of a geometry is consistent. A complicated model, on the other hand, will have a linear rise in slicing time. The slicing algorithm is usually used in conjunction with the contour generating method to combine each segment of the slice line into a single or mutiple closed contour loop.

2.7 ABS characteristic

The number of polymers compatible with material extrusion 3D printing platforms is rather limited, due to the precise qualities required for a successful print, such as a relatively low glass transition temperature (T_g), melting point (T_m), and a low tendency to shrink upon solidification. The ease with which the material may be extruded, how the components shrink throughout the cooling process, and the thermostability of the final item are all affected by T_g. Although the T_m can provide some insight into the extrusion temperature (T_e), the final T_e is greatly reliant on the machine's feeding system configuration. The majority of today's 3D printers can work at temperatures below 300°C. Acryliconitrile butadiene styrene (ABS, T_g = 110 °C, not a real melting point) and polylactic acid (PLA, T_g = 60 °C, T_m = 175 °C) are two of the most widely used materials for material extrusion 3DP due to their dimensional stability and low T_g. Other printable polymers include polycarbonate (PC, T_g = 145 °C, T_m = 230–260 °C), polyvinyl alcohol (PVA, T_g = 85 °C, T_m = 170 °C), and polythermide (Ultem, T_g = 185–216 C, T_m = 350–400 °C), albeit their use has a number of limitations. These materials demand extrusion temperatures of over 300°C.

Acrylonitrile, Butadiene, and Styrene are the three monomer units that make up the Acrylonitrile-Butadiene-Styrene polymers. Plastic has a wide range of qualities, including thermal resistance, light weight, easy formability, and reflectivity. With all of these qualities, it has opened up new possibilities for materials like ABS. This is beneficial for industrial applications such as manufacturing decorative items such as wheel covers and air conditioning parts. Plastic metallization is also used to manufacture electronic housing, indicating that it will be a viable option. ABS also combines impact, heat, chemical, and abrasion resistance with dimensional stability, tensile strength, surface hardness, stiffness, and electrical properties.

ABS is considered a food grade thermoplastic, and can be acceptable for use in food processing. Even at low temperatures, ABS plastic stays hard, rigid, and durable. It comes in three different types: fire-retardant, heat-resistant, and platable grades. The impact strength varies depending on the grade. The majority of natural ABS resins are translucent to opaque, however transparent grades can be made and tinted to practically any colour. Although general purpose grades may be suitable for some outdoor applications, extended exposure to sunlight produces colour changes as well as a reduction in surface gloss, hardness, impact strength, and elastic modulus.

2.8 Mechanical Properties of FDM ABS parts

Several test prototypes are produced by Jason et al. (2017) to test the tensile strength which the variables that are manipulated is the orientation in printing process. The specimens' geometries followed the ASTM standard specifications. Figure 2.11 shown the type of the specimens used and their respective dimension. Solidwork is used to generate the prototypes and saved in STL type file to be transferred to the slicer software that is needed for producing the G-code for printing.

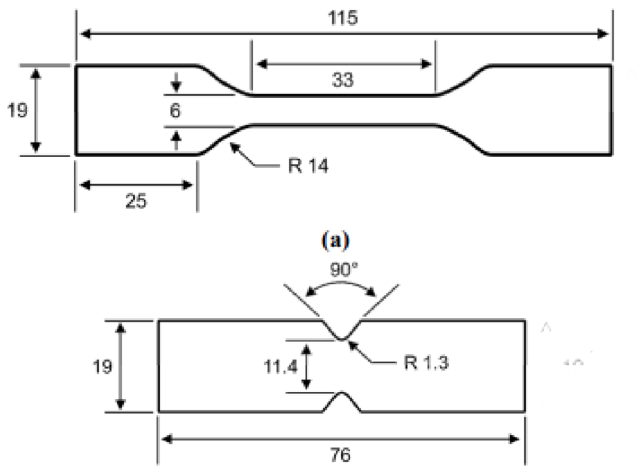


Figure 2.11: 2D sketching of (a) Tensile specimen with dimensions and (b) Shear specimens with dimension

Table 2.4: Tensile properties and Confidence Intervals of ABS specimens tested

Property	Orientation					
	[+45/-45] flat	[0/90] flat	[+45/-45] on-edge	[0/90] on-edge	[+45/-45] up-right	[0/90] up-right
Poisson's Ratio	0.36 ± 0.03	0.37 ± 0.04	0.38 ± 0.03	0.36 ± 0.02	0.36 ± 0.03	0.36 ± 0.03
Young's Modulus (MPa)	1960 ± 60	2020 ± 60	2020 ± 110	1910 ± 60	2040 ± 90	2050 ± 110
Yield Strength (MPa)	30.3 ± 0.6	32.0 ± 0.8	30.0 ± 1.1	29.0 ± 0.6	29.3 ± 0.8	29.9 ± 1.6
Ultimate Strength (MPa)	32.8 ± 0.6	33.5 ± 0.5	31.9 ± 0.9	30.7 ± 0.7	30.0 ± 0.8	30.9 ± 1.3
Strain at Failure (%)	8.89 ± 2.34	7.14 ± 2.79	5.41 ± 1.13	5.82 ± 1.26	1.72 ± 0.16	1.84 ± 0.15
Breaking Strength (MPa)	29.6 ± 0.5	30.7 ± 0.5	30.1 ± 0.9	29.4 ± 0.7	29.9 ± 0.8	30.8 ± 1.3
Strain Energy Density (MJ/m3)	3.17 ± 1.04	2.14 ± 1.03	1.46 ± 0.37	1.66 ± 0.41	0.29 ± 0.04	0.32 ± 0.03

The data from the ABS specimen testing revealed that some tensile qualities behaved isotropically, while others behaved anisotropically, with property variances of up to 91 percent. Table 2.4 lists all of the ABS tensile qualities that were assessed, as well as the orientation combinations that were examined. When comparing raster and print orientations, the Poisson ratio and Young Modulus revealed that there is no noticeable changes because each value are in those 95 percent CI. The results from the table also shown that the yield strength is heavily affected by the raster orientation of printing where prototypes that printed in flat orientation showed the greatest strength in tensile test.

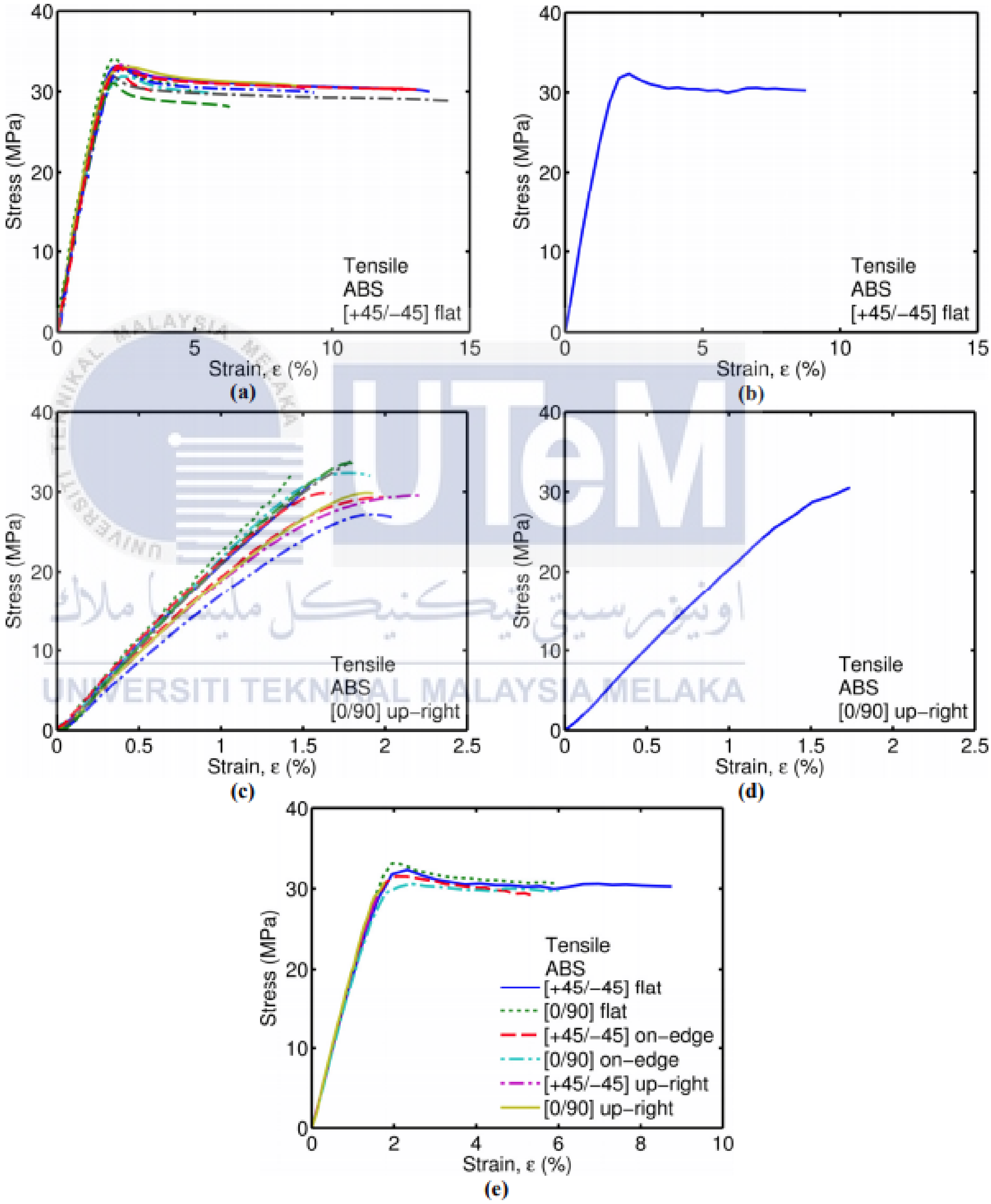


Figure 2.12: Stress-strain graphs for (a) Data of all ABS specimens tested on flat orientation (b) Average result of all prototypes (c) Data of all ABS specimens tested on upright orientation (d) Average results of all prototypes (e) The combination of all data from prototypes that is tested

Each orientation combination's ten tests are plot simultaneously to gain a sense of the data dispersion, and then averaged to produce a depiction of the normal stress-strain behaviour for that combination. Two examples of the data scatter are shown in Figure 2.12a and Figure 2.12c. From the figures shown, a conclusion could be made which mechanical properties of ABS prototypes varies when printing orientation is manipulated. The mechanical properties of ABS material could be obtained in such experiment. The ductility and brittleness of a material can be known by comparing the strength analysis that has been attained.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will go over the methods that were utilised to finish this project and compare the strength of FDM printed ABS manufactured by different companies in further detail. ABS material for 3d printing from different companies has been chosen for study and strength research to make it easier for consumers to decide which brand is the best and offers the lowest price with good quality. Tensile and compression tests will be carried out in order to ensure that the analysis of each material's strength is valid and trustworthy. In this project, 4 different brands of ABS filament weighing 1 kilogramme will be purchased, and several specimens will be 3D printed and evaluated. The finding of the strength data via graphs and tables from compression test and tensile test will further be analysed.

The major goal of this project is to show that the ABS material strength varies by manufacturer, despite the fact that the plastic material is the same, namely Acrylonitrile Butadiene Styrene.

3.2 Flowchart

The procedure begins with a meeting with the supervisor to provide an early briefing and notion about the project scope, as illustrated in Figure 3.1. Then, interpreting and determining the right measurement according to the global ISO for the test specimens. The specimens for the compression and tensile tests will then be created in CATIA V5R with the proper measurements. After that, 3D printers will be used to create the specimens. The test will be completed when all of the specimens have been generated and the measurements have been verified to be accurate. The manufacturer with the strongest ABS material will be identified and analysed as a result of the test. After all of the tests have been completed, report writing and analysis must be done.

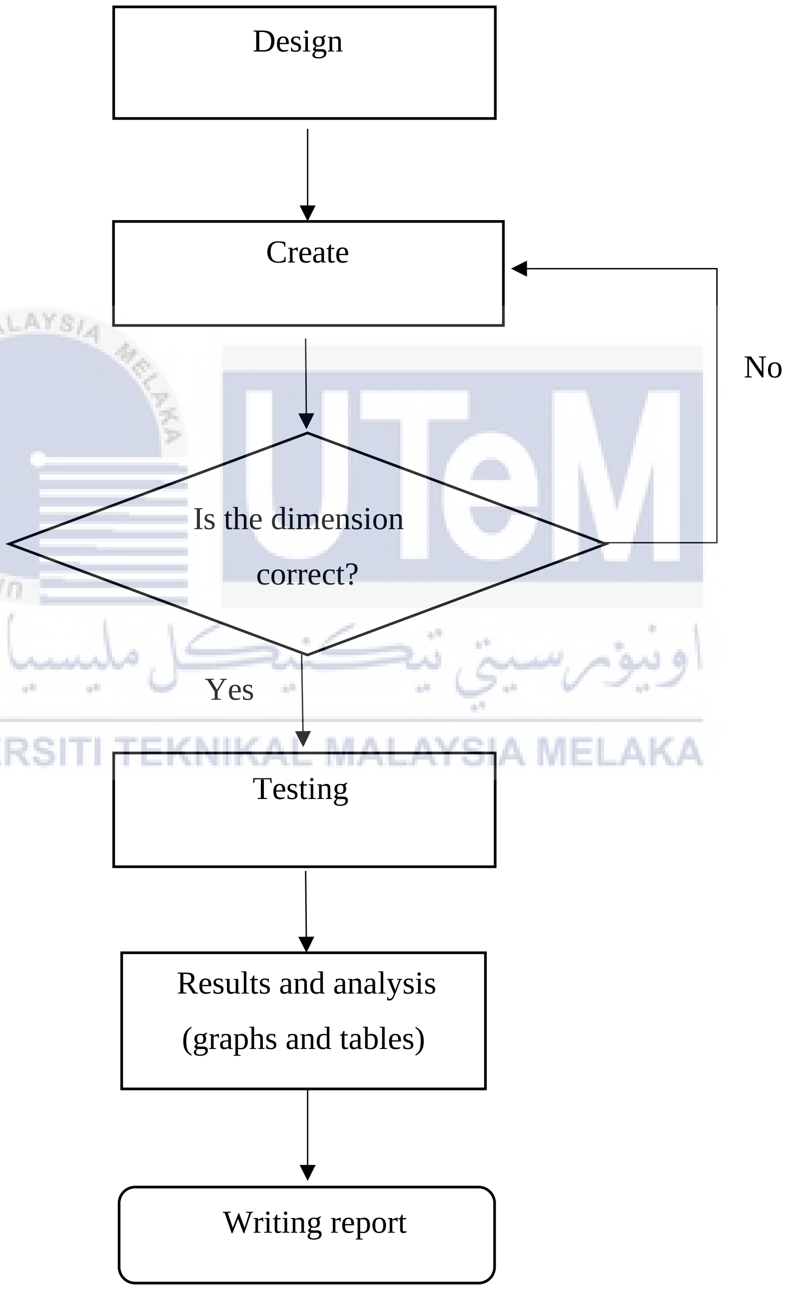


Figure 3.1: Methodology of this project

3.3 Test Specimens' Design

Before designing the test specimens in CAD 3D model in CAD applications, the dimensions of the specimens for both tensile and compression test must be confirmed following the global ISO. According to ISO 527, samples used in tensile test must have following dimensions:

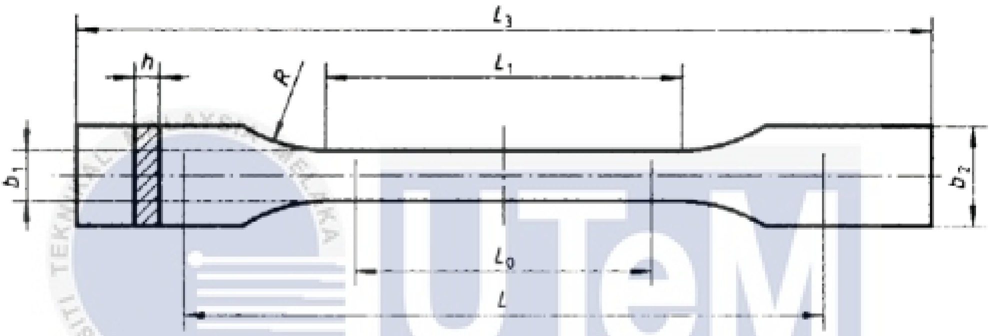


Figure 3.2: ISO 527 standard dogbone sample

L_3	Total length	≥150mm
L_1	Length of parallel edges narrow zone	60±0,5mm
R	Radius	≥60mm
b_2	Width at ends	20±0,2mm
b_1	Width at narrow zone	10±0,2mm
h	Thickness	2 to 10 mm
L_0	Reference length	50±0,5mm
L	Length between clamps	115±1mm

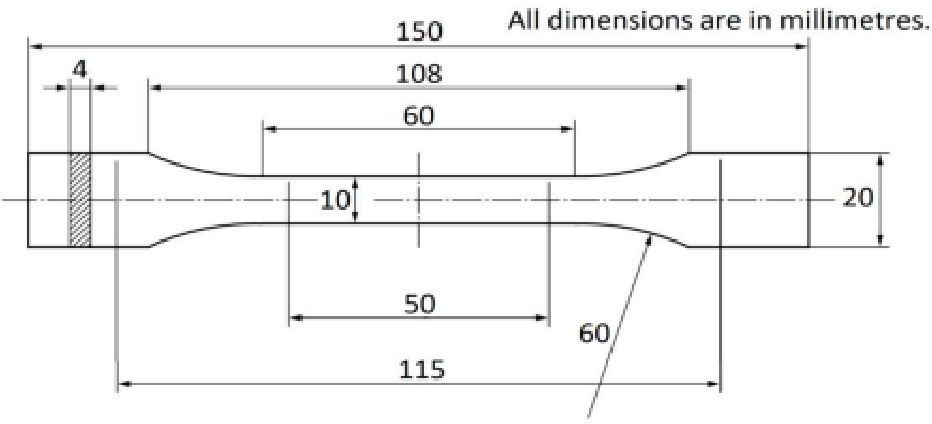


Figure 3.3: Dimension of the dogbone for the project

The dimensions for the dogbone that is used in this project is shown in Figure 3.3. The specimens in a compression test were designed in accordance with the PN-EN ISO 604-2006 standard and the dimension in millimetre is shown in Figure 3.4.

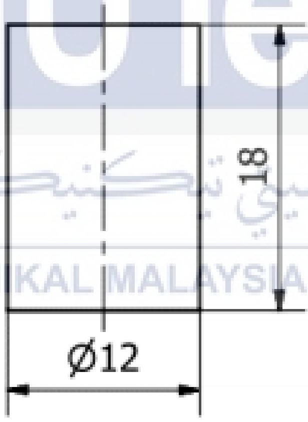


Figure 3.4: Dimension of test specimen under static compression

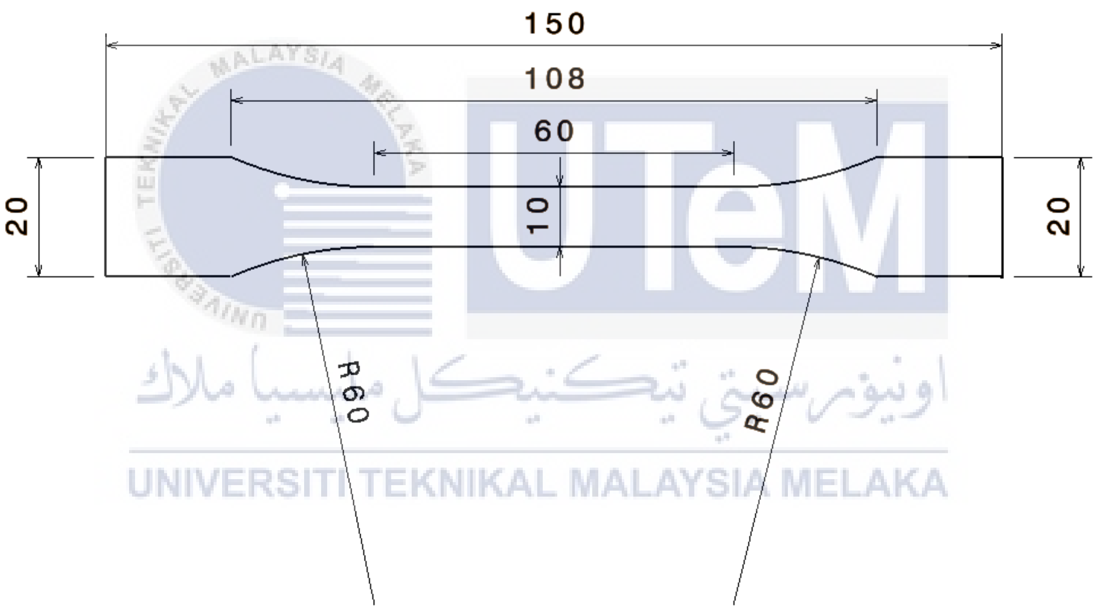
Table 3.1: List of ABS material manufacturers and specifications

Manufacturer	Colour	Price/Kg (RM)
FABBXIBLE	White	RM 50
SUNLU	White	RM 47

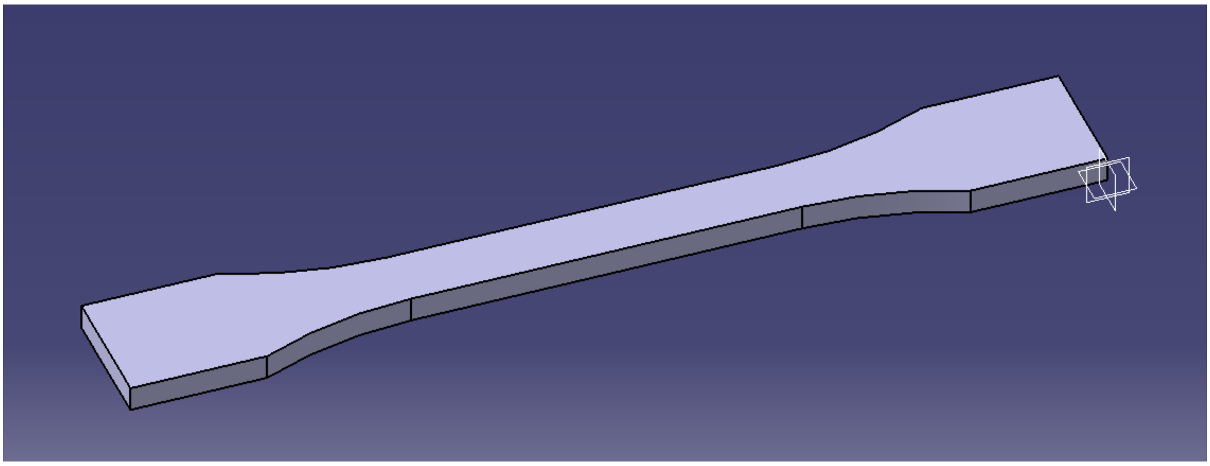
FLASHFORGE	White	RM 47
ESUN	White	RM 60

The ABS material from several manufacturers that is purchased to carry out this project is shown in Table 3.1. All the material is purposely chosen with the same colour to avoid any interference of the strength test results.

CATIA V5R is used to design test specimens for both tensile and compression test which is dogbone and cylinder.



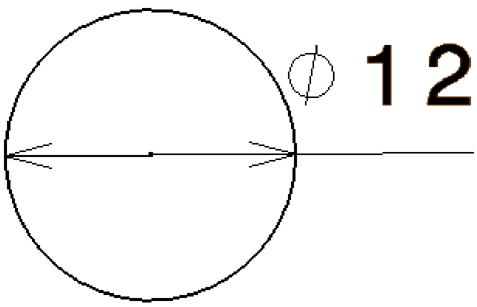
a) 2D sketching of dogbone with dimensions

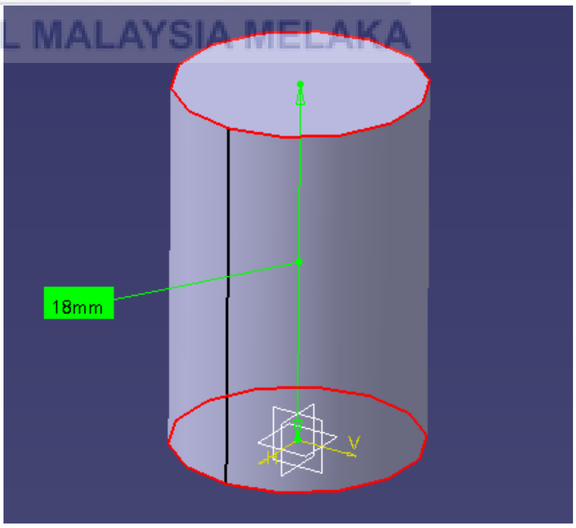


b) 3D representation of dogbone specimen

Figure 3.5: 2D and 3D sketching of tensile test specimen

Figure 3.5 showed the design of dogbone specimen for which will be created to test tensile strength of the ABS material from different manufacturers. The dimension that is shown is in millimetres and the thickness of the dogbone is 4 mm.





a) 2D sketching of cylinder with dimension

b) 3D representation of cylinder shaped test specimen

Figure 3.6: 2D and 3D sketching of compression test specimen

Figure 3.6 showed the design of cylinder specimen that will be used for compression test to study the compressive strength of the ABS material.

3.4 Print Parameters and Specimens' Fabrication

The test specimens were sliced using Ultimaker CURA 4.9.1 and printed on Creality Ender-3 3D printer as shown in Figure 3.7. The specimens were printed using Acrylonitrile Butadiene Styrene (ABS) filament of 1.75mm diameter.

Table 3.2: Printing parameters for dogbone and cylinder specimens

Printing parameters	Value
Nozzle size	0.4 mm
Layer height	0.15 mm
Wall thickness	1.0 mm
Infill density	50%
Print speed	70 mm/s
Infill pattern	Grid

Figure 3.7: Creality Ender-3 3D Printer

Ultimaker CURA Slicer version 4.9.1 was used to generate the G-code. By selecting "Standard Quality 0.15 mm" in the CURA slicer, predefined 3D printing settings are utilised, and key factors such as infill design, nozzle size, layer height, wall thickness, and printing speed are listed in Table 3.2. Five specimens were created for each test and each manufacturer for a total of 40 specimens analysed.

3.4.1 Printing specimens

After transporting the generated G-code for dogbone and cylinder specimens in a SD card, the printing process is proceeded. The temperature set up to melt ABS filament is kept constant which is 240°C for all 40 specimens. Figure 3.8 below shows the printing process of dogbone specimen using setting from G-code file that have been set up in Ultimaker CURA software.

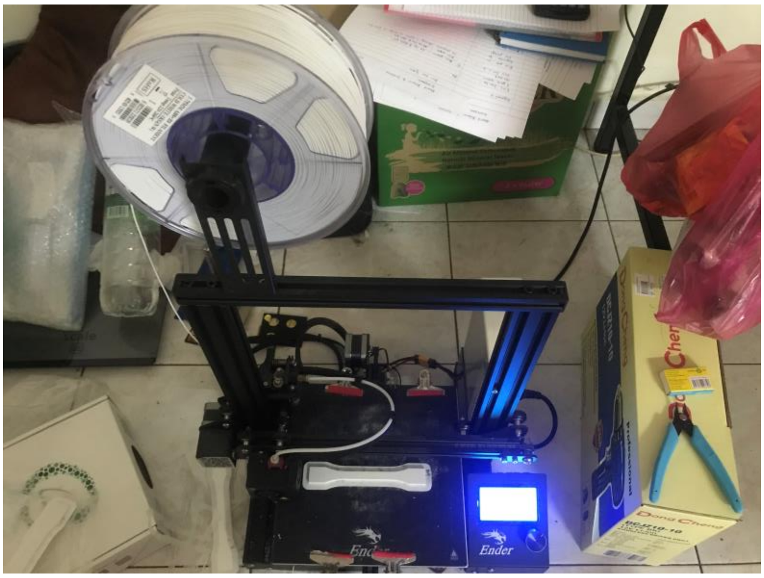


Figure 3.8: Printing process of dogbone

Before beginning the printing process, the printer's bed level is adjusted, and a piece of paper is placed beneath the nozzle as a guide to ensure that the nozzle is not too high or too low. If the nozzle is set too high, there is a chance it will not touch the printing bed, and the heated filament will just flush out of the nozzle instead of making the intended shape. If the gap of the nozzle is too close, the nozzle will be stuck at the printing bed and printing motor will not operates. Figure 3.8 shows a good dogbone specimen is created when the printer runs smoothly without any error.

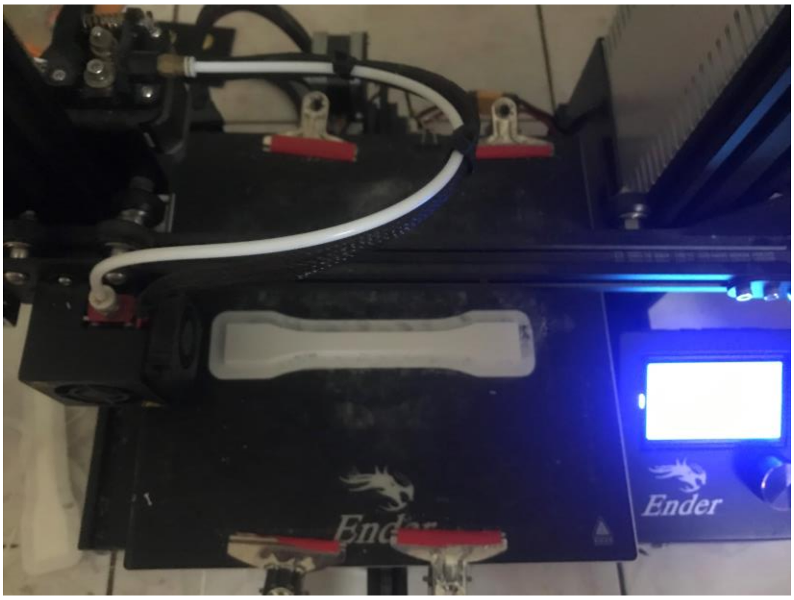


Figure 3.9: Successful dogbone specimen

The same method was used to print all of the specimens from various manufacturers until there were a total of 40 specimens, 5 dogbone and 5 cylinder specimens from each manufacturer. Figure 3.9 below shows the product of the printed specimens and has been detached from raft type support.

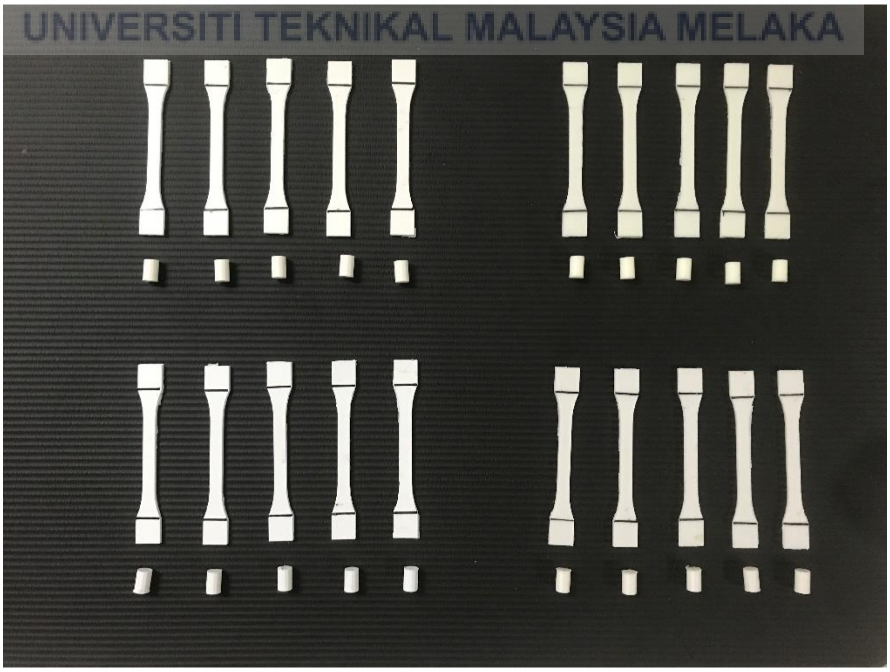


Figure 3.10: 40 specimens for tensile and compression test

3.5 Testing

In this project, two tests were conducted to determine the strength of the ABS materials. The results of the test were further analysed and concluded.

3.5.1 Tensile Test

After 3D printing, tensile testing was done on the Instron 5585 Universal Testing Machine (Fig. 3.11). Specimens are evaluated at a same strain rate of 5mm/min according to ISO 527-2 for both tensile and compression test. Stress strain diagram and the experimental data is collected from the machine after testing all the specimens from different manufacturers. The expected data from tensile test also including maximal forces that the ABS can withstand, tensile strength, yield strength, Young Modulus, strain and repeatability of strain results.

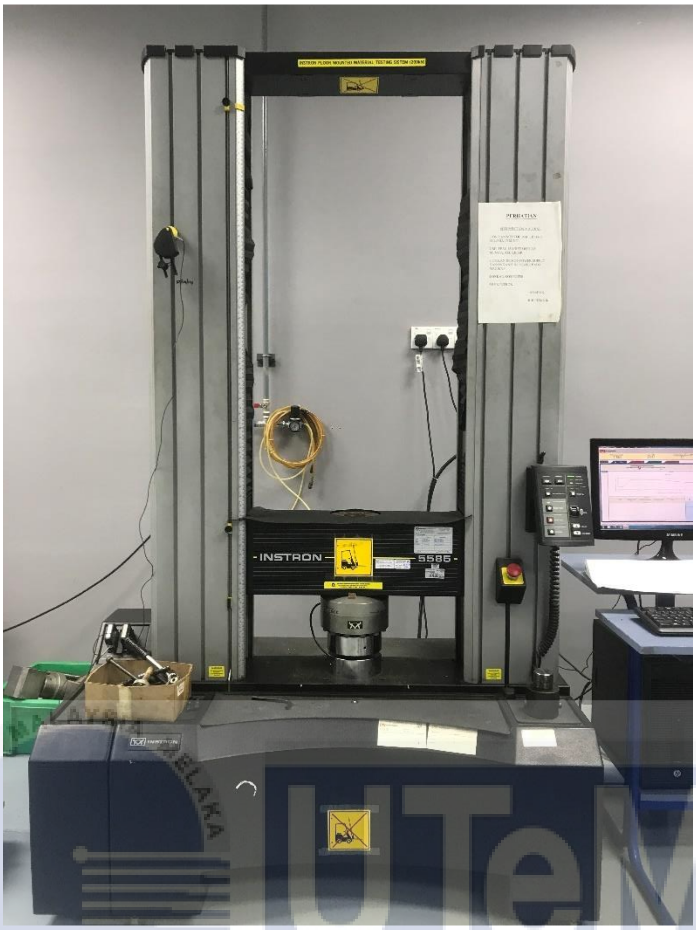


Figure 3.11: Instron 5585

To obtain results from tensile test at Instron machine, a Bluehill software is used to obtain the data. Figure 3.11 shows the Bluehill software interface and the parameter for testing is being kept constant for all specimens. Table 3.3 shows the parameter that is kept constant throughout the experiment.

Figure 3.12: Bluehill software interface

Table 3.3: Parameter for tensile test

Parameter	Value
Gage length	108 mm
Gage width	10 mm
Thickness of specimen	4 mm
Speed	5 mm/min

To start the tensile test, dogbone shaped specimen is clamped at Instron grip powered by air compressor. It is crucial to make sure that the specimen is gripped correctly vertical as this will affect the tensile test. Figure 3.13 shows the process of placing the specimen on the grip. After clamping the specimen at upper grip, jog down the upper grip close to lower grip until the lower part of specimen is clamped correctly.

Figure 3.13: Process of placing the specimen

Press start in the software and the machine will began pulling the specimen until it is fractured. Stop the machine after fracture and continue the process for other specimens. All the data is being saved in a removable disk and further analysis will be presented.

3.5.2 Compression Test

Instron 5585 will also be utilised in compression tests to determine the elastic modulus, yield strength, compression strength, and the maximum force that the ABS specimens can withstand before fracture. At the end of both tests, the presented data will be the mean values of 5 samples that has been evaluated for each ABS manufacturer. Figure 3.14 has shown the process of compressing the specimen.

Figure 3.14: Compression process of cylinder specimen

Before starting the compression test, the parameter of the test is set up in the Bluehill software as shown in Table 3.4 and is kept constant throughout the experiment. The geometry chosen for the compression is cylinder.

Table 3.4: Parameter for compression test

Parameter	Value
Diameter	12 mm
Length	18 mm
Speed	5 mm/min

Cylinder is placed at the middle of compression jig and the level of the jig is adjusted close to the specimen until approximately as close as a piece of paper for the gap between the specimen and the upper jig. The levelling of the jig is adjusted by pushing the jog down or jog up button on the side of Instron 5585 machine. The experiment started with the speed compression of 5mm/min. After fracture occurred, the experiment is stopped and cylinder specimen is replaced with another one. The process is repeated until all cylinder specimen is tested. The data obtained is saved to removable disk for further analysis.

3.7 Analysis

The results that are obtained in the tensile and compression test will further be analysed in Excel for greater understanding. To make comparisons easier, the data will be presented as graphs and tables. The average of each mechanical properties for each test from various manufacturer were taken to be studied. At the end of the analysis and report writing, the best ABS material manufacturer is identified and perhaps will benefiting consumers all over the world.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Tensile testing

The tensile tests performed on Instron 5585 machine has been grouped into several subcategories to compare the mechanical properties of ABS material manufactured by different companies. The specimens are labelled with a symbol A, B, C, and D to differentiate it and representing each company as shown in Table in 4.1. The Figure 4.1 shows the condition of every specimen after undergo tensile test. The collected data that is being compared between different manufacturer is stress vs strain graph, maximum load (N), tensile stress at maximum load (MPA), tensile strain extension at maximum load (mm/mm) and Young Modulus (MPa). The presented data are the mean value of 5 examined specimens that is tested for each manufacturer.

Table 4.1: Symbol representing each manufacturer

Manufacturer	Symbol
FABBXIBLE	A1-A5
FLASHFORGE	B1-B5
ESUN	C1-C5
SUNLU	D1-D5

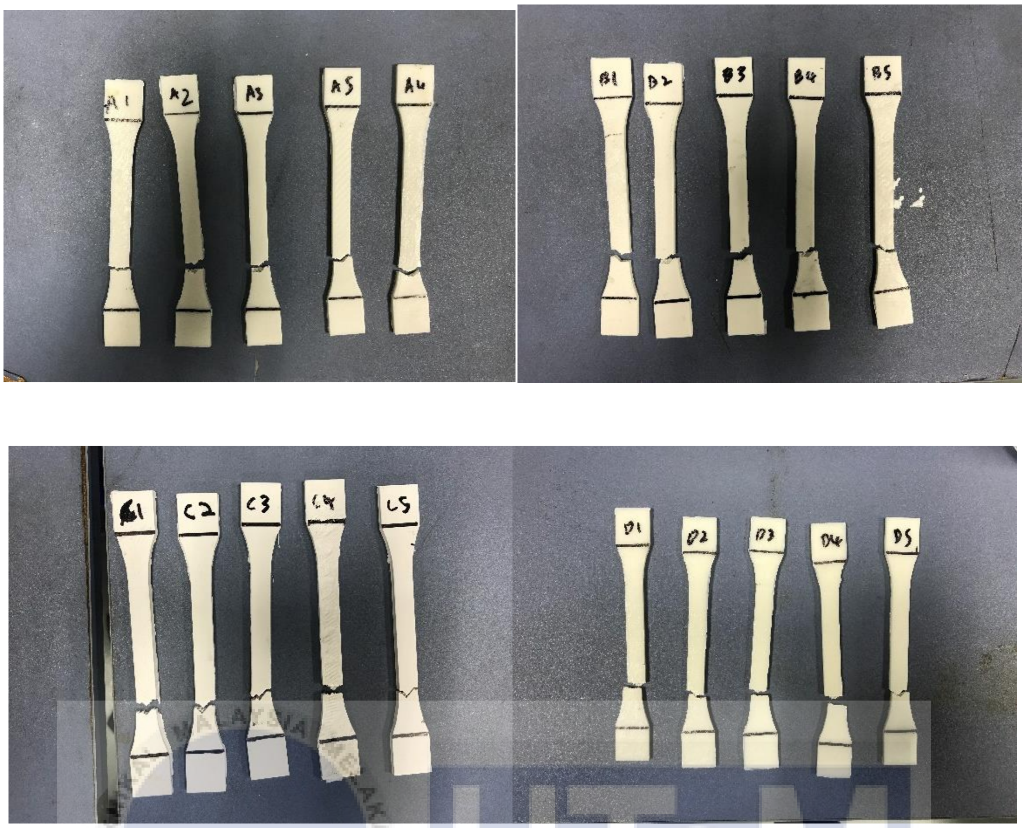


Figure 4.1: Specimens condition after tensile test

The graph of stress vs strain for tensile tests shows the differences and consistency of the results between each specimen. The fracture point of the specimens from the tensile test, on the other hand, is constant and is located around two-thirds of the way from the centre of the gauge section of the dogbone. Figure 4.2 shows the schematic diagram to show the gauge section of a dogbone test specimen.

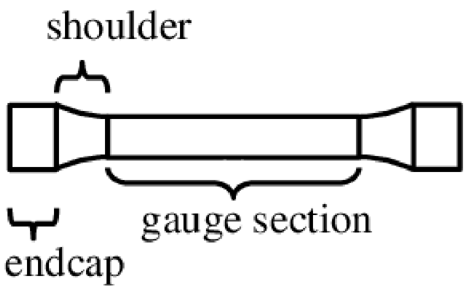


Figure 4.2: Schematic diagram of tensile test specimen

4.1.1 Maximum Load for Tensile Test

The maximum load results that were obtained clearly demonstrated that there was a significant variation in maximum load between specimens from each manufacturer. The maximum load that a specimen can sustain varies depending on the manufacturer of the ABS material used in the specimen. For each manufacturer, Table 4.2 displays the average maximum load that can specimen from ABS material withstand, whereas Figure 4.3 illustrates the maximum load that ABS material can bear.

Table 4.2: Average maximum load for each manufacturer

Manufacturer	Maximum Load (N)
Fabbxible	678.322
FlashForge	736.412
eSUN	630.922
SUNLU	858.880

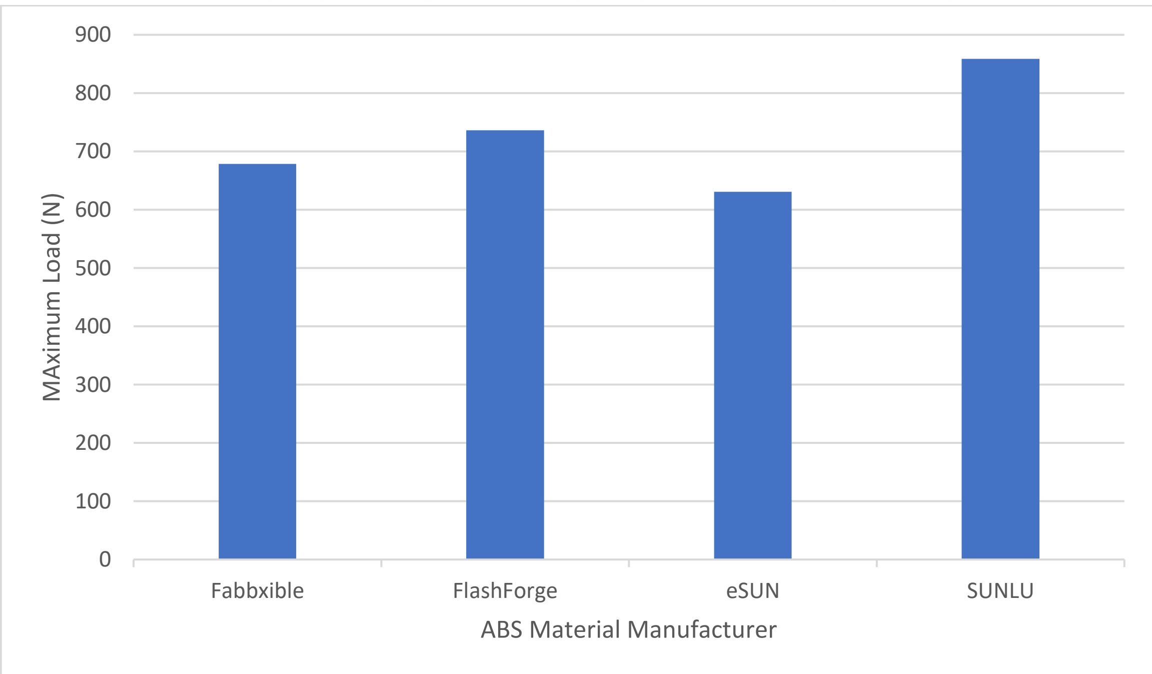


Figure 4.3: Maximum load that ABS material can withstand

According to Figure 4.3, the maximum load that ABS can bear when compared amongst manufacturers demonstrates that each manufacturer has a different maximum load. The ABS material from SUNLU can handle the highest maximum load (858.88 N), while the ABS material from eSUN can tolerate the lowest force (630.922 N) before breaking. This demonstrates that SUNLU's ABS material has the greatest capacity to endure the highest load when compared to other manufacturers.

4.1.2 Tensile Stress at Maximum Load

When the tensile stress at maximum load was measured in this research, the results revealed a significant disparity between the results from each manufacturer. The tensile stress at maximum load varies depending on the manufacturer of the ABS material used in the test. Table 4.3 illustrates the inconsistency of the tensile stress at maximum load, which differs from manufacturer to manufacturer. Figure 4.3 depicts a comparison of tensile stress at maximum load for various manufacturers.

Table 4.3: Average tensile stress at maximum load

Manufacturer	Tensile stress at maximum load (MPa)
Fabbxible	16.96
FlashForge	18.41
eSUN	15.77
SUNLU	21.47

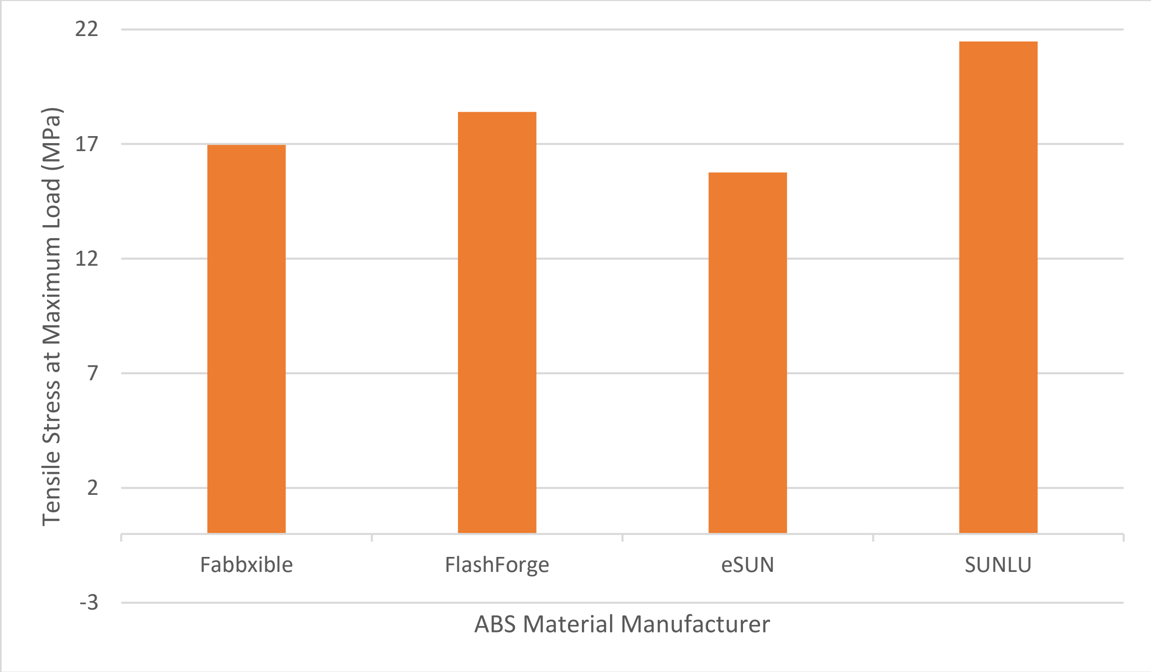


Figure 4.4: Tensile stress at maximum load for different manufacturers

Based on Figure 4.4 above, analysing all five ABS materials, it can be seen that there is a difference in tensile stress at maximum load up to 26 %. The ABS material from SUNLU is showing the highest tensile stress (21.47 MPa), while the material from eSUN is showing the lowest tensile stress at maximum load (15.77 MPa) as shown in the Table 4.3. The SUNLU ABS is the greatest specimen to withstand failure compared among specimens from other manufacturers.

4.1.3 Tensile Strain at Maximum Load

Tensile strain is the maximum extension of the specimen at fracture. The result of tensile strain at maximum load (mm/mm) obtained by Bluehill Software is shown in Table 4.3. Figure 4.5 shows the comparison of tensile strain from each manufacturer and it has shown every manufacturer has different tensile strain. Tensile strain that is also known as the capacity of each ABS specimen to endure breaking while changing form, is defined as the amount of strain applied to the specimen at the time of the break.

Table 4.4: Tensile strain at maximum load

Manufacturer	Tensile strain at maximum load (mm/mm)
Fabbxible	0.029078
FlashForge	0.025160
eSUN	0.019666
SUNLU	0.020424

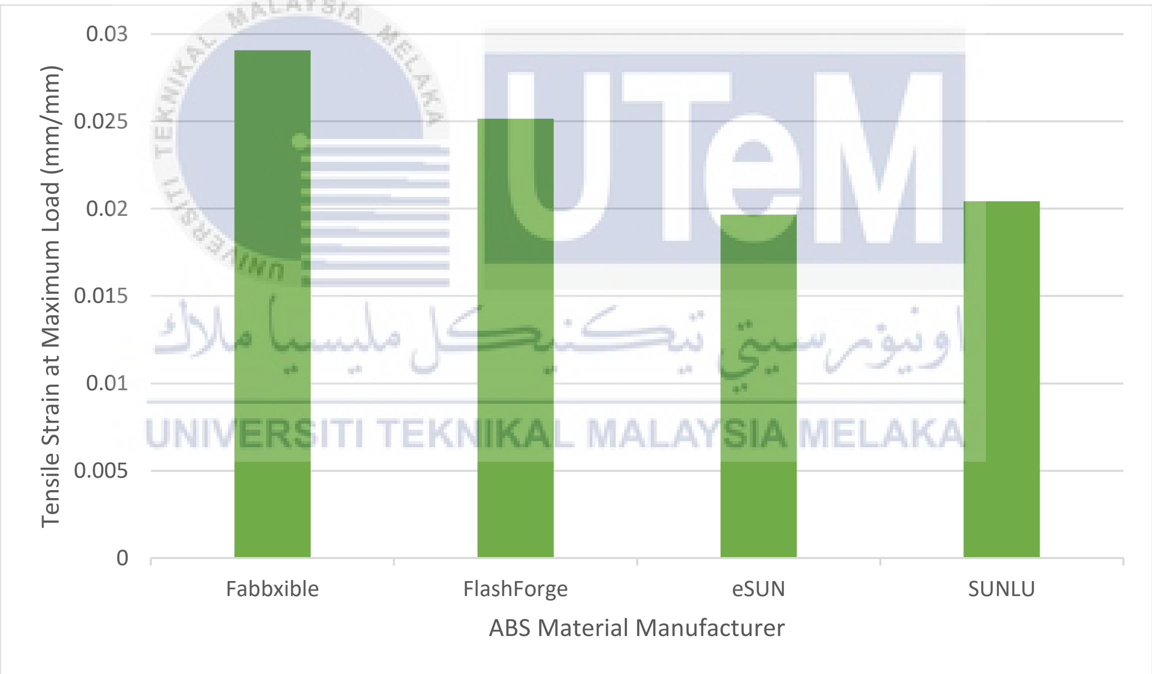


Figure 4.5: Tensile strain at maximum load for different manufacturers

It can be seen that material from Fabbxible shows the highest tensile strain at maximum load (0.029078 mm) while eSUN shows the lowest tensile strain (0.020424 mm). When compared to other ABS material producers, the tensile strain at maximum load for ABS material from eSUN is the smallest.

4.1.4 Young Modulus for Tensile Test

Young Modulus (E) is obtained to measure the ability of the ABS material to withstand changes in length when subject to this tensile test. The findings of Young Modulus from each manufacturer are provided in Table 4.5, and it can be observed that there is a significant difference in the value of Young Modulus between the manufacturers.

Table 4.5: Young Modulus for each manufacturer

Manufacturer	Young Modulus, E (GPa)
Fabbxible	0.712
FlashForge	0.818
eSUN	1.004
SUNLU	1.294

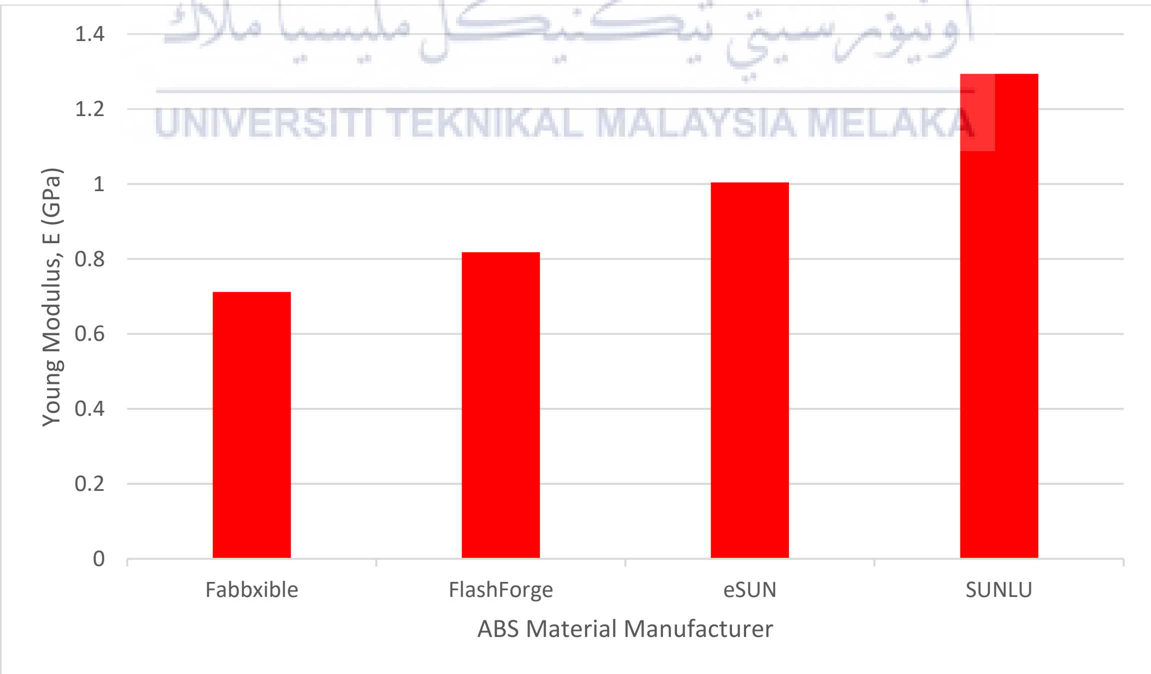


Figure 4.6: Comparison of Young Modulus for different manufacturer

The ABS from each manufacturer have demonstrated a variation of Young Modulus data collected from Bluehill software as shown in Figure 4.6 where SUNLU has the highest value of Young Modulus (1.294 GPa) while ABS material from Fabbxible shows the lowest (0.712 GPa). Analysing the data from Figure 4.6 which shows the comparison of the Young Modulus, the difference in Young Modulus is up to 45%. ABS material from SUNLU is the stiffest because it has the greatest Young Modulus among other manufacturers.

4.2 Compression Testing

Same process is repeated for compression test, where 5 specimens from each manufacturer were tested and average value will be taken to be analysed. Figure 4.7 showed every specimen that is labelled with a symbol after subjected to compression test. This is to differentiate the specimens from every manufacturer. Table 4.6 showed what symbol that is representing each manufacturer.

Figure 4.7: The condition of cylinder specimen after test

Table 4.6: Symbol representing each manufacturer

Manufacturer	Symbol
Fabbxible	A1-A5
FlashForge	B1-B5

eSUN	C1-C5
SUNLU	D1-D5

From the data obtained in compression test using Bluehill Software, the results show that each manufacturer affect the strength of ABS differently. It is important to note that even while each manufacturer uses the same ABS material, this does not always mean that their strength is the same.

4.2.1 Maximum Load for Compression Test

From compression test, the maximum load is obtained by Bluehill Software. Different manufacturer shows different maximum load in kN. Table 4.7 shows the maximum load for compression test from each manufacturer while Figure 4.8 shows the comparison of the maximum load for different manufacturer.

Table 4.7: Maximum load for compression test

Manufacturer	Maximum load (kN)
Fabbxible	3.9236
FlashForge	4.0536
eSUN	3.0716
SUNLU	3.4650

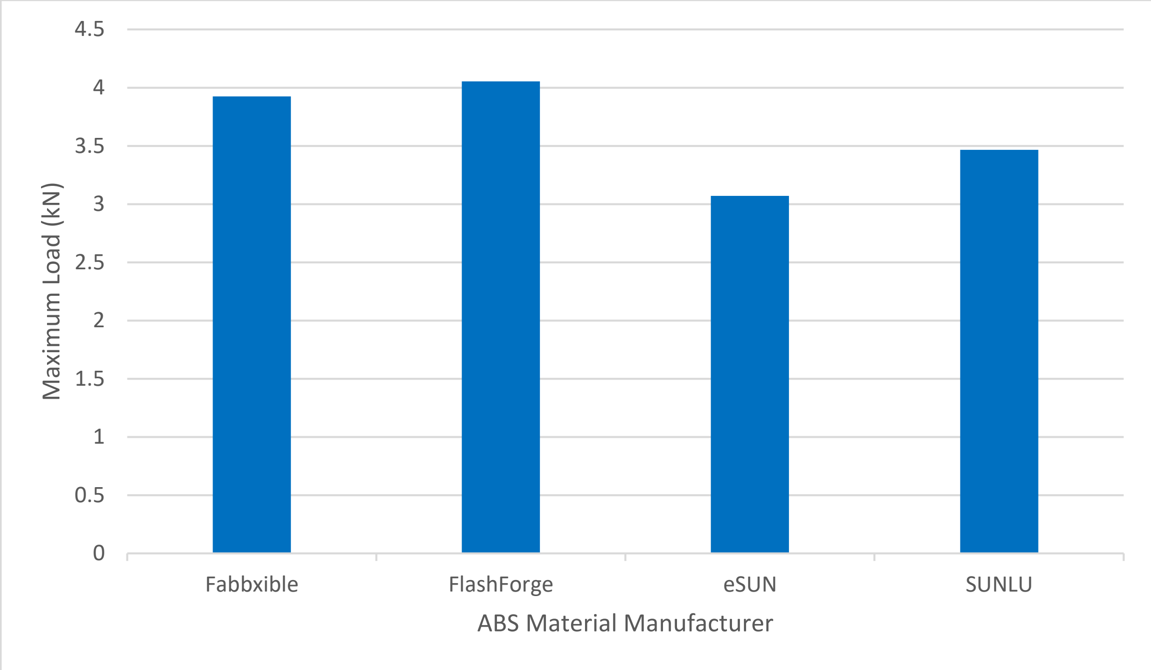


Figure 4.8: Maximum load for compression test

Maximum load shown from compression test in Table 4.7 shows the FlashForge has the highest (4.0536 kN) while eSUN has the lowest maximum load value (3.0716 kN). From the Figure 4.8, it can be clearly seen that FlashForge ABS can withstand the highest maximum load and is the strongest ABS material in dealing with compression among other brands.

4.2.2 Compressive Stress at Maximum Load

The compressive stress at maximum load were also analysed. Compressive stress the stress that happens from the shortening in one dimension of a body when subjected to oppositely directed collinear forces crushing it. Once again, different manufacturer results in different value of compressive stress when being compressed. Table 4.8 shows the compressive stress at maximum load in MPa while Figure 4.9 shows comparison of compressive stress at maximum load for different manufacturer.

Table 4.8: Compressive stress at maximum load for every manufacturer

Manufacturer	Compressive stress at maximum load (MPa)
Fabbxible	34.6914
FlashForge	35.8382
eSUN	27.1576
SUNLU	30.6360

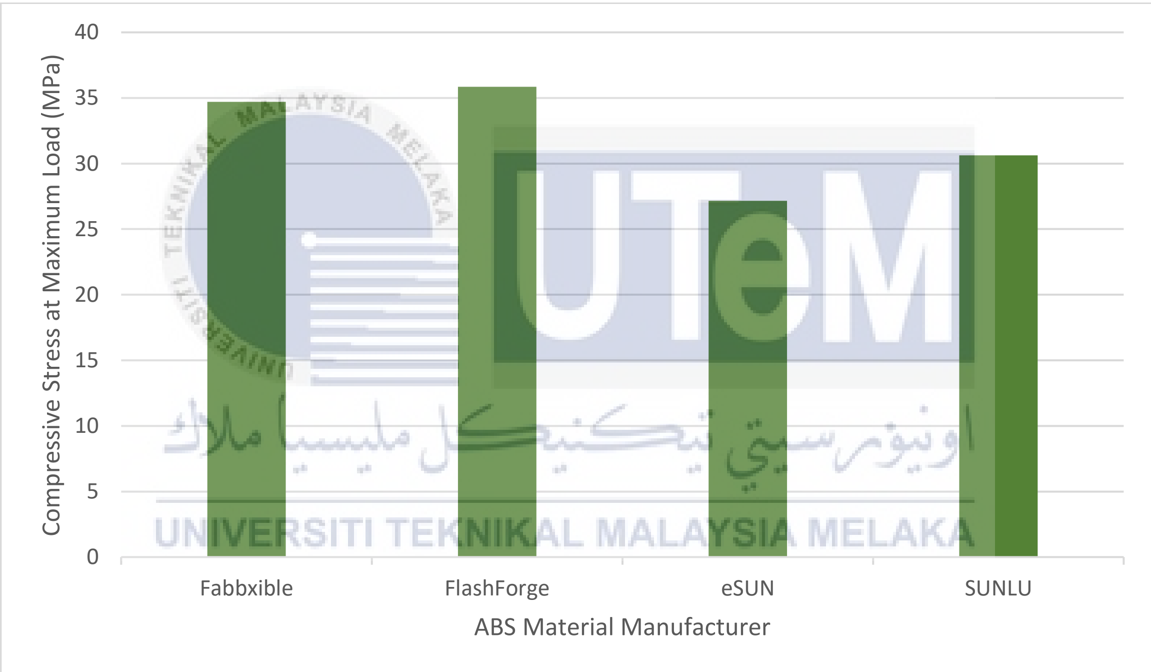


Figure 4.9: Compressive stress at maximum load for different manufacturer

From the Table 4.8, it can be seen that FlashForge also shows the highest compressive stress at maximum load (35.8382 MPa) than other manufacturer. There is a difference in compressive stress up to 24%. FlashForge has the ability to withstand compression better than other manufacturers before failure.

4.2.3 Compressive Strain at Maximum Load

Compressive strain is the fractional decrease in length of an object. From the results discovered, the compressive strain at maximum load revealed the strength of Flashforge manufacturer where eSUN has the highest compressive strain at maximum load (0.2112 mm) while FlashForge has the lowest compressive strain (0.0594 mm) as shown in Table 4.9. Figure 4.10 shows the compressive strain at maximum load comparison for different manufacturer.

Table 4.9 Compressive strain at maximum load for every manufacturer

Manufacturer	Compressive strain at maximum load (mm/mm)
Fabbxible	0.0610
FlashForge	0.0594
eSUN	0.2112
SUNLU	0.1188

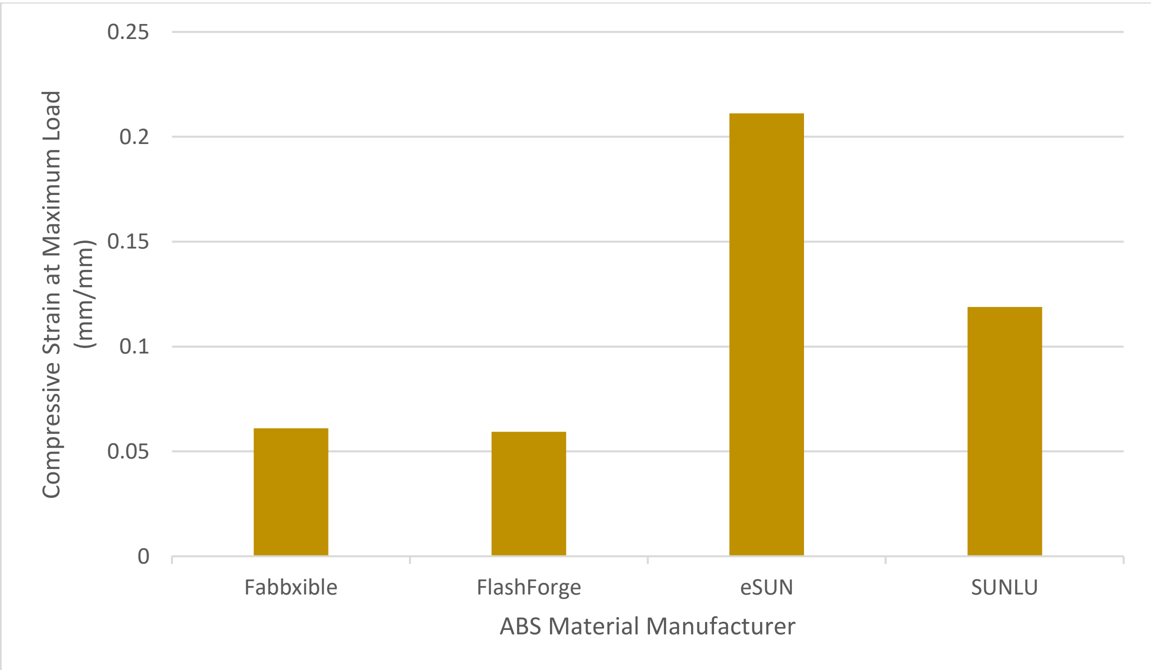


Figure 4.10: Compressive strain at maximum load for different manufacturer

The results of the tests are still varied where different manufacturer gives different value of compressive strain. For compression test, FlashForge manufacturer is consistent in proving the strength of their ABS material when subjected to compression.

4.2.4 Young Modulus for Compression Test

Young Modulus (E) is also observed in the compression test to measure the ability of the ABS material to withstand changes in length. From the finding in Table 4.10, different manufacturer displayed different value in Young Modulus (E). Figure 4.11 shows the comparison of Young Modulus from each manufacturer.

Table 4.10: Young Modulus for each manufacturer

Manufacturer	Young Modulus, E (GPa)
Fabbxible	0.9486
FlashForge	1.1306
eSUN	0.7534
SUNLU	0.9208

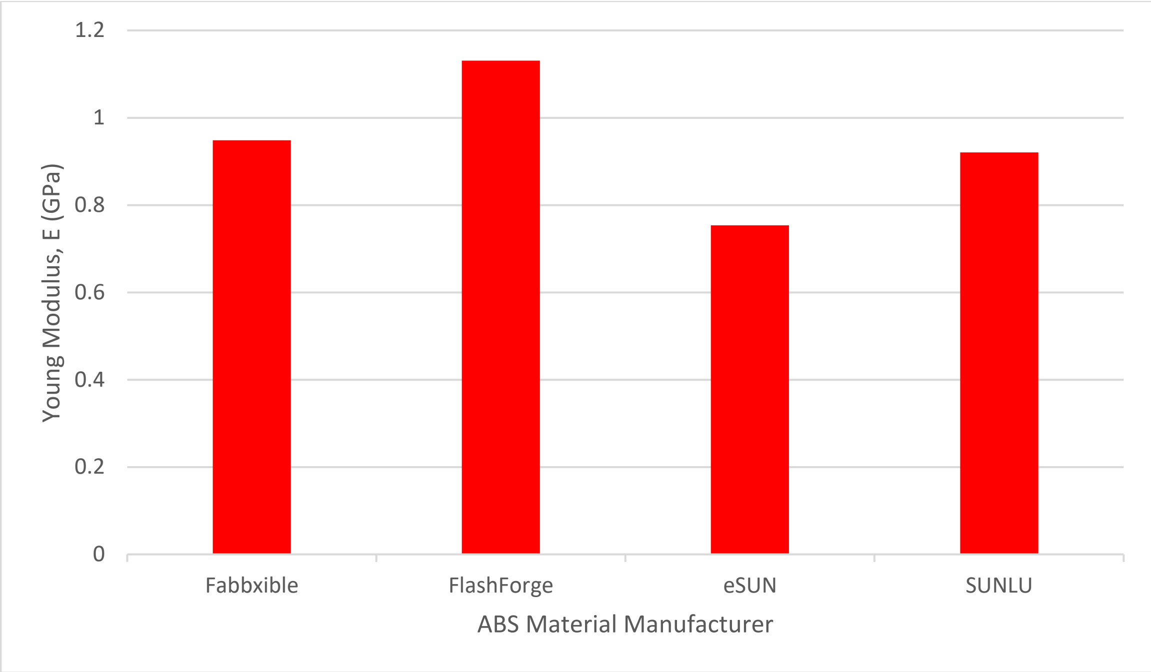


Figure 4.11: Comparison of Young Modulus for compression test

ABS material from FlashForge demonstrate the highest Young Modulus (1.1306 GPa) while eSUN has the lowest (0.7534 GPa) as shown in Table 4.10. Analysing the collected data from Figure 4.11 that shows the comparison of the Young Modulus for compression test, the difference in Young Modulus value can be up to 33%.

In spite of the fact that Young Modulus data is recorded for both compression and tensile tests, there is no consistency in which manufacturers report the greatest or lowest value. In the tensile test, SUNLU demonstrated the greatest Young Modulus value, however in the compression test, Flashforge demonstrated the highest Young Modulus value. The higher value of FlashForge Young Modulus compared to other ABS manufacturer indicates that the ABS from FlashForge is stiffer material.

4.3 Stress Vs Strain Relationship

From the Figure 4.12 that shows the stress vs strain diagram obtained from Bluehill software after having done the experiment for every specimen from each manufacturer, ABS from FlashForge has shown the most consistent results. Every color in the diagram indicating every specimen that have been tested. For each manufacturer, 5 specimens were tested in tensile test and compression test. The stress-strain diagram collected is the average results of 5 speimens tested from each manufacturer.

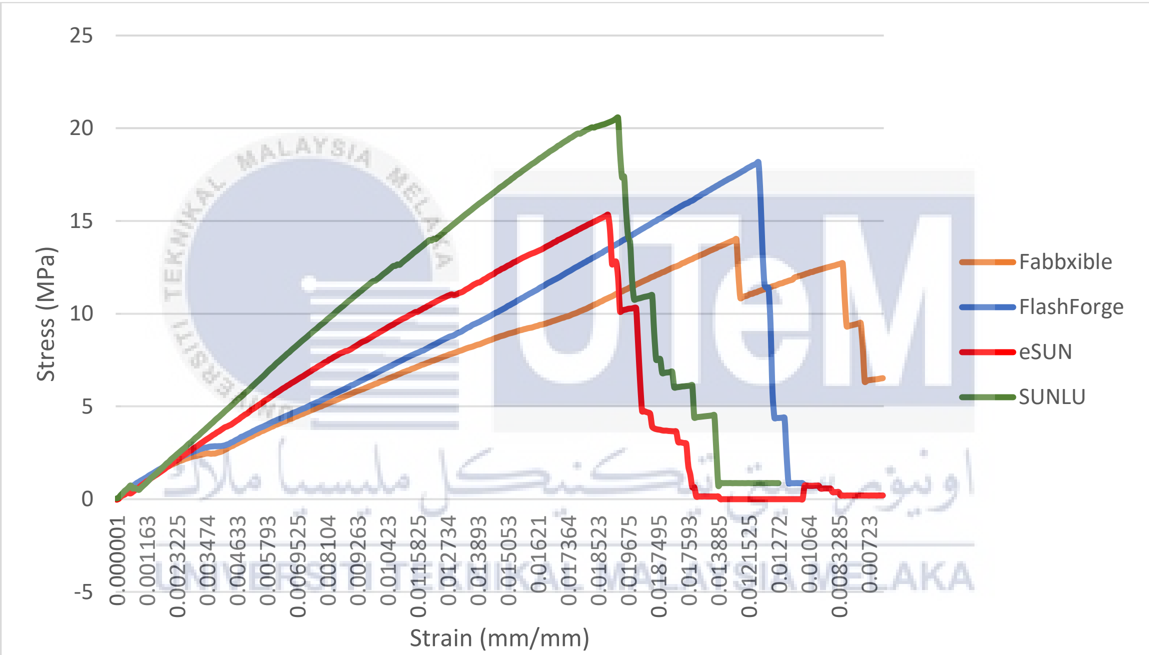


Figure 4.12: Stress vs strain tensile test diagram for each manufacturer

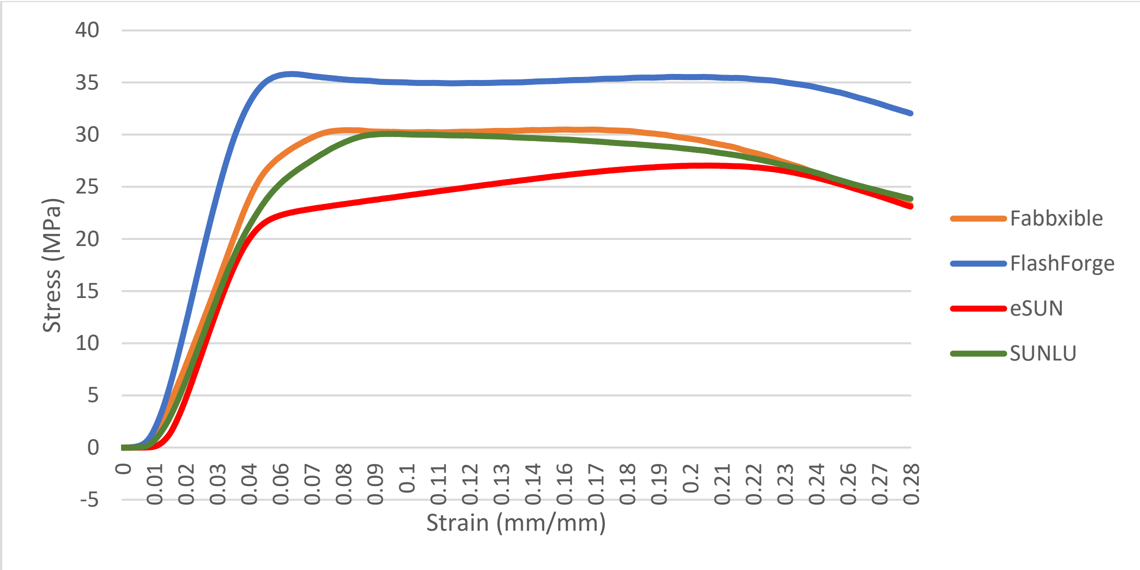


Figure 4.13: Stress vs strain compression test diagram for each manufacturer

Based on Figure 4.12, results of tensile stress shown by the highest point which is SUNLU is varied from 15.77 MPa to 21.47 Mpa which indicating the difference is up to 25%. According to Figure 4.13, comparing the results stress strain diagram in compression test which representing FlashForge as the highest stress point before curve where it is varied from 27.1576 MPa until 35.8382 MPa which results to percentage difference up to 24%. The results shown from both test is significantly different where the manufacturer that has the highest point of stress vs strain is not the same for both compression and tensile test.

4.4 Mechanical Properties of Material from Different Manufacturers

Based on the information provided by Bluehill 3 software, the average mechanical properties of the specimens from each manufacturer were also calculated. Table 4.11 lists the mechanical parameters of each of the specimens in from various manufacturer. From the table, it is possible to compare the mechanical properties of each coloured specimen to the other coloured specimens. In this instance, the difference in mechanical properties between every ABS from each manufacturer is just marginally different.

Table 4.11: The mechanical properties of the specimens from every manufacturer

Manufacturer	Ultimate Tensile Strength (MPa)	Ultimate Compressive Strength (MPa)
Fabbxible	16.96	34.69
FlashForge	18.41	35.83
eSUN	15.77	27.15
SUNLU	21.47	30.63

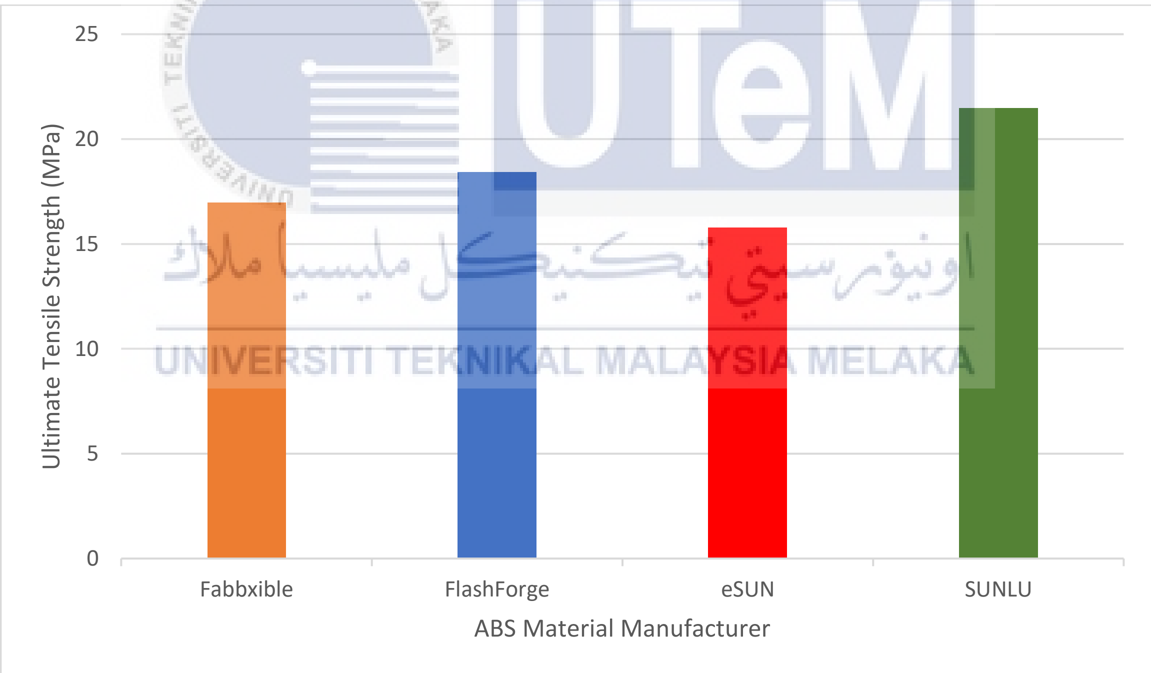


Figure 4.14: The comparison of Ultimate Tensile Strength from every manufacturer

The Ultimate Tensile Strength is the maximum stress that a specimen can withstand before breaking during a tensile test. From Figure 4.14, ABS material from SUNLU has the highest Ultimate Tensile Strength which is 21.47 MPa compared to other manufacturers.

The material from eSUN demonstrated the lowest Ultimate Tensile Strength at 15.77 MPa making the range is between 5.7 MPa. Figure 4.14 shows that there are differences in Ultimate Tensile Strength value from different manufacturers, thus proving the brands of ABS material affected the tensile strength.

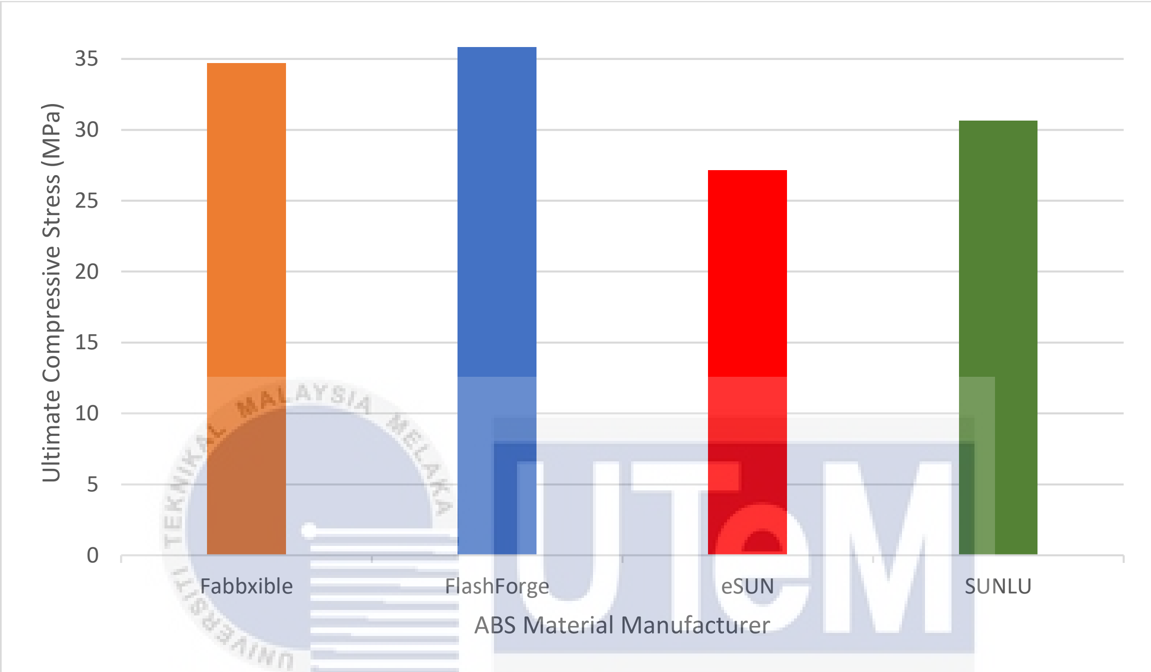


Figure 4.15: The comparison of Ultimate Compressive Strength from every manufacturer

Moreover, the Ultimate Compressive Strength for ABS material from each manufacturer is displayed in a distinct way. According to Table 4.11, FlashForge exhibited the highest compressive strength, indicating that it can withstand the highest maximum amount of compressive stress before fractures occur, which was 35.83 MPa. eSUN has the lowest value of Ultimate Compressive Strength (27.15 MPa), which was also found in the study. Thus, eSUN can endure compressive stress at a lower level than any other manufacturer, making it the weakest in compression tests. According to Figure 4.15, the difference in Ultimate Compressive Strength between the greatest and lowest values is 8.68 MPa.

Ultimate Compressive Strength was shown to be the mechanical property that was most affected in the study. When comparing the Ultimate Compressive Strength of the ABS specimens from each manufacturer, the difference is bigger than the difference between the Ultimate Tensile Strength. As a result, the goal of this study has been accomplished, as to study the strength comparison of ABS material from different manufacturer. The manufacturer of ABS material is proven to has an impact on the strength of the ABS material.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this project, to study whether the strength of ABS material is affected by the manufacturer, the parameters for 3D printing were all kept constant. Four different manufacturers were chosen to be studied on whether their ABS material will impact the strength. The dimension of every specimen for each tensile and compression also were kept constant to avoid the interference with the experimental result. The quality of the specimens was set to standard quality in Ultimaker Cura Software before printed with Creality Ender-3. All the specimens were then be put into compression and tensile test utilising the Universal Testing Machine Instron 5585 while the experimental results were collected via Bluehill Software.

There was success in achieving the objectives of this study, which were to compare the strength of ABS materials from different manufacturers. According to the findings, there are significant differences in the tensile strength and compressive strength of the ABS materials produced by each of the manufacturers. Different manufacturers produce different levels of strength. In contrast to this, the manufacturer with the highest Ultimate Tensile Strength does not necessarily correspond to the company with the highest Ultimate Compressive Strength. This means that the ABS material that is the strongest in terms of tensile strength does not necessarily imply that it is the strongest in terms of its ability to withstand compressive stress before breaking. Furthermore, the consistency of the point at which the specimen breaks can be easily observed on the stress-strain diagram, and it differs for each manufacturer. The comparison of strength between ABS material from each manufacturer were successfully made and analysed.

5.2 Recommendation

There are some recommendations that are appropriate for improving the project. When printing specimens, the first issue noticed is stringing or oozing, which results in the failure to generate the first layer. The solution to this is to conduct the printing procedure in an airtight room to prevent the specimen from being blown away and allow it to harden before the first layer is properly generated. Additionally, the stringing issue will cause the filament extruder to become jammed and harden inside the tip. This results in no filament being extruded, the filament that has become lodged inside the tip must be removed first in order for the filament to extrude smoothly. Additionally, warping might be a concern when printing specimens. When the specimen side becomes warped or bent, the extruder will collide with the side due to the difference in levelling, resulting in printing failure. Selecting raft support aids in the adhesion of the first layer to the bed, and utilising a glue stick on the printing bed also aids in the successful creation of the first layer. It is critical to ensure that all specimens are correctly printed, as a minor difference in dimension or failure can result in inconsistency when collecting experimental data following tensile and compression tests.

REFERENCES

Nuñez, P.J., Rivas, A., García-Plaza, E., Beamud, E. and Sanz-Lobera, A., 2015. Dimensional and surface texture characterization in fused deposition modelling (FDM) with ABS plus. *Procedia Engineering*, *132*, pp.856-863.

Baich, L., Manogharan, G. and Marie, H., 2015. Study of infill print design on production cost-time of 3D printed ABS parts. *International Journal of Rapid Manufacturing*, *5*(3-4), pp.308-319.

Kaveh, M., Badrossamay, M., Foroozmehr, E. and Etefagh, A.H., 2015. Optimization of the printing parameters affecting dimensional accuracy and internal cavity for HIPS material used in fused deposition modeling processes. *Journal of materials processing technology*, *226*, pp.280-286.

Ferro, C.G., Brischetto, S., Torre, R. and Maggiore, P., 2016. Characterization of ABS specimens produced via the 3D printing technology for drone structural components. *Curved and Layered Structures*, *3*(1).

Hodžić, D., Pandžić, A., Hajro, I. and Tasić, P., 2020. Strength Comparison of FDM 3D Printed PLA Made by Different Manufacturers. *TEM Journal*, *9*(3), p.966.

Wong, K.V. and Hernandez, A., 2012. A review of additive manufacturing. *International scholarly research notices*, *2012*.

Alavi, R., Trenggono, A., Champagne, S. and Hermawan, H., 2017. Investigation on mechanical behavior of biodegradable iron foams under different compression test conditions. *Metals*, *7*(6), p.202.

Standard, A.S.T.M., 2012. Standard terminology for additive manufacturing technologies. *ASTM International F2792-12a*.

Kun, K., 2016. Reconstruction and development of a 3D printer using FDM technology. *Procedia Engineering*, *149*, pp.203-211.

Rayegani, F. and Onwubolu, G.C., 2014. Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE). *The International Journal of Advanced Manufacturing Technology*, *73*(1-4), pp.509-519.

Shahrubudin, N., Lee, T.C. and Ramlan, R., 2019. An overview on 3D printing technology: Technological, materials, and applications. *Procedia Manufacturing*, *35*, pp.1286-1296.

Vishwakarma, S.K., Pandey, P. and Gupta, N.K., 2017. Characterization of ABS material: a review. *Journal of Research in Mechanical Engineering*, *5*, pp.13-16.

Adnan, F.A., Romlay, F.R.M. and Shafiq, M., 2018, April. Real-time slicing algorithm for Stereolithography (STL) CAD model applied in additive manufacturing industry. In *IOP conference series: materials science and engineering* (Vol. 342, No. 1, p. 012016). IOP Publishing.

Cantrell, J.T., Rohde, S., Damiani, D., Gurnani, R., DiSandro, L., Anton, J., Young, A., Jerez, A., Steinbach, D., Kroese, C. and Ifju, P.G., 2017. Experimental characterization of the mechanical properties of 3D-printed ABS and polycarbonate parts. *Rapid Prototyping Journal*.

Rane, R., 2019. *Enhancing Tensile Strength of FDM parts using Thermal Annealing and Uniaxial Pressure* (Doctoral dissertation).

Majid, F., Zekeriti, N., Lahlou, M. and Mrani, B., 2020. Mechanical behavior and crack propagation of ABS 3D printed specimens. *Procedia Structural Integrity*, *28*, pp.1719-1726.

LIST OF APPENDICES

APPENDIX A

	Maximum Load [N]	Tensile stress at Maximum Load [MPa]	Tensile strain (Extension) at Maximum Load [mm/mm]	Modulus (E-modulus) [MPa]
1	717.29	17.93	0.02778	-----
2	651.95	16.30	0.02863	-----
3	635.49	15.89	0.02384	-----
4	713.78	17.84	0.03088	-----
5	673.10	16.83	0.03426	-----

	Modulus (Automatic) [MPa]
1	718.55524
2	647.63012
3	729.83626
4	696.53213
5	767.44920

Tensile test results for Fabbxible ABS specimens.

	Maximum Load [N]	Tensile stress at Maximum Load [MPa]	Tensile strain (Extension) at Maximum Load [mm/mm]	Modulus (E-modulus) [MPa]
1	750.36	18.76	0.02477	-----
2	734.44	18.36	0.02516	-----
3	741.95	18.55	0.02546	-----
4	752.55	18.81	0.02500	-----
5	702.76	17.57	0.02469	-----

	Modulus (Automatic) [MPa]
1	842.34240
2	792.77803
3	795.90321
4	849.70767
5	811.01855

Tensile test results for FlashForge ABS specimens.

	Maximum Load [N]	Tensile stress at Maximum Load [MPa]	Tensile strain (Extension) at Maximum Load [mm/mm]	Modulus (E-modulus) [MPa]
1	531.94	13.30	0.02029	-----
2	609.00	15.22	0.01883	-----
3	655.97	16.40	0.02006	-----
4	654.34	16.36	0.01924	-----
5	703.36	17.58	0.01991	-----

	Modulus (Automatic) [MPa]
1	860.44534
2	1005.89044
3	1014.78096
4	1053.13616
5	1087.26185

Tensile test results for eSUN ABS specimens.

	Maximum Load [N]	Tensile stress at Maximum Load [MPa]	Tensile strain (Extension) at Maximum Load [mm/mm]	Modulus (E-modulus) [MPa]
1	853.32	21.33	0.01968	
2	888.73	22.22	0.02060	-----
3	905.70	22.64	0.02300	-----
4	825.77	20.64	0.01952	-----
5	820.88	20.52	0.01932	-----

	Modulus (Automatic) [MPa]
1	1309.65456
2	1300.05159
3	1220.39996
4	1313.54906
5	1326.99809

Tensile test results for SUNLU ABS specimens.

APPENDIX B

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 5.571	> 49.263	> 0.782	> 14.081

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	959.928	955.294	978.045

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.496	> 30.910	> 0.053	> 0.958

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	937.797	943.214	965.368

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.439	> 30.408	> 0.054	> 0.975

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	949.680	945.658	963.027

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.547	> 31.358	> 0.081	> 1.459

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	951.847	951.614	973.817

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.565	> 31.518	> 0.056	> 1.000

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	943.917	945.479	969.724

Compression test results for Fabbxible ABS specimens.

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 4.032	> 35.650	> 0.058	> 1.042

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	1141.607	1136.597	1178.904

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 4.065	> 35.946	> 0.059	> 1.067

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	1155.394	1151.751	1187.081

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 4.044	> 35.756	> 0.063	> 1.142

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	1140.268	1145.597	1177.017

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 4.091	> 36.176	> 0.058	> 1.042

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	1076.503	1068.658	1098.048

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 4.033	> 35.663	> 0.059	> 1.069

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	1139.114	1129.709	1170.895

Compression test results for FlashForge ABS specimens.

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 2.948	> 26.064	> 0.197	> 3.550

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	756.883	718.133	788.122

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.135	> 27.719	> 0.225	> 4.059

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	739.277	668.048	776.539

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.178	> 28.100	> 0.218	> 3.925

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	772.764	691.087	803.792

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.045	> 26.920	> 0.198	> 3.567

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	748.175	708.843	780.438

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.052	> 26.985	> 0.218	> 3.917

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	750.348	669.789	781.925

Compression test results for eSUN ABS specimens.

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.515	> 31.079	> 0.186	> 3.350

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	928.096	931.806	932.415

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.414	> 30.185	> 0.057	> 1.034

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	907.976	909.399	916.918

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.524	> 31.157	> 0.095	> 1.717

	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	968.585	961.168	993.088

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.405	> 30.107	> 0.063	> 1.125

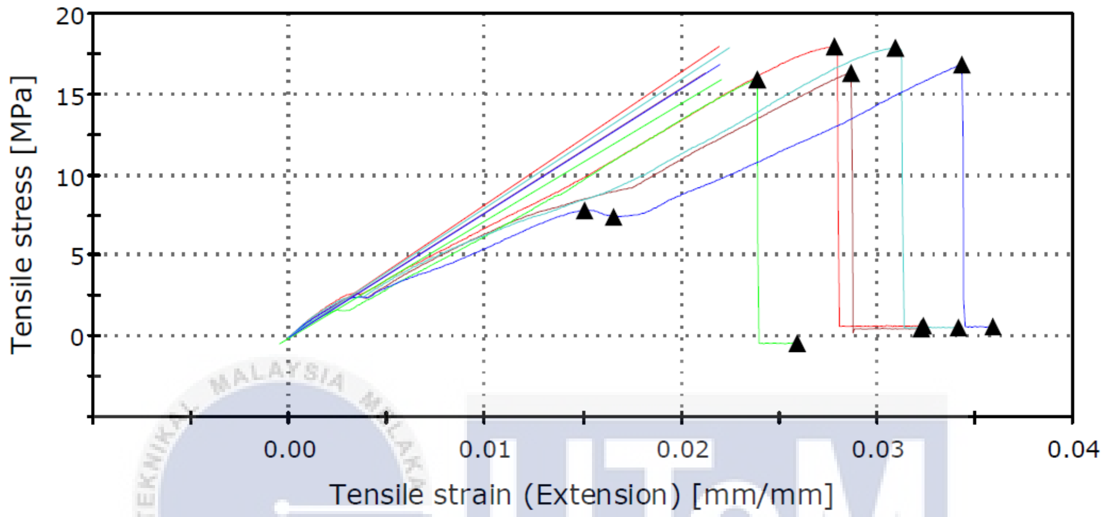
	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	886.359	881.908	898.275

	Max Load [kN]	Compressive stress at Maximum Load [MPa]	Compressive strain (Extension) at Maximum Load [mm/mm]	Compressive extension at Maximum Load [mm]
1	> 3.467	> 30.652	> 0.193	> 3.475

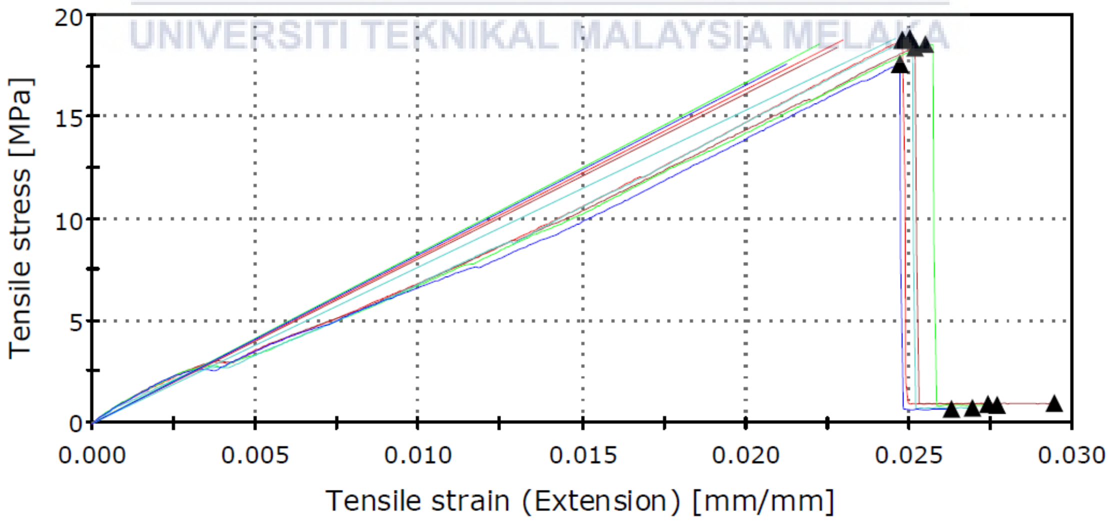
	Modulus (E-modulus) [MPa]	Modulus (Automatic) [MPa]	Modulus (Automatic Young's) [MPa]
1	913.126	916.538	930.503

Compression test results for SUNLU ABS specimens.

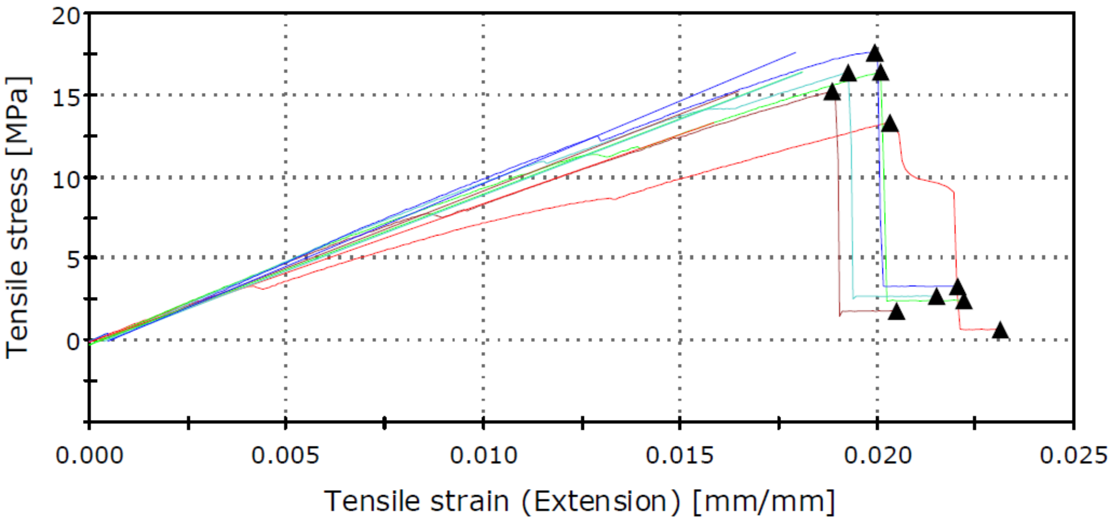
APPENDIX C



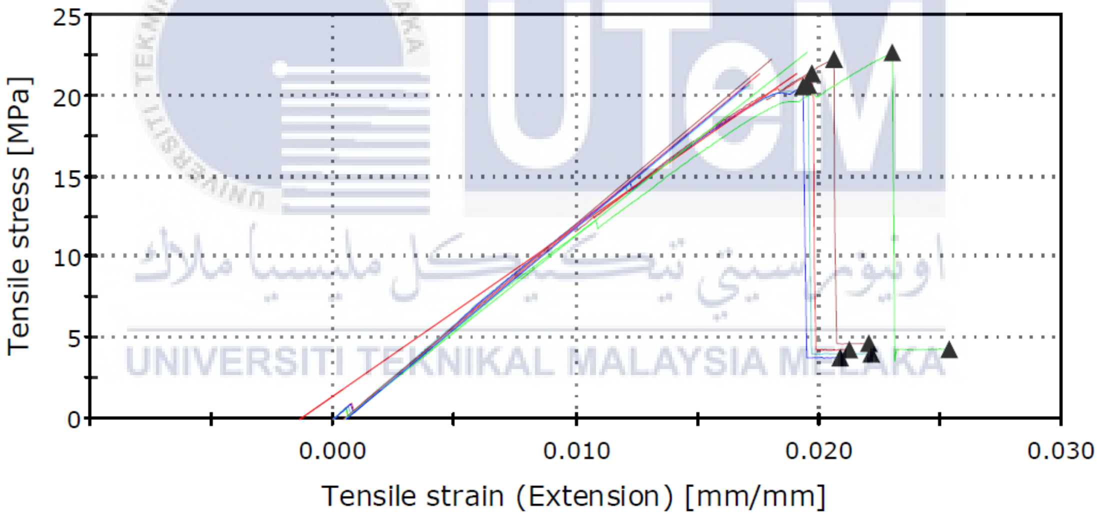
Tensile test stress-strain diagram of ABS specimen from Fabbxible.



Tensile test stress-strain diagram of ABS specimen from FlashForge.

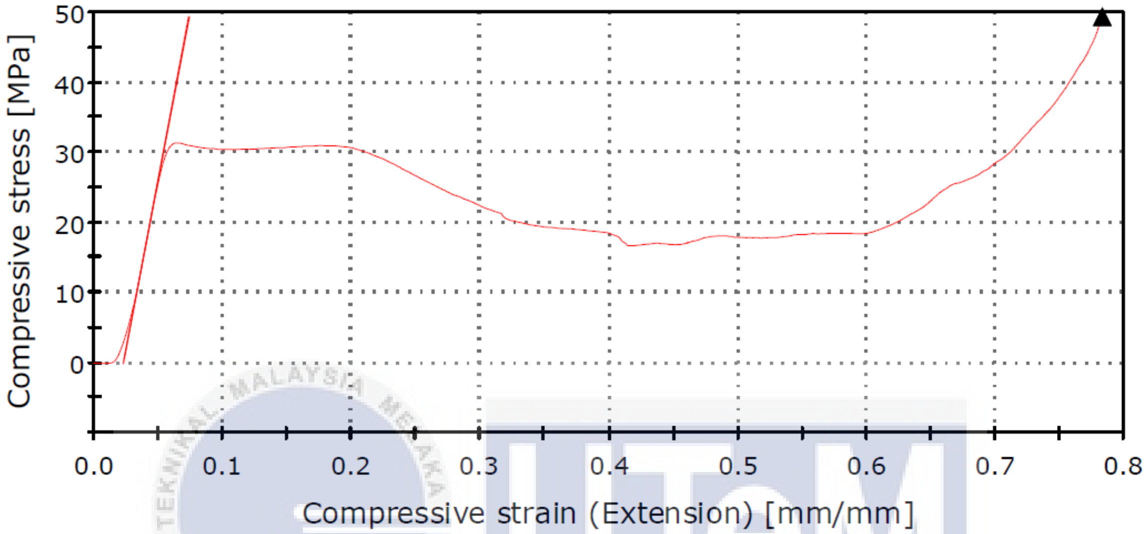


Tensile test stress-strain diagram of ABS specimen from eSUN.

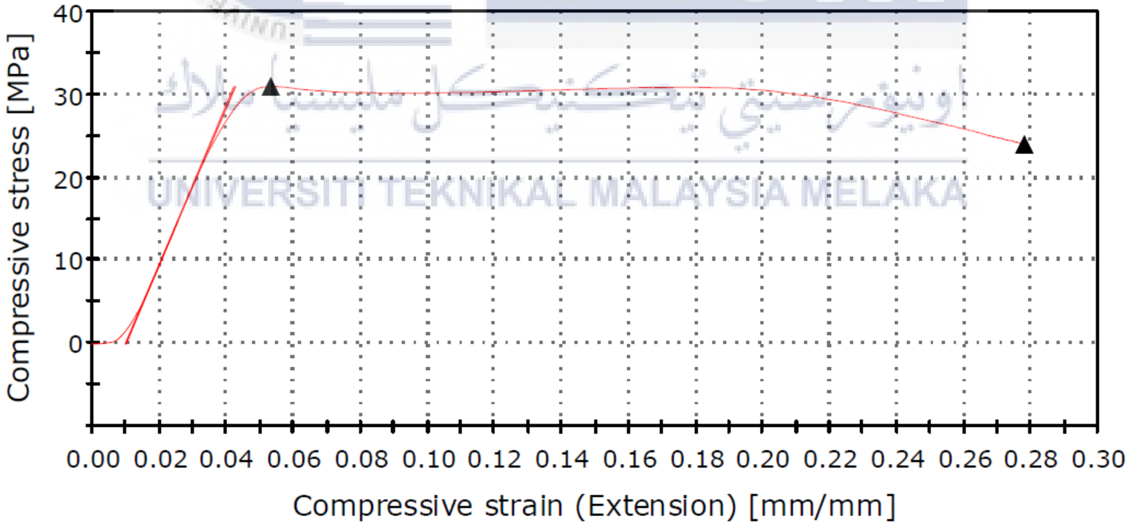


Tensile test stress-strain diagram of ABS specimen from SUNLU.

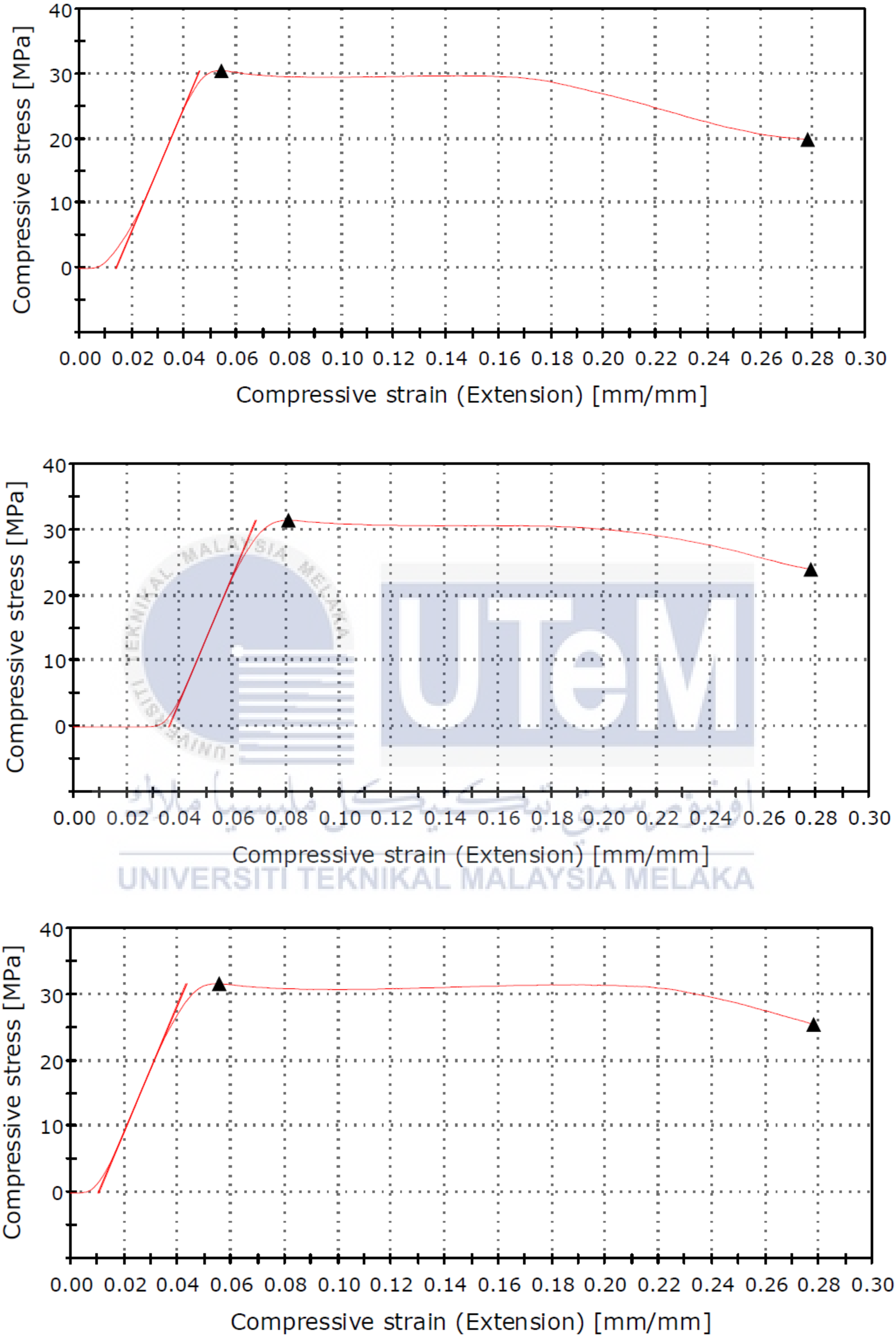
APPENDIX D



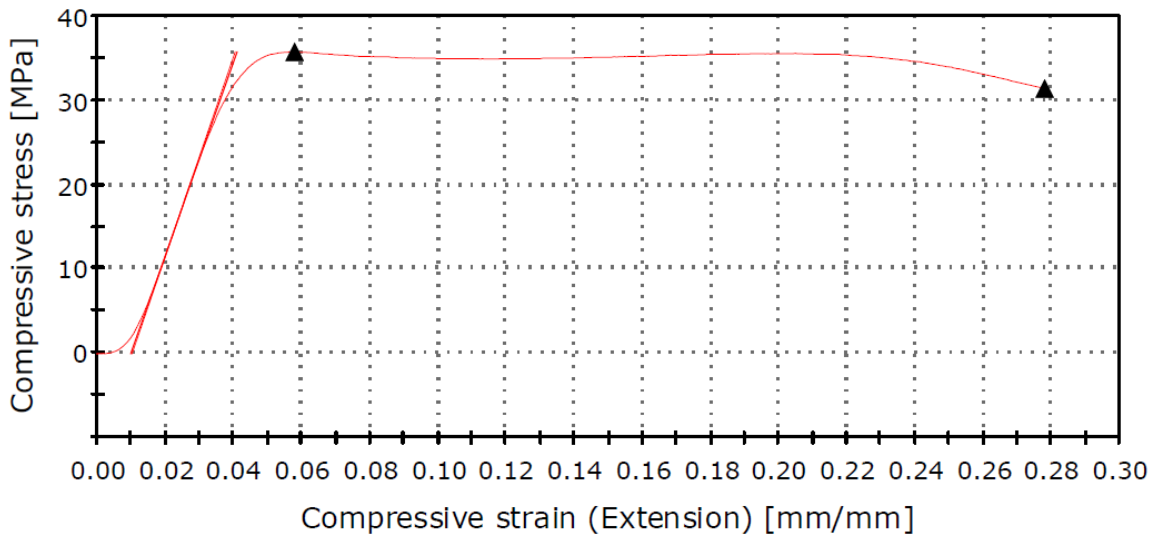
Compressive stress [MPa]
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Compressive strain (Extension) [mm/mm]

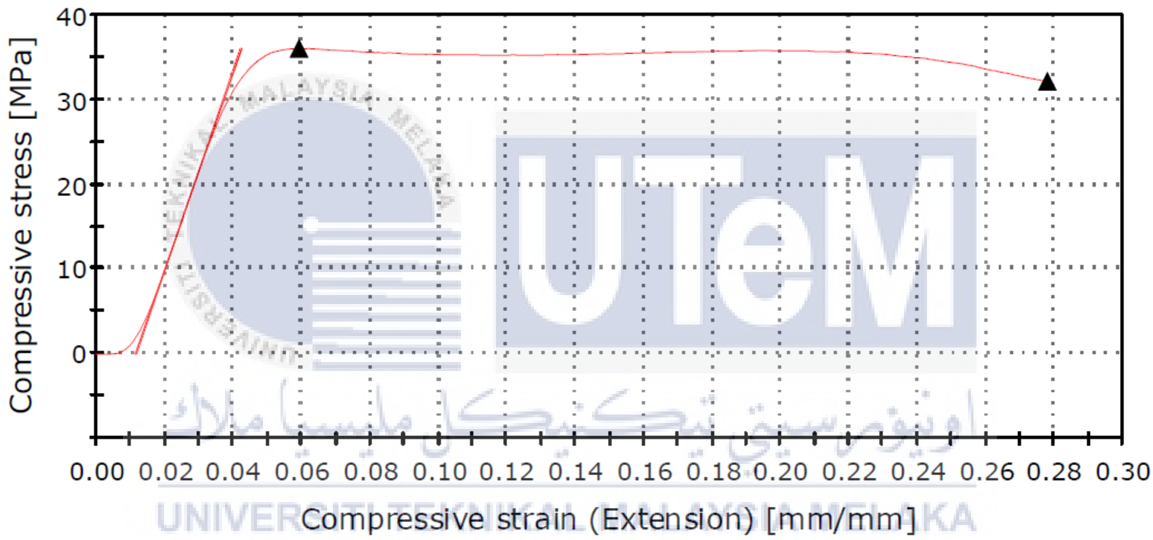


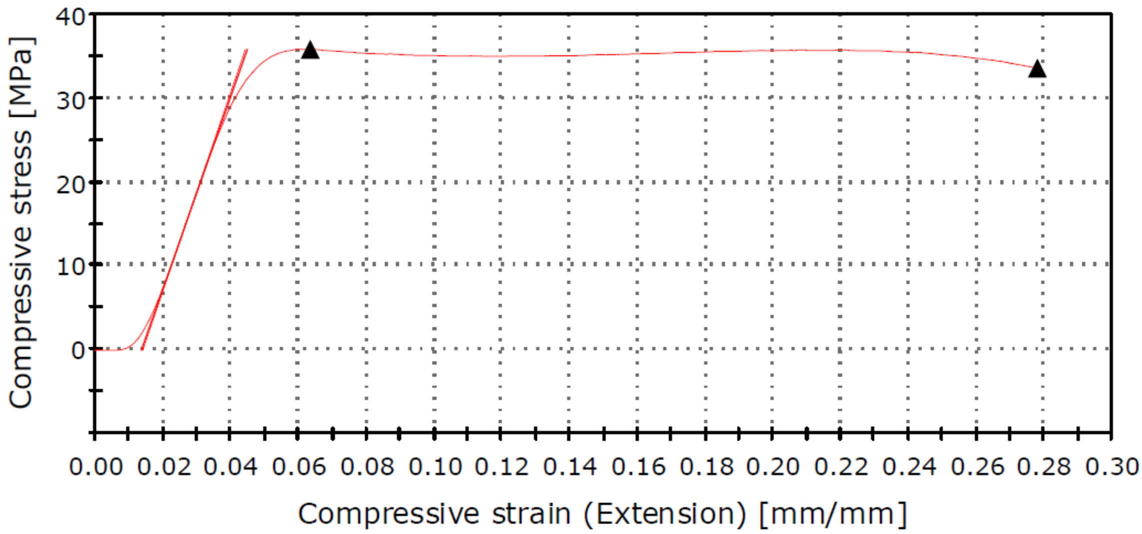
Compressive stress [MPa]
40
30
20
10
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
Compressive strain (Extension) [mm/mm]

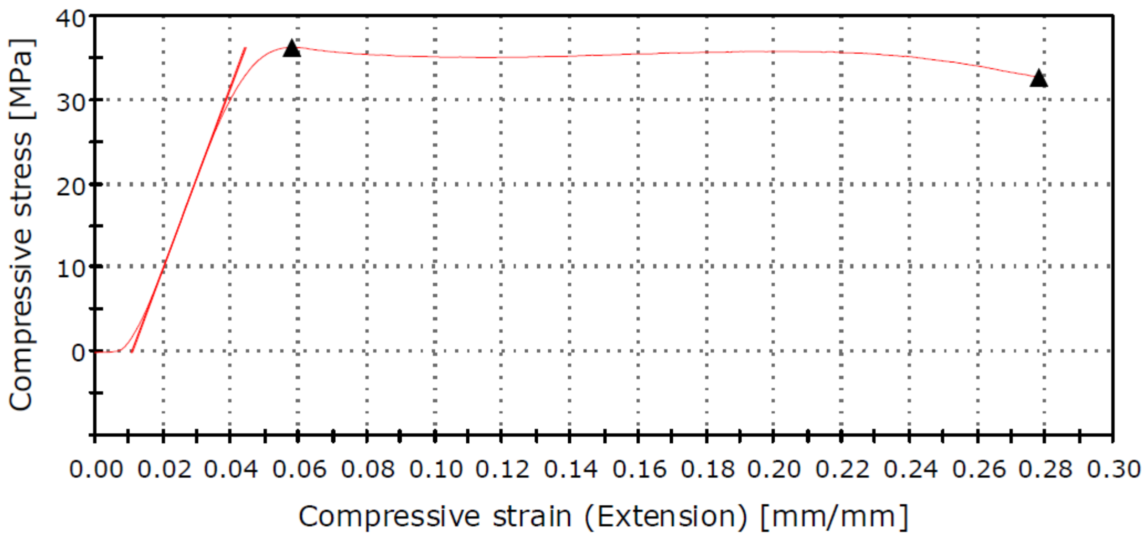


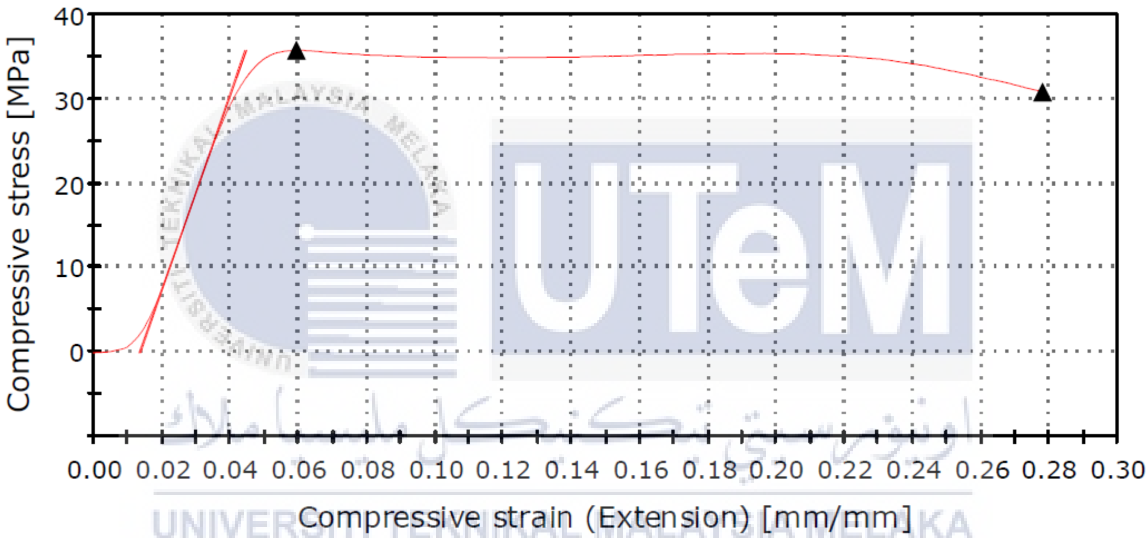
Stress-strain diagram for compression from Fabbxible ABS specimen.


Compressive stress [MPa]
40
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]

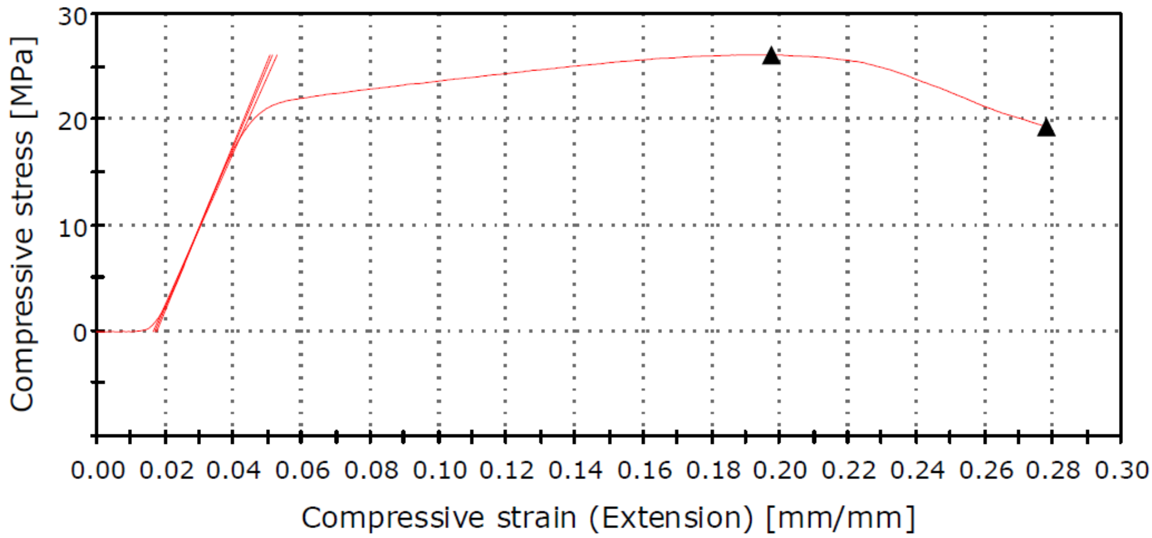

Compressive stress [MPa]
40
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]

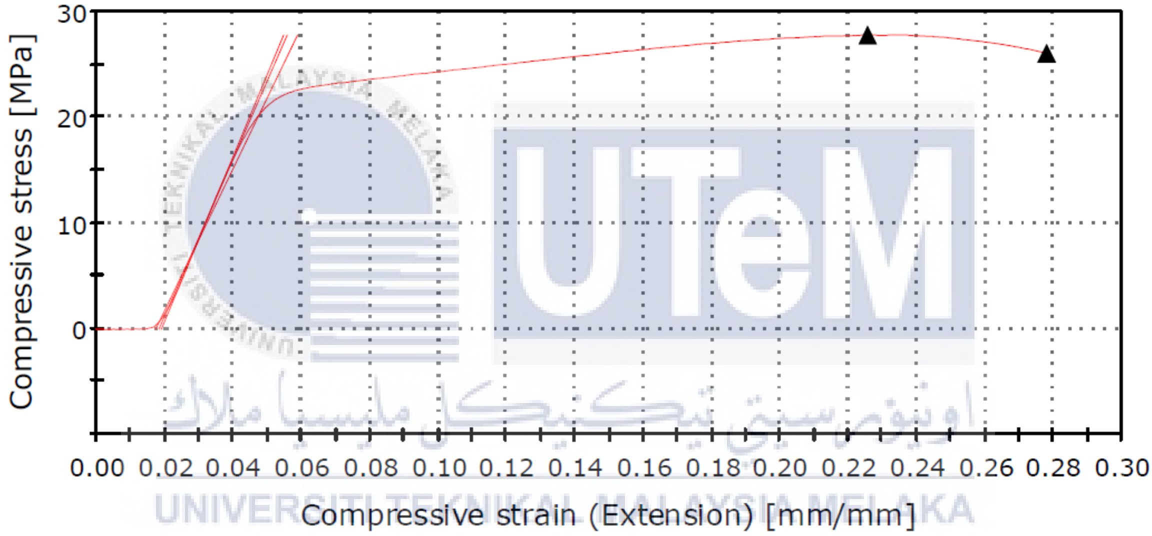

Compressive stress [MPa]
40
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]

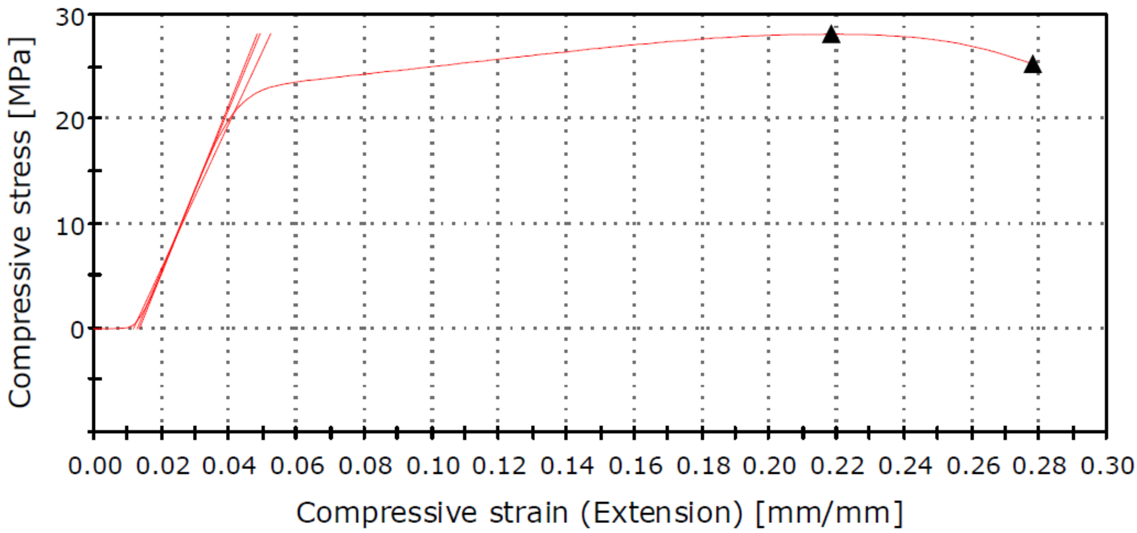


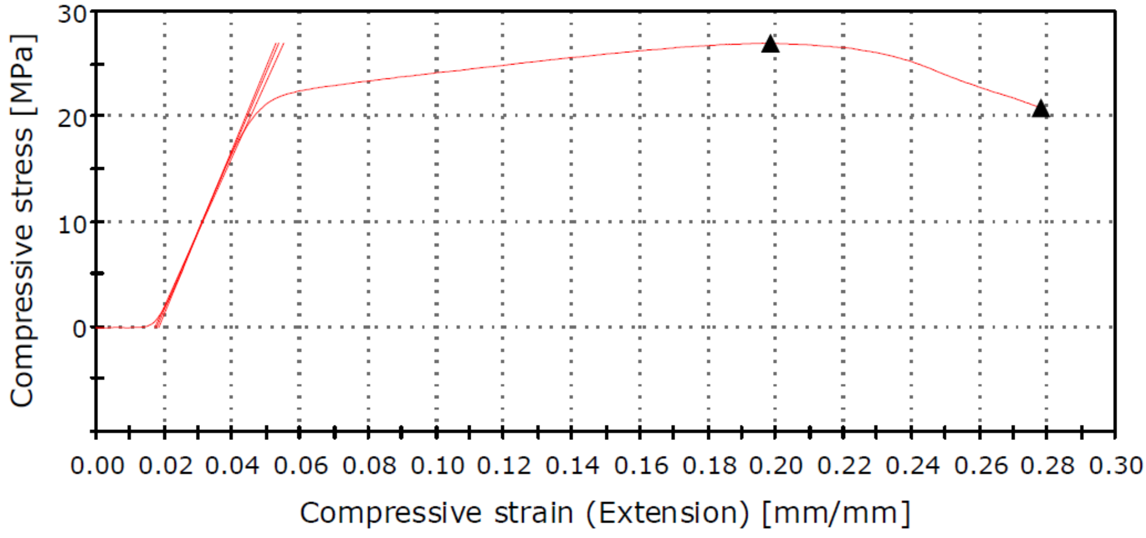


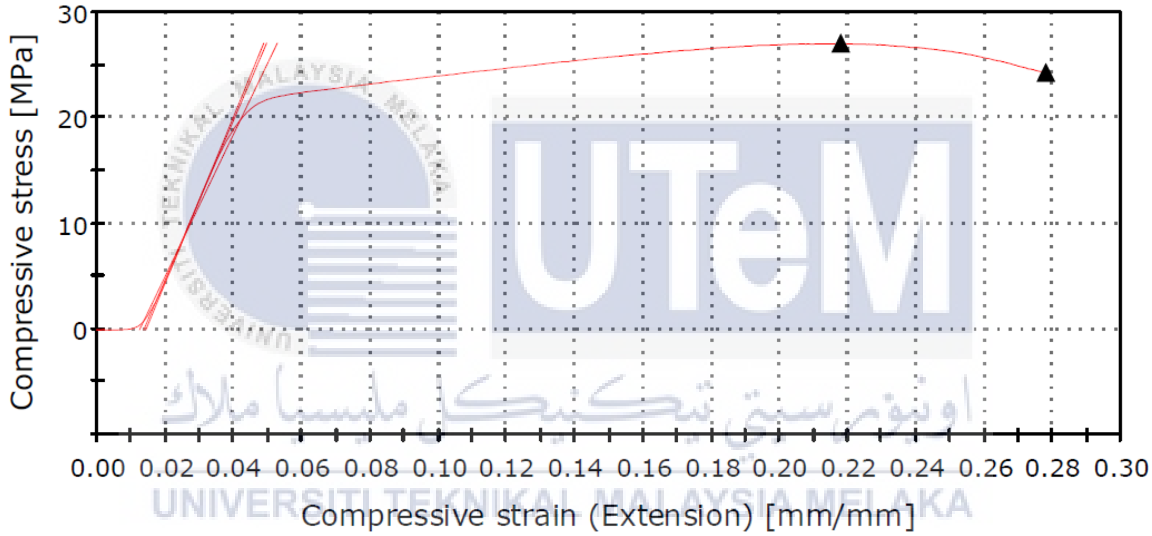
Stress-strain diagram for compression from FlashForge ABS specimen.


Compressive stress [MPa]
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]

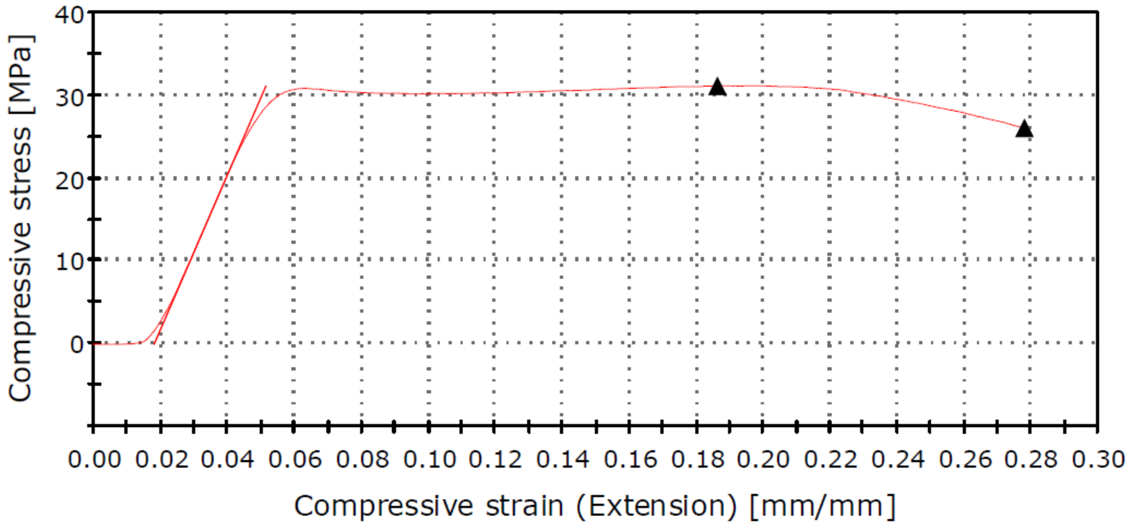

Compressive stress [MPa]
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]


Compressive stress [MPa]
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]

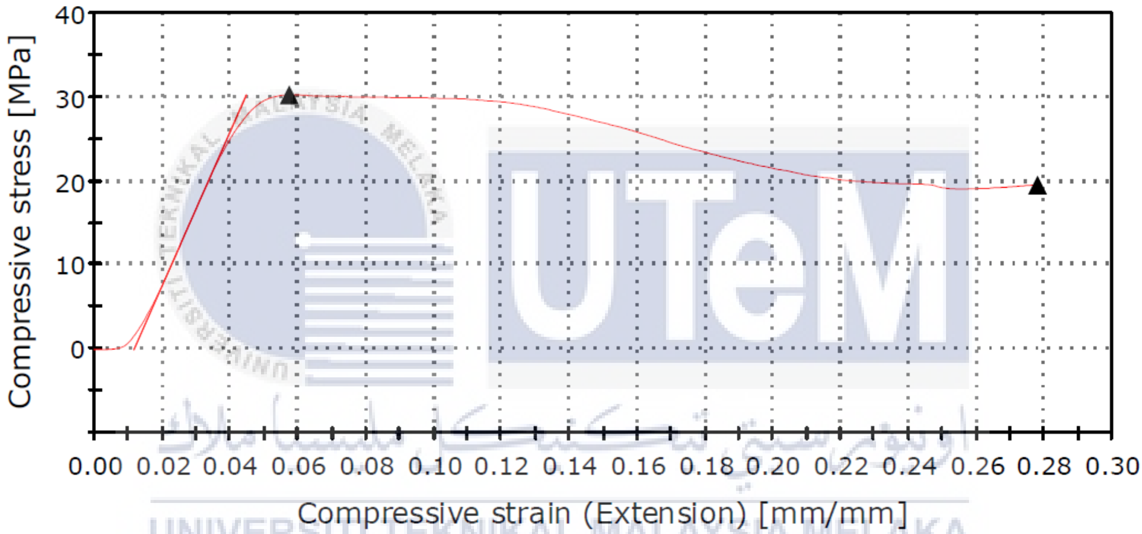




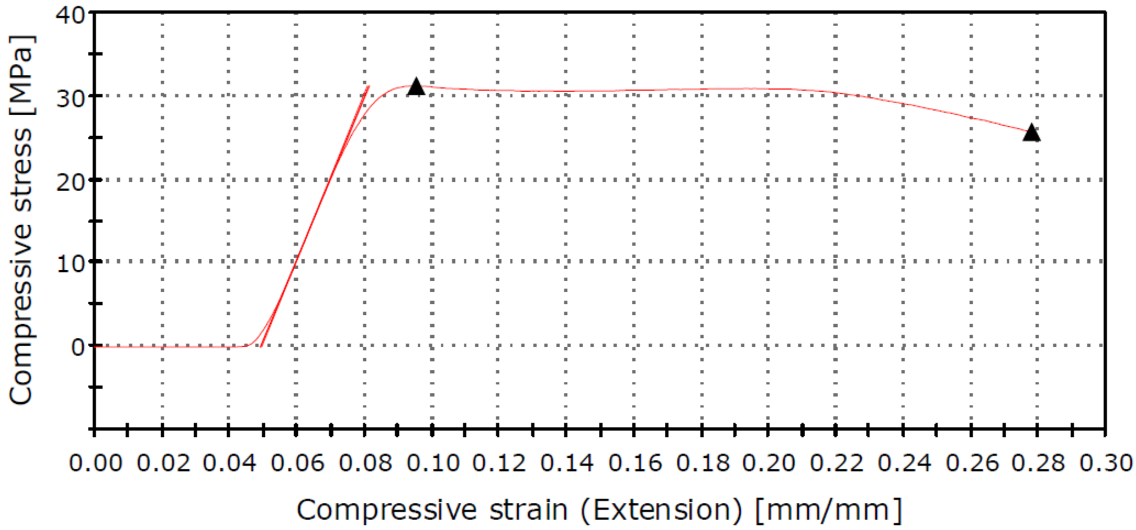
Stress-strain diagram for compression from eSUN ABS specimen.



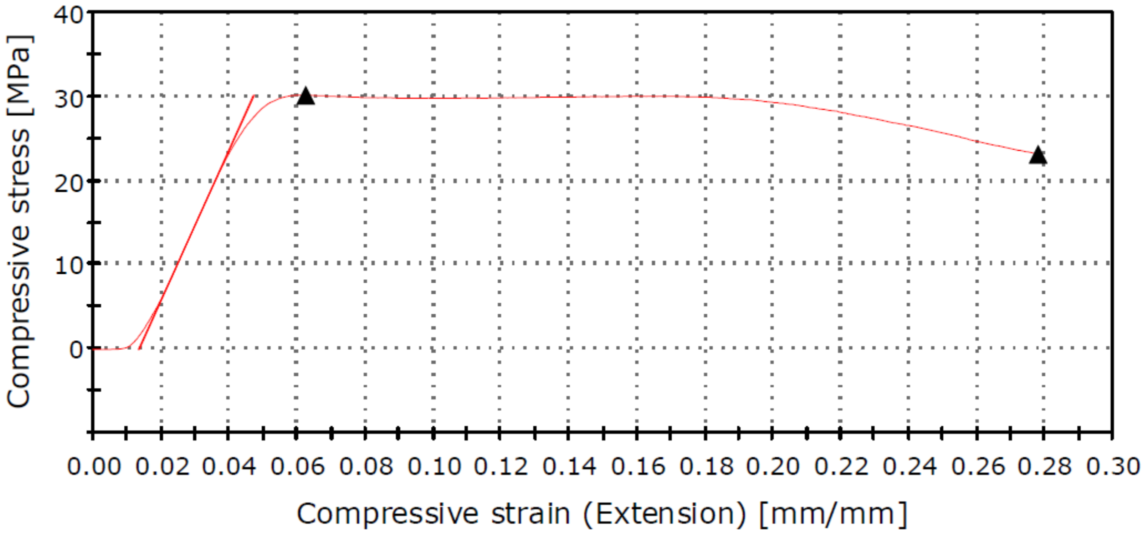
Compressive stress [MPa]
40
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]

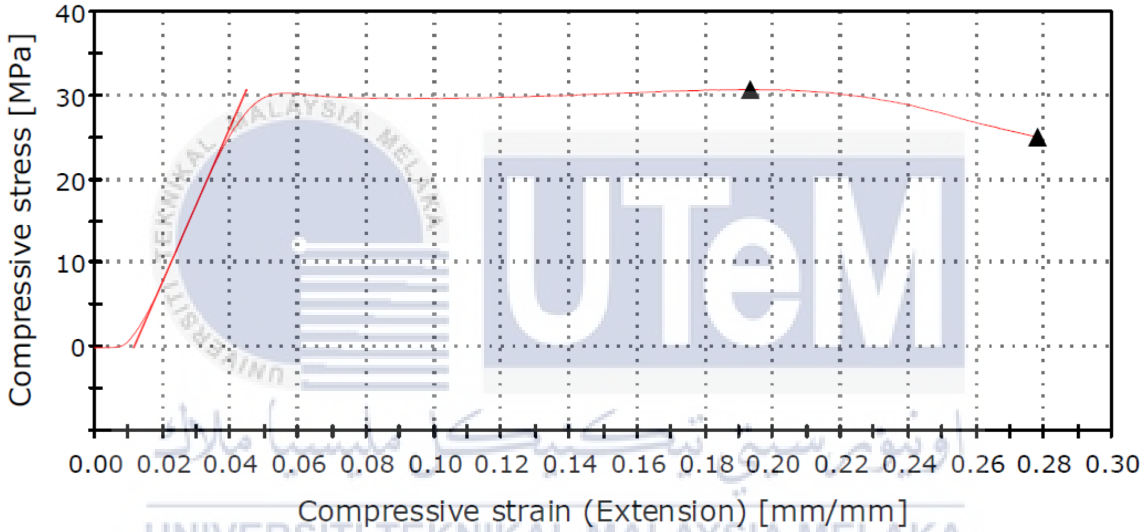


Compressive stress [MPa]
40
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]



Compressive stress [MPa]
40
30
20
10
0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Compressive strain (Extension) [mm/mm]





Stress-strain diagram for compression from SUNLU ABS specimen.