Faculty of Mechanical Engineering

INVESTIGATION OF STARCH ADHESION IN AN OPEN SOURCE 3D PRINTER

Jerventh Rau A/L Kusraju

Bachelor in Mechanical Engineering

2018

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JERVENTH RAU A/L KUSRAJU

A thesis submitted
in fulfilment of the requirements for the degree of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I hereby declare that this project entitled “Investigation of Starch Adhesion in An Open Source 3d Printer” is the results of my own work except as cited in the references.

Signature	: …………………………..
Name	: Jerventh Rau A/L Kusraju
Date	: …………………………..

SUPERVISOR DECLARATION

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

Signature : ....

Name : Dr. Faiz Redza bin Ramli

Date : ....

ABSTRACT

Three-dimensional (3D) product are normally produced by using a 3D printer by converting 3D drawing from software such as SolidWorks to .stl file. This process is known as additive manufacturing process (AM). Generally, a common 3D printer uses heating element to melt its filament to semi molten and extrude out on a platform, the platform where the filament is printed have adhesive which act as a medium to hold the printed specimen together. Many types of adhesive had been used for this past few years which are synthetic and bio-based adhesive. Bio-based adhesive in 3D printing is starting to grow rapidly but there are still many flaws throughout the process. Many researches can be carried out to study the problems occur in 3D printer, one of the highlighted problems are warping deformation which occur during the first layer of specimen. The specimen vertex tends to warp upwards causing it to peel off from the platform resulting in material, time and energy waste. New mixture of plant-based bio adhesive was studied and experimented to reduce warping deformation at the same time maintaining its environmentally friendly criteria. Besides, viscosity of the adhesive has been tested and analyse to ensure it can be used for 3D printer application. Provided that the mixture has been done, comparison between synthetic and plant-based bio adhesive was carried out by conducting tensile test in order to identify the maximum load it can withstand. From all the data collected, it can be concluded that synthetic adhesive is stronger but plant-based bio adhesive still can be use in 3D printer application as it greatly reduces warping deformation and environmentally friendly.

ABSTRAK

Produk tiga dimensi (3D) biasanya dihasilkan dengan menggunakan pencetak 3D dengan menukar lukisan 3D dari perisian seperti fail SolidWorks ke .stl. Proses ini dikenali sebagai proses bahan tambahan pembuatan (AM). Pada umumnya, pencetak 3D biasa menggunakan proses pemanasan untuk mencairkan filamennya kepada separa lebur dan mencetak pada platform, platform di mana filamen yang dicetak mempunyai pelekat yang bertindak sebagai medium untuk memegang spesimen. Pelbagai jenis pelekat telah digunakan untuk beberapa tahun kebelakangan ini yang terdiri daripada pelekat berasaskan sintetik dan bio. Pelekat berasaskan bio dalam percetakan 3D mula berkembang pesat tetapi masih terdapat banyak kelemahan sepanjang proses. Banyak penyelidikan boleh dijalankan untuk mengkaji masalah yang berlaku dalam pencetak 3D, salah satu masalah kemuncak dalam kajian ini adalah ubah bentuk meleding yang berlaku semasa pencetakan lapisan pertama spesimen. Bucu spesimen cenderung meledingkan ke arah atas menyebabkan ia mengupas dari platform mengakibatkan pembaziran dari segi bahan, masa dan tenaga. Campuran baru pelekat bio berasaskan tumbuhan telah dikaji dan dieksperimen untuk mengurangkan ubah bentuk meleding pada masa yang sama mengekalkan kriteria mesra alam. Selain itu, kelikatan pelekat telah diuji dan dianalisis untuk memastikan ia boleh digunakan untuk aplikasi pencetak 3D. Dengan syarat bahawa campuran baru terjadi itu, perbandingan antara pelekat bio berasaskan sintetik dan tumbuhan dibuat dengan menjalankan ujian tegangan untuk mengenal pasti beban maksimum yang dapat ditahan. Daripada semua keputusan yang diperolehi, dapat disimpulkan bahawa pelekat sintetik lebih kuat tetapi pelekat bio berasaskan tumbuhan masih boleh digunakan dalam aplikasi pencetak 3D kerana ia mengurangkan leding dan juga mesra alam.

ACKNOWLEDGEMENT

I am grateful and would like to express my sincere gratitude to my supervisor Dr Faiz Redza bin Ramli for his invaluable guidance, continuous encouragement and constant support in making this project possible. I really appreciate his guidance from the initial to the final level that enabled me to develop an understanding of this project thoroughly. Without his advice and assistance, it would be a lot tougher to completion. I also sincerely thanks for the time spent proofreading and correcting my mistakes.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I am really thankful for their sacrifice, patience, and understanding that were inevitable to make this work possible. Their sacrifice had inspired me from the day I learned how to read and write until what I have become now. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to achieve my dreams.

Lastly, I would like to thanks any person which contributes to my final year project directly or indirectly. I would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this study.

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LIST OF ABBREVIATIONS

3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene
BJ	Binder Jetting
CAD	Computer Aided Drawing
DED	Directed Energy Deposition
DLP	Digital Light Projector
DOD	Drop-On-Demand
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
LOM	Laminated Object Manufacturing
PLA	Polylactic Acid
RVA	Rapid Visco Analyser
SFF	Solid Freeform Technique
SGC	Solid Ground Curing
SL	Stereolithography
SLA	Stereo Lithography Apparatus
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

LIST OF SYMBOLS

ε	=	Strain
σ	=	Stress
E	=	Modulus of elasticity

CHAPTER 1

INTRODUCTION

1.1 Background of Study

A process that converts from digital technology to physical object is called Additive Manufacturing (AM) which also refers to 3D printing. 3D printing machine can print objects from a simple to complex design but with limited dimensions. Objects can be of any shape or geometry and typically are delivered using advanced model information from a 3D model. 3D objects are formed by printing thousands of layers from the base to top. Most of the printers nowadays uses Fused Filament Fabrication (FFF) additive manufacturing process where it works by extruding of heated or melted thermoplastic materials through an extrusion nozzle which is then carefully positioned on the bed of the 3D printer forming layer upon layer based on the drawing drawn in the Computer Aided Drawing (CAD) software. The filament most likely will be hardened upon leaving the nozzle which will then fused together forming a strong bond between layers. The final product obtain after printing must be examined properly to avoid product from breaking or damage easily. Layer thickness, materials used and bonding strength between layers should be taken into account in order to produce a good and quality 3D product.

3D printable models can be drawn in Computer Aided Drawing (CAD) software for example Solidworks, Autodesk, and OpenSCAD or obtained by scanning the object using 3D scanner which will then further convert into 3D drawing. 3D printed models created with CAD result in reduced errors and can be corrected before printing, allowing verification in the design of the object before it is printed (Jacobs, 1992).

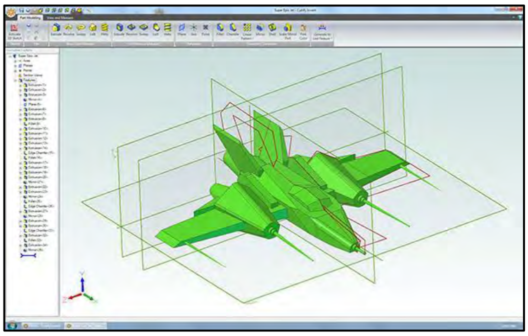


Figure 1.1 CAD model used for 3D printing

The term Additive Manufacturing (AM) holds within such technologies like Rapid Prototyping (RP), Digital Manufacturing (DDM), Layered Manufacturing and 3D printing (Types of 3D printers or 3D printing technologies overview, 2015). There are various types of 3D printing methods that are available in the current market to build 3D structures and objects. Some of them are extremely prevalent these days while others have been ruled by contenders. Below is the Table for the types of 3D printers and its printing method.

Table 1.1 3D printer

3D Printing	Material extrusion	Fused Deposition Modeling (FDM)
	Vat Polymerization	Stereo Lithography Apparatus (SLA) Digital Light Projector (DLP)
	Powder Bed Fusion (Polymers)	Selective Laser Sintering (SLS)
	Material Jetting	Material Jetting Drop-On-Demand
	Binder Jetting	Binder Jetting
	Powder Bed Fusion (Metals)	Selective Laser Melting (SLM) Electron Beam Melting (EBM)

In the process of 3D printing, adhesion plays an important role to ensure the product always remain on the platform or print bed. Platform is a place where materials from the extrusion nozzle is extruded layer by layer to produce a solid product. Therefore, a good adhesion is needed to avoid product from warping, damaging or having uncertain dimensions. Adhesion can be used only if the bottom of the product is flat and smooth surface otherwise the bonding strength between product and the print bed will be weak and causing it glide around the bed while printing (Platform Adhesion, 2018). So, if the base of the product is not even or flat, a skirt will be drawn by the printer. Skirt is a line drawn around the print on the first layer to prime the extruder and also have a good balance on the print bed which will reduce the printing error.

Figure 1.2 Warping

1.2 Problem Statement

Open source 3D printer is an additive manufacturing process that is used to build parts out of plastics and it's replacing conventional method over time. Two materials are chosen for this experiment which are ABS and PLA. Problem occurs when the filament being extruded to the print bed tend to shrink and causes warping at the bottom edge of the product. This is a major drawback for 3D printers when poor adhesives are applied between platform and the first layer of the object thus, it will eventually loss contact or peel from the platform overtime. This is a common problem among all the 3D printers where ample of time and materials are wasted when the final design differs from the original drawing. Solution to this problem had been solved by using synthetic adhesive or tape but it may cause major impact of globalization on the environment thus an eco-friendlier adhesive is needed to preserve the environment in the future. Hence, plant-based bio adhesive will be the best solution to substitute synthetic adhesives.

1.3 Objectives

The objectives of this project are:

1. To compare warping deformation based on the original design using plant-based adhesive
2. To investigate the new mixture of plant-based bio adhesive using Dioscorea Oppositifolia and Ipomoea Batatas by conducting viscosity test
3. To obtain the maximum load of plant-based bio adhesives by conducting tensile test experiment

1.4 Scope of Project

The scope of this project covers the type of 3D printers where a low-cost 3D printer is used. 2 types of materials, ABS and PLA are used for the filament printing testing using 3D printer throughout the entire project. Furthermore, the strength of the bio adhesives is measured at the first layer of 3D print product.

1.5 Content Overview

In chapter one, student will describe about the problem statement, objectives of the project and the scope of study. In chapter two, it will be more focus on literature review. For chapter three, discussion about the methods to use during the project to solve the problem. Chapter four will cover the result, analysis and the discussion. Finally, the chapter five will be the conclusion for the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Rapid Prototyping

Rapid prototyping is a general term which depicts an assortment of frameworks that can build three dimensional models directly from electronic data. This innovation, first created in the mid 1980's, is based on the solid modeling portion of computer-aided design, or CAD. Solid modeling uses CAD information to completely portray the parts general shape, as well as it's inside volume and outside surfaces.

Rapid prototyping system uses this information to build fabrications layer by layer in thin cross sections. Each layer is stacked upon a past layer until the point that the model is finished. Rapid prototyping construct complex shapes substantially speedier and more essentially than by customary modeling methods. Moreover, these systems can also produce models from data generated from the 3-dimensional digitizing of existing parts, and medical imaging devices (Pham & Dimov, 2001).

Materials used to fabricate prototype models are commonly classified as either liquid, powder, filament, or foil such as thermoplastics, metal powders, photopolymers and ceramic powders (Crow, 2016). Prototyping systems normally work untended, and upon completion, the models can require some post-processing. These post-processing process includes surface finishing and support removal.

Rapid prototyping divided into two main types which are material removing manufacturing and additive manufacturing (Groover, 2010). In general, material removing manufacturing process works in which cutting tools removes unwanted material from a workpiece to form a desired shape of the product using milling or drilling process. Usually, the workpiece will be in a larger piece of stock and various shape. In this project, focusing on additive manufacturing process which are divided into three main prototyping systems which are:

i. Solid-Based Rapid Prototyping
ii. Liquid-Based Rapid Prototyping
iii. Powder-Based Rapid Prototyping

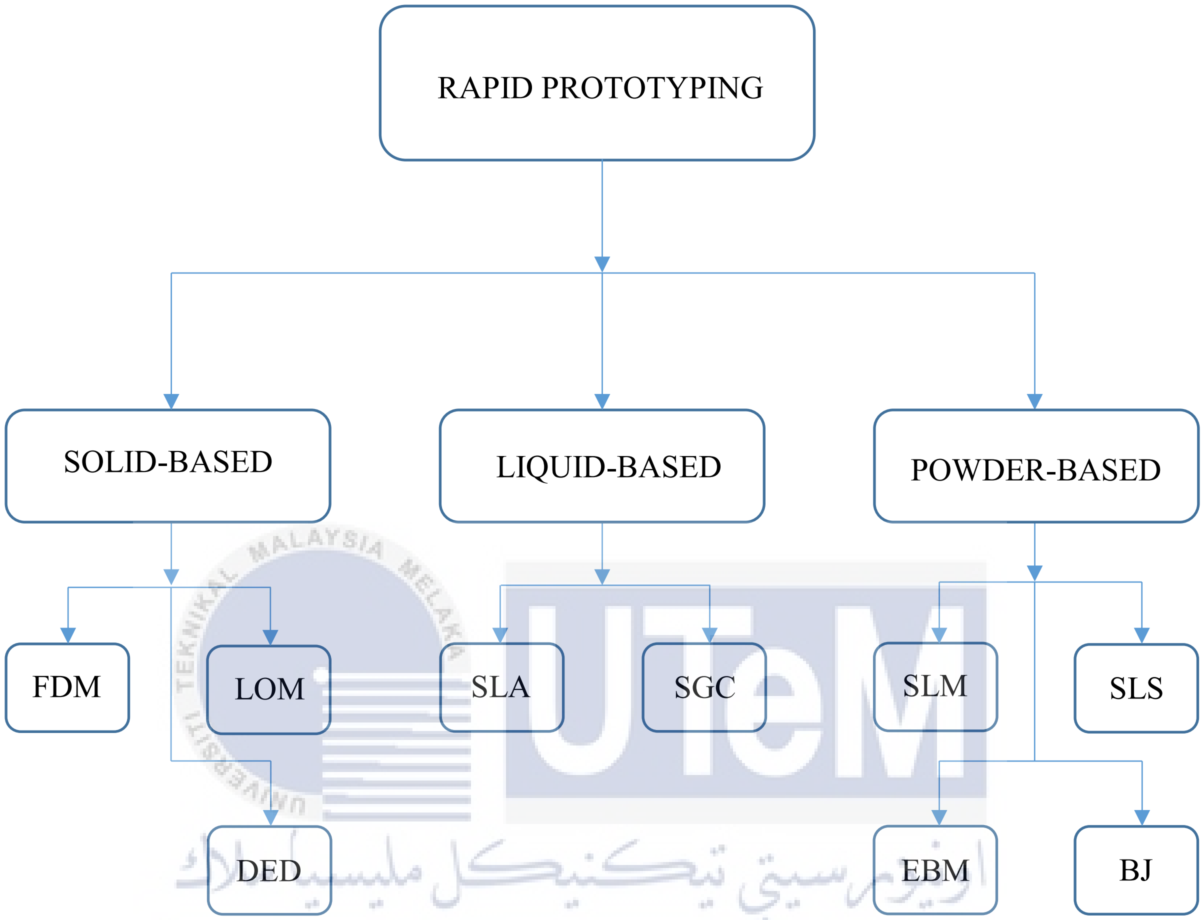


Figure 2.1 Flow chart of rapid prototyping

2.1.1 Solid-Based Rapid Prototyping

Solid-based rapid prototyping systems is one of the process that uses solid form as its starting material. The solid form can include the shape in the form of a wire, roll, laminates and pallets. This material will undergo melting and solidifying or fusing method before spreading the layer on the printing bed (Chua, Leong, & Lim 2010). There are various processes that are involved in solid-based rapid prototyping process but the selected process that need to be focused on are fused-deposition modeling and laminated-object manufacturing.

2.1.1.1 Fused-Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) printers use a thermoplastic filament, which is heated to its melting point and then extrude, layer by layer, to make a three-dimensional object. The most well-known printing material for FDM is acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) these materials have wide variety of colors and relatively cheap.

The innovation behind FDM was developed in the 1980s by Scott Crump, prime supporter and director of Stratasys Ltd., a leading manufacturer of 3D printers. Other 3D printing associations have since embraced comparable advances under various names. The Brooklyn-based company MakerBot, was founded with similar technology known as Fused Filament Fabrication (FFF). Objects made with a FDM printer begin as computer-aided design (CAD) files but before the printing, CAD files must be changed over to an arrangement that a 3D printer can comprehend usually to STL design.

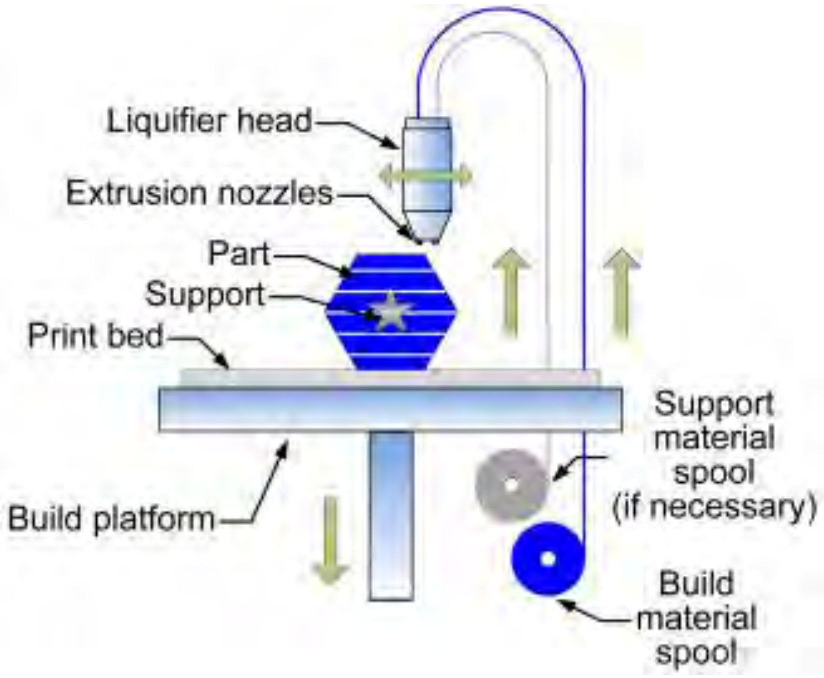


Figure 2.2 Deposition of material through nozzle (Ning, Cong, Qiu, Wei & Wang, 2015)

There are two types of materials used in FDM printer, a modelling material, which represents the object, and a supporting material which act as the base of the object during printing. Amid printing, these materials appear as plastic threads, or filaments, which are loosened up from a coil and pass through an extrusion nozzle. Later, the nozzle melts the filaments and expels them onto a printing bed or its base. Both the nozzle and the printing bed are controlled by a computer using computer-aided manufacturing (CAM) software that deciphers the measurements of an object into X, Y and Z coordinates (Palermo, 2013). Building process by depositing materials layer by layer begin from bottom to top.

In FDM system, the extrusion nozzle will move in both directions, horizontal and vertical creating a cross-section of an object on to the print bed. Once a layer of material is fully spread out, the base is further brought down by approximately one-sixteen of an inch to start a whole new layer and the process is continued until the whole object was built completely. Finally, when it is complete, its support materials are removed either by soaking in a soap or plain water or, if it is a thermoplastic support, snap the support material off by hand. Objects may undergo surface finishing process if necessary, to further improve their appearance and function.

2.1.1.2 Laminated-Object Manufacturing

The process of lamination 3D-printing involves the stacking of laminated on top of one another after a layer contour definition was achieved by cutting tools. This technology, also known as laminated object manufacturing (LOM), was invented at Helisys during the late 1980s (Bártolo, 2007). Adhesive-coated sheet materials are used as a medium in LOM process. The sheet material carries the adhesive either on one side or both sides, or it contains the adhesive in itself. The adhesive which can be pre-coated onto material or be deposited prior to bonding, enables layers of sheet material to be attached to each other so as to construct a three-dimensional object. After one layer is deposited, peripheries of this layer's cross-section are cut by a laser beam based on the information from the CAD model. This process is repeated until the full height of the part is reached (Park, Tari, & Hahn 2000).

The working cycle of a LOM machine is as follows (Bártolo, 2007):

- A computer which runs the system is capable of slicing a 3D solid model into thin two-dimensional cross-sections. The thickness of each cross-section is equal to the thickness of the material used in the process. At first, the geometry of a cross-section is generated by the computer.
- The geometrical information is fed into the LOM system where it will guide the laser to cut around its cross section. The laser can only cut one layer of material at a

time. Material that surrounds the cross section will be crosshatch by laser beam into squares for separation at the end of process

- Then, the platform moves down and the ribbon moves at an increment above the length of a cross-section onto the rewinding roll. As the platform moves, the heated roller travel across the stack pressing the ribbon against the stack creating a strong bond to the upper layer.
- Next layer based on the desired measurement is computed by sending fed back from the machine to the computer by measuring the height of the stack
- Laser beam then cut a new cross-section and this process is repeated until all the cross-sections have been deposited and cut.

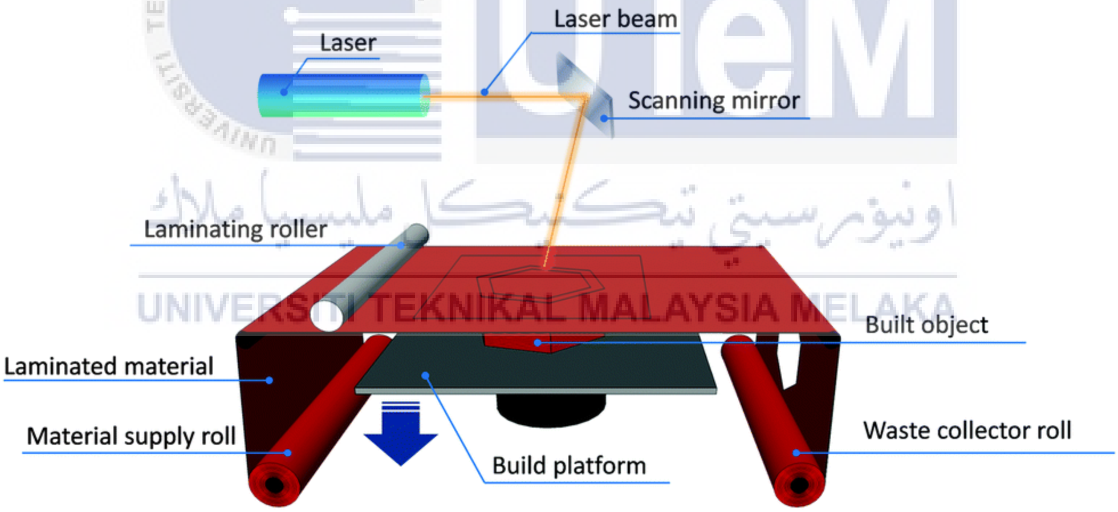


Figure 2.3 Laminated-object manufacturing (Ambrosi & Pumera 2016)

2.1.2 Liquid-Based Rapid Prototyping

Liquid-based rapid prototyping uses liquid as a starting material. In 1980, Charles Hull discovered that solid polymer patterns could be produced using layer by layer which give the idea of stereolithography technology. This technology uses liquid-based materials.

It is called liquid-based because the materials are in liquid form without melting solid process. The most common material used is photopolymer because most of the photopolymers are able to react to radiation in ultraviolet (UV) range of wavelengths which will undergo chemical reaction to become solid (Chua, Leong, & Lim 2010).

2.1.2.1 Stereolithography (SL)

Stereolithography which also known as SL is one the common rapid prototyping manufacturing technology used in industries. It is an additive manufacturing process that belongs to Vat Polymerization family. Stereolithography is a solid freeform technique (SFF) that was presented in the late 1980s. Despite the fact that numerous different techniques have been produced from that point forward, stereolithography stays a standout amongst the most capable and adaptable of all SFF techniques. It has the highest fabricating accuracy and an expanding number of materials that can be prepared is becoming available (Melchels, Feijen, & Grijpma 2010). SLA printer produces prototypes, models and pattern by using photopolymerization. It is a process where resin react with chemical to change phase from liquid to solid when they are exposed to the radiation in UV range of wavelength.

Stereolithography Apparatus (SLA) is a device used in stereolithography process. It consists of three main parts which are tank filled with resin, UV laser and scanner system. At the beginning stage of the printing, the platform of the SLA 3D printing is lowered into the resin by a very small amount where it allows the UV laser to draw the desired pattern on the platform with contact to the resin. This platform is resting or supported by an elevator which allows vertical movement (Z direction) only, while the laser beam can move in both X and Y directions. The pattern then hardened almost immediately creating the first layer.

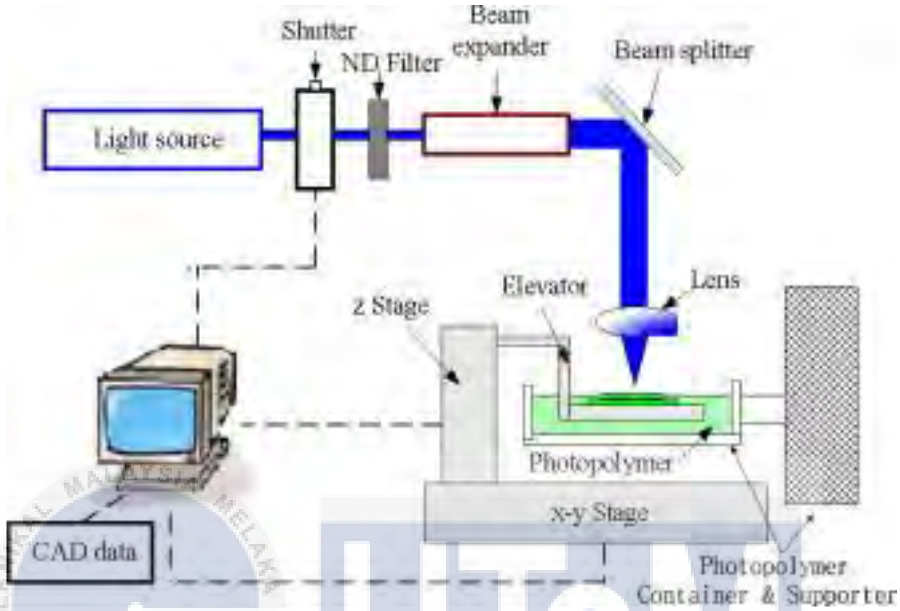


Figure 2.4 Stereolithography Apparatus (SLA) (Kang, Lee, & Cho 2004)

The process involved in stereolithography are:

- A desired shape that need to be printed are drawn in computer-aided program (CAD) such as AutoCAD or SolidWorks which is then converted into STL file
- Similar software such as PreForm was used to slice the model into multiple series of layers together with support structure
- The STL file is then connected to the stereolithography printer
- The tank is filled liquid photopolymer resin and the build platform is lowered by 0.15mm immersing into the resin
- Using the UV laser beam, the first layer of the model from the STL file is drawn out on the platform where photopolymer resin is available. The resin hardened almost immediately upon contacting with laser

- After the first layer have been completed, the platform is further lowered by 0.15mm with a new coated resin overlay on it
- The stereolithography process repeats layer after layer until it completes building the entire model
- The resin is then drained out before removing the model from the platform
- Further surface finishing can be done if it is necessary

2.1.2.2 Solid Ground Curing

Solid Ground Curing (SGC), otherwise called the Solider Process, is a procedure that was invented and created by Cubital Inc. of Israel. The SGC procedure uses photosensitive resin solidified in layers as with the Stereolithography (SL) process. Be that as it may, as opposed to SLA, the SGC procedure is considered as a high-throughput creation process. The high throughput is achieved by solidifying each layer of photosensitive resin at once. Large parts can be made due to the wide workspace (Braila, 1986).

Before printing process begin, a series of plates must be printed. Software will then slice the CAD display up into thin layers, and each layer is printed in 2D form onto a plate. The plate goes about as a mask. A mask by any means, model cross-section is transparent while the remaining is opaque. The machine initially exposed a layer of photopolymer into the working area. The first printed plate is stacked directly beneath an UV light, then a shutter opens and the whole plate is exposed to the photopolymer at once. The cross-section that was uncovered solidifies the photopolymer, and a short time later the uncured photopolymer is sucked up by a vacuum.

Next a layer of wax is put down covering the unexposed territory to ensure the bed is even and the whole layer is milled so that it is completely flat. Another layer is then spread on, the next plate is loaded and the process continues till the whole part is formed (Stetz, 2009). At the end of the process, the wax that was within the block will eventually melts away and no further post processing is required.

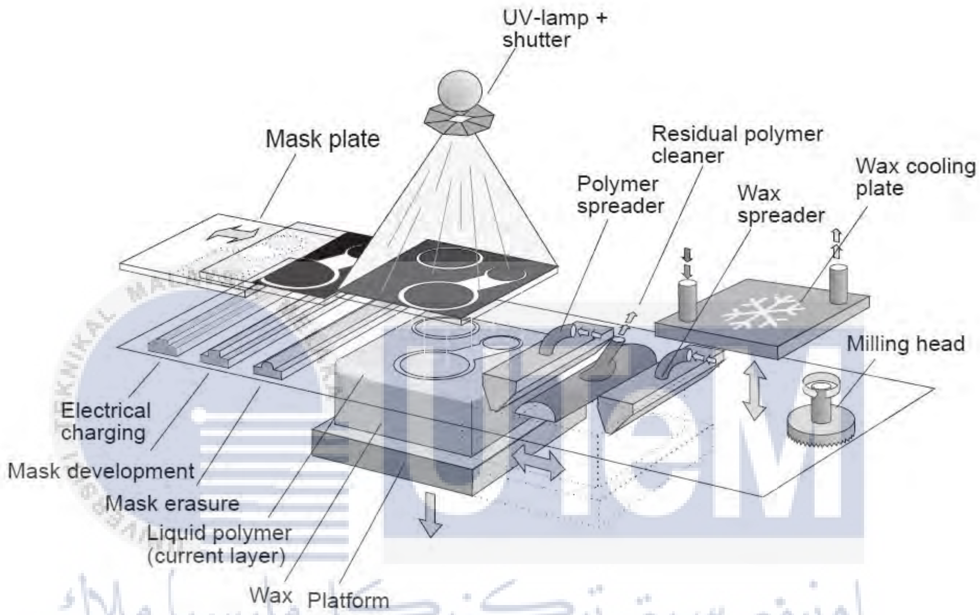


Figure 2.5 Solid ground curing

2.1.3 Powder-Based Rapid Prototyping

Powder-based rapid prototyping is one of the rapid prototyping that uses powder as a starting material. This powder is based on the solid-state material but processed into grain form. There are various types of powder-based rapid prototyping available in the current market now but the main rapid prototyping that will be discussed in this topic is Selective Laser Sintering (SLS) rapid prototyping.

2.1.3.1 Selective Laser Sintering

Selective Laser Sintering (SLS) was first invented by Dr. Carl Deckard with the help of his academic adviser, Dr. Joe Beaman at University Texas located at Austin in the 1980s. In pursuing their development, Deckard and Beaman were associated with the subsequent new business Desk Top Manufacturing (DTM), built up to design and fabricate the SLS machines (Deckard, 1986). Selective laser sintering is an intelligent manufacturing process with the use of powder covered metal additives, a procedure for the most part used for rapid prototyping and instrumentation. A continuous laser beams are used as heating source for examining and adjusting particles in desired shapes and sizes of the layers.

One of the lasers that can be used in this process is Carbon Dioxide laser and it is controlled by computer command. The geometry of the scanned layers corresponds to various sections of the models established by computer-aided design (CAD). After each layer have been made, a roller mechanism will spread out a new fresh powder overlaying the previous layer to start over the sintering process, repeating the process from bottom to top until the whole model is built up. Similar to other machines, a computer-aided design (CAD) is required such as SolidWorks, CATIA or AutoCAD to construct geometry model. The CAD data will further be converted into STL file to begin the sintering process (Despa & Gheorghe 2011).

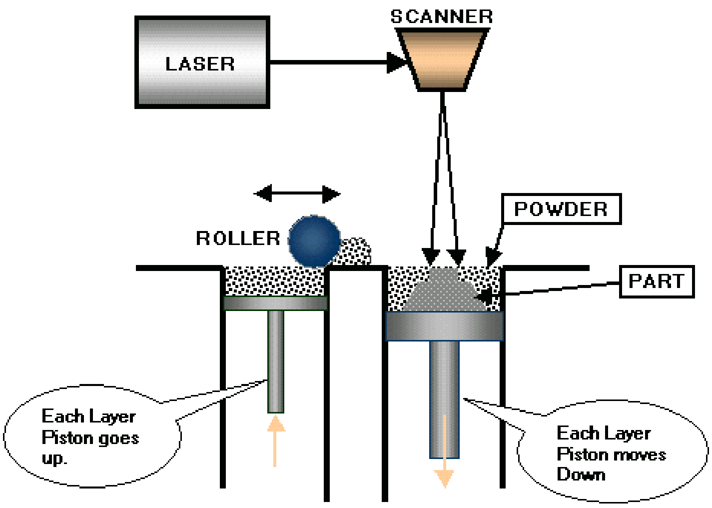


Figure 2.6 Selective Laser Sintering

2.2 Thermoplastic

Thermoplastic is a polymer where its material is made up in long chain with unlinked polymer molecules with a high molecular weight. Furthermore, since it is unlinked, the interactions of molecules have to rely on each other either by aromatic ring stacking, dipole-dipole interaction or by Van de Waals forces. Generally, this material when exposed to heat will gradually soften and eventually change to liquid form and hardened through cooling process where it will become glass-like subject to fracture (Johnny, 2003). The advantage of this thermoplastic is, it can be recycled for further usage as the process stated above are reversible which means it can be reshape, reheat and freeze multiple times depending on the quality of the thermoplastics.

There is various type of thermoplastics available and being used mostly in engineering industries such as Polylactic Acid (PLA), Polycarbonate (PC), Polyethylene (PE), Acrylic, Acrylonitrile Butadiene Styrene (ABS), Polyetherimide (PEI), Polyoxymethylene (POM), Polybenzimidazole (PBI) and Polystyrene (PS). In 3D printing process, the usage of thermoplastic has been implemented very long ago and it is still being used due to the superior performance of the product using plastic as material. Among all the thermoplastics material listed above, the most common thermoplastics that are used as the 3D printing filament are ABS and PLA because of its stability properties and long-term performance (Fischer, 2011). However, since the thermoplastic filaments are able to melt and cool down rapidly, certain factors are affected during the printing process especially on the specimen or product where warping will be formed the moment the layer of filaments starts to cool down.

2.3 Warping

Warping deformation is a common problem happened during 3D printing process. This is because of the temperature that acts on the specimen. This problem occurs when the filament printed through the nozzle warp, as it lays on the platform to produce a full layer of product. Few stages were undergone in the midst of forming a full layer which are solid filament have to go through melting process inside the nozzle to change its form to liquid and finally back to solid form again at the end of the process by cooling after printing on the print bed.

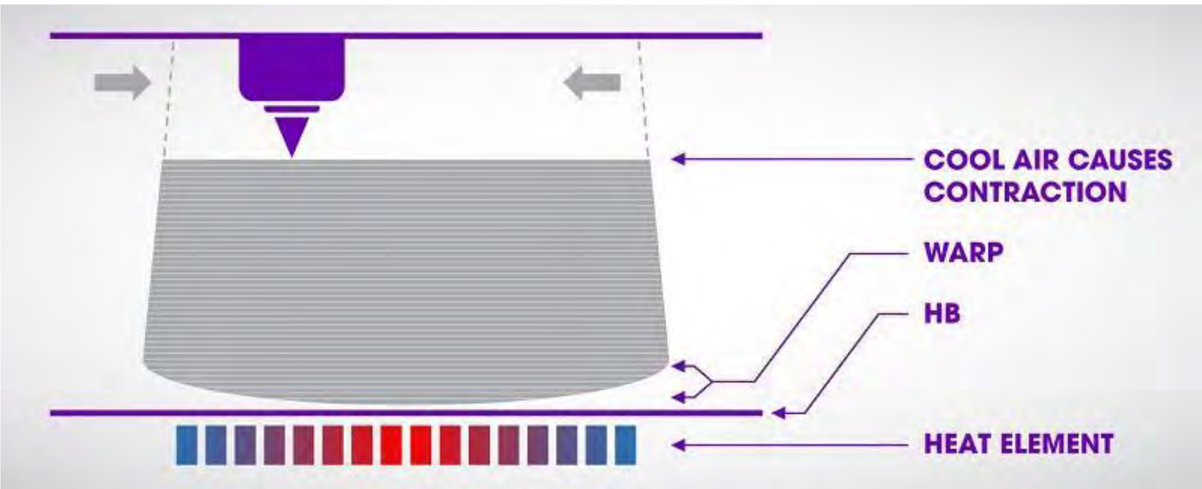


Figure 2.7 Warping deformation

These stages are the main cause of warping deformation because of the poor temperature distribution throughout the process which will result in bending at the end side of the product and causing it to be not flat or parallel to the surface. Moreover, deformation subjected by torsional behaviour is also a factor of warping deformation that distorting the filament from its original plane.

2.4 Adhesive

Adhesive in general means a glue or some high viscosity substances that is capable of holding two different or identical materials by surface attachment that resist separation. Adhesive also referring to the properties of how a substance is physically or chemically formed or how the materials are being joined and under which criteria that can be applied. Adhesives are separated into two different types which are synthetic adhesive such as silicones and epoxy and bio-based adhesive or more likely to be called as natural adhesive mainly from cereals or plant roots.

2.4.1 Synthetic Adhesive

Synthetic adhesive is made by combining few chemicals into a solution to produce glue. The first synthetic adhesive was first invented by Karlsons Klister in the 1920s (Karlsons, 2016). Most of the synthetic adhesive uses vinyl-based where it is classified under polymers. Besides, synthetic adhesive is widely used in most of the adhesive industry and had a huge range of adhesive properties. Apart from industrial usage, it also can act as a coating for abrasion and chemical resistant. Synthetic adhesive is widely used for textiles, plywood, pipes and papers. Furthermore, it is classified as one of the thermoplastic type adhesives where heating is required to lower down the viscosity of fluid. Synthetic adhesive is not suitable to be used to bond between the model and print bed because it will cause stress concentrations between materials thus leading to shrinkage and damaging the surface of the product. Moreover, synthetic adhesive produces bad smell to the environment during 3D printing therefore it is not environmental-friendly

2.4.2 Bio-Based Adhesive

Bio-based adhesives are of developing interest for late decades because of their environmental interest as well as due to their mechanical and chemical properties that are increasing effectively (Mathias, Grediac, & Michaud 2016). Bio-based adhesive in simple terms means natural adhesive where it is an adhesive made of renewable biomass from plant, vegetables and animals or from starch. Since it is a non-toxic adhesive, therefore there is no harm towards environment. Among the bio-based adhesive material that have been are starchy vegetables such as cassava plant, potato, soy bean and glutinous rice. Akpa (2014) emphasize on cassava plant as it has remarkable characteristics such as good stability, rich in concentration of starch, high viscosity and paste clarity. Akpa, (2014) prepared a simple procedure on making adhesive using cassava starch by adding gelatinization enhancer (NaOH/HCL) and stir it continuously while heating the beaker at a specified temperature. Then a small amount of viscosity enhancer which also known as Borax was added and the mixture was stirred continuously until it becomes sticky. In another study, yam starch also considered as one of the bio-based adhesives. Although cassava, potato and rice starch were labelled as natural binder while yam starch was totally ignored, it still shows that yam starch have good values in terms of viscosity which is a great benefit to be used in adhesive industries and also as food thickeners (Oluwamukomi & Akinsola, 2015).

2.5 Tensile Test

Tensile test, also known as tension test is one of the most fundamental mechanical tests that can be carry out on material. Tensile test is conducted to identify the characteristic or behaviour of a specimen or material. Furthermore, those characteristics also includes the strength and elasticity of the material by pulling the material apart during the test. Various information of the particular material can be identified under tensile test by constructing stress-strain graph such as proportional limit, elastic limit, upper and lower yield stress point, ultimate tensile strength and breaking or rupture point.

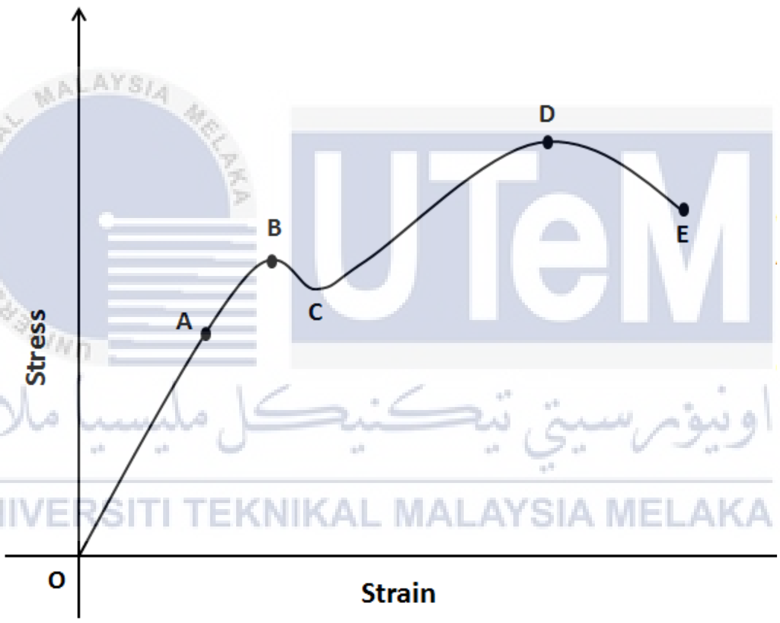


Figure 2.8 Stress-strain graph

Stress strain curve has different regions and points. Based on Figure 2.6, these regions and points are (Mishra, 2016):

- OA: Proportional limit
- A: Elastic limit
- B: Upper yield stress point
- C: Lower yield stress point
- D: Ultimate tensile strength
- E: Breaking or rupture point

Proportional limit is the region which obeys Hooke's law where elastic limit is directly proportional to strain. Within this limit, the ratio of stress gives a constant number called young's modulus. Besides, elastic limit is a maximum point of which the material will return to its original form when the load acting on it is completely removed. Beyond this limit, plastic deformation will occur thus, the material cannot be back to its original position. Yield stress points begins right after elastic region where materials completely or permanently deform plastically. This process cannot be reversible once it begins to deform. Ultimate tensile strength is maximum load that a material can undergo before failure. Point E, fracture or breaking point is the point where the material completely breaks into two and therefore the tensile test is complete.

In tensile test, Hooke's law (2.1) is used to determine the relationship of force, load and elongation. Hooke's law states that within the limit of elasticity, the stress induced in the solid due to some external force is always directly proportional to strain (Borese & Schmidt, 2003).

$$\sigma = \frac{P}{A} \tag{2.1}$$

$$\boldsymbol{\varepsilon} = \frac{\Delta L}{L} \tag{2.2}$$

$$E = \frac{\sigma}{\varepsilon} \tag{2.3}$$

Where: E = modulus of elasticity, σ = stress, $\boldsymbol{\varepsilon}$ = strain, P = load, A = cross section area, L = length

2.6 Viscosity Test

Viscosity test is a simple process where it is tested using a viscometer. Viscosity in general is a measure of fluid flow under resistance. The liquid is considered as high or low viscosity depends on the internal friction of a moving fluid. A fluid with high viscosity resists its motion because of the molecule in the flow have high internal resistance whereas a low viscosity has a minimal resistance that causes the fluid to flow easily due to less internal resistance. Viscosity also called as coefficient of dynamic, is determine by finding the ratio of shear stress and shear rate. Formula (2.4) can only be used when the fluid is a Newtonian fluid.

$$\text{Viscosity} = \frac{\text{shear stress}}{\text{shear rate}} \tag{2.4}$$

Furthermore, viscosity test is one of the process to determine the effectiveness of the adhesive either for industry or home usage. Low and high viscosity are both ideal for adhesive depending on the requirement. Low viscosity will simply make the adhesive less sticky where as high viscosity will be very sticky and can be used in many industries such as plywood industry and 3D printing company.

2.7 Summary on Previous Study

By referring to few articles that suits the objectives of this project, few researches did some test regarding yam-based adhesive however, none of the researches by far produce any articles related to the use of bio-based adhesive for 3D printer. Therefore, in this project two types natural adhesive will be tested which are Chinese yam (Dioscorea Oppositifolia) and orange sweet potato (Ipomoea Batatas) to determine whether is it suitable to use these bio-based adhesives for 3D printer.

2.7.1 Dioscorea Species

Journal title, rheological characterization of yam and potato paste for adhesive purpose and evaluation of starches obtained from four Dioscorea species as binding agent in chloroquine phosphate tablet formulations which written by Gumus et al. (2014) and Okunlola et al. (2011) respectively, proves that yam starch has a very good binding properties in terms of swelling power, water binding capacity, viscosity, density, pasting temperature and strength. Besides, by mixing yam starch with chemicals such as hydrochloric acid (HCL) and sodium borate which also known as borax in general term causes an increase in viscosity and strength which clearly proves that yam starch can be used as an adhesive. By referring to this and other related journals, yam starch can be labelled as one of the bio-based adhesives that can be used widely either in home or industries.

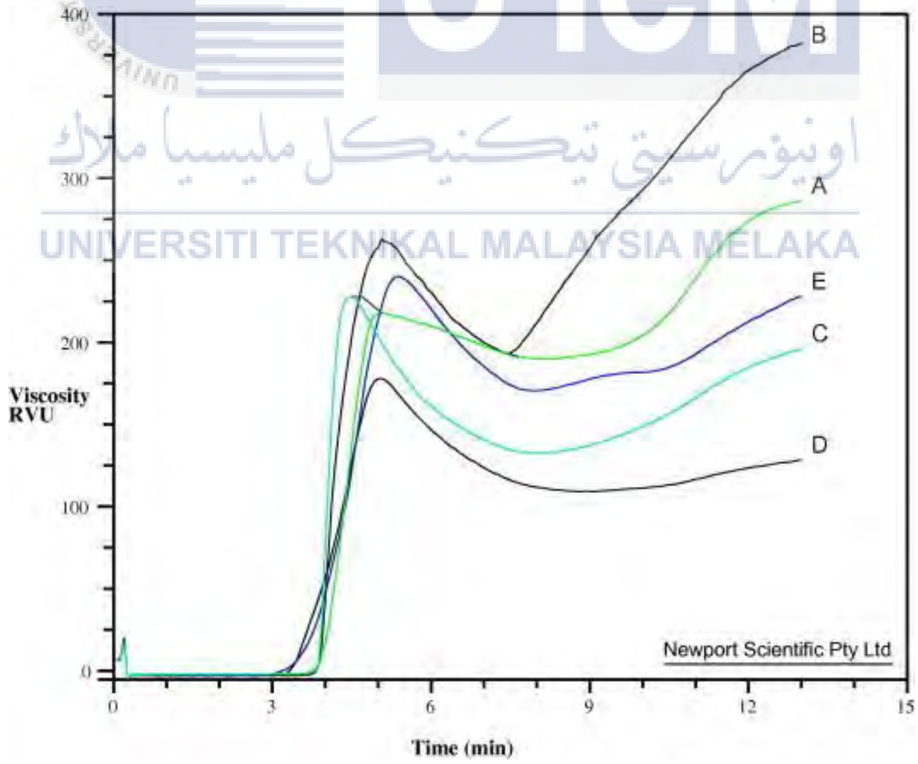


Figure 2.9 Viscosity profile (Okunlola & Odeku, 2011)

Figure 2.9 shows a viscosity profile of different types of yams and corn where A, B, C, D and E is bitter, Chinese, white, water and corn respectively. From Figure 2.9, Chinese yam (Dioscorea Oppositifolia) clearly shows that it has higher viscosity compared to other types of yam and corn but all of the yam species gives different viscosity at different timing. The peak time where peak viscosity happened are the inverse relative sensitivity for the starch to heat which means the ranking of pasting time are different for each yam. The pasting time depends on the granule size. Larger granule size tends to gelatinize faster and smaller size gelatinize slower. Hence, white yam having largest granule size among all and bitter yam having smallest size (Odeku & Picker-Freyer 2007). Figure 2.10 below shows the granules of Dioscorea Oppositifolia.

Figure 2.10 Dioscorea Oppositifolia granules

The characterization of the starch granules is carried by using X-ray Powder Diffraction (XRD). XRD method is used to identify information on a single cell dimension and also is used to find out the characteristics of a crystalline material. The common material that is used for this method are homogenized, average bulk composition and finely ground (Zhou, Wang, Fang, Sun, & Dou, 2012).

Table 2.1 Rheological properties

Starch	Peak viscosity (RVU)	Peak time (min)	Pasting temperature (ºC)	Trough viscosity (RVU)	Final viscosity (RVU)
Bitter	217.67±2.40	5.76±0.04	88.80±0.87	189.83±1.19	286.08±1.14
Chinese	262.92±2.97	5.74±0.05	84.90±0.96	193.25±1.39	382.33±1.04
Water	177.92±3.40	5.44±0.04	87.50±0.66	109.00±1.07	128.33±1.56
White	227.75±2.02	4.94±0.04	85.75±0.92	132.58±1.53	196.08±1.11
Corn	240.00±1.08	5.43±0.03	88.55±0.87	170.50±1.60	227.83±1.61

Lower values in viscosity such as water yam indicates that the starch have high resistance to temperature where its characteristics of starch will not change frequently over time even when exposed to high or low temperature. Final viscosity in the Table above was recorded by using direct measure of the viscosity and its proven that Chinese yam starch have the highest viscosity among all the other yams. This clearly shows that Chinese yam are the most ideal yam that can be tested to be use as bio-based adhesive for 3D printing because of the good characteristics especially in terms of viscosity and swelling power and the availability of Chinese yam in Malaysia is high.

2.7.2 Ipomoea Batatas

Ipomoea Batatas is a scientific name for orange sweet potato. A research about sweet potato starch properties was conducted and written by Oladebeye et al. (2009) with the journal title physicochemical properties of starches of sweet potato (Ipomea Batatas) and red cocoyam (Colocasia esculenta) Cormels. Ipomoea Batatas have a good characteristic of swelling power and bulk density which are 8.16% and 0.76g/ml as shown in the below. Besides, Ipomoea Batatas have outstanding reading in terms of amylose content and water absorption capacity with reading of 80.80% and 84.91%. According to Board (2010), high content of amylose is suitable to be used as an adhesive as it has better water resistance and increase speed of corrugation.

Table 2.2 Physicochemical properties

Sample	Sweet Potato
Bulk Density (g/ml)	0.76±0.01
Water Absorption Capacity (%)	84.91±0.02
Content (%)	19.20±0.02
Amylose Content (%)	80.80±0.03
Amylopectin Power (g/g)	10.23±0.02
Swelling Solubility (%)	8.16±0.02

Apart from amylose content and water absorption capacity, viscosity of starch plays an important role in forming bio-based adhesive as low viscosity will cause the solution to be slimy and less sticky while high viscosity causes the starch to be sticky.

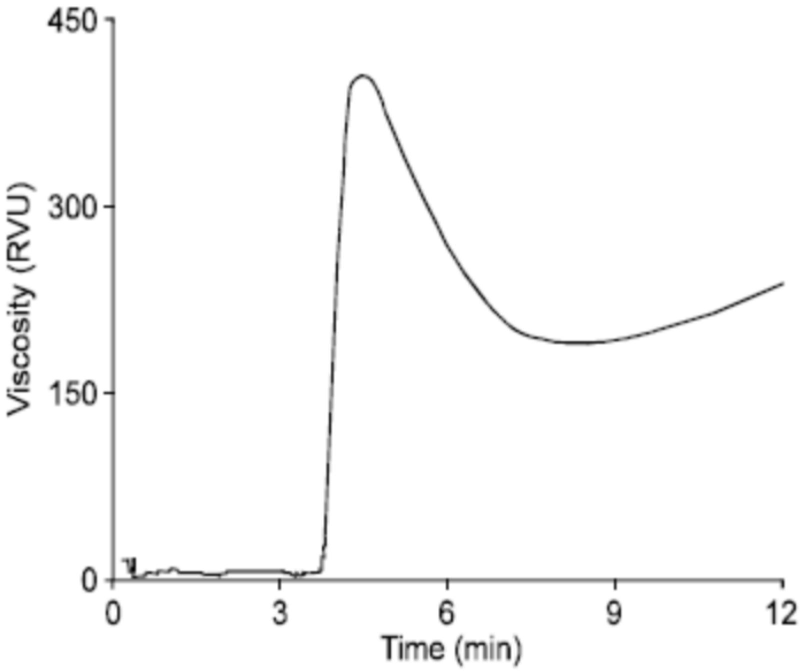


Figure 2.11 RVA pasting curve of sweet potato starch

From Figure 2.11, sweet potato starch requires less time to reach its peak to achieve highest viscosity. In spite of lower waiting time, it possesses higher viscosity and it proves that sweet potato starch paste has higher value of stability at temperature of 61.60º (Oladebeye, Oshodi, & Oladebeye 2009). Rapid Visco Analyser (RVA) was used to analyse the viscosity of starch where RVA is a rotational viscometer with a capability of shearing and varying temperature.

2.8 Conclusion

In conclusion to this chapter, few parameters had been identified by referring through few journals, articles, books and web sites to proceed with the project. Furthermore, methods on how to proceed and important measurements had been noted to ensure the methodology runs smoothly throughout the project.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the methodology of the study is explained in detail attend the three main hypothesis that have aforesaid in the objectives. Preparation of bio-based adhesive are based on Gumus et al. (2014) journal as the methods on producing adhesive are simple and can be found in chemistry lab. The methodology of this project is divided into several processes which are starch preparation, adhesive preparation, viscosity test, printing process, methods on applying adhesive onto the platform of 3D printer, measurement of warping deformation and tensile test.

3.2 Flow Chart

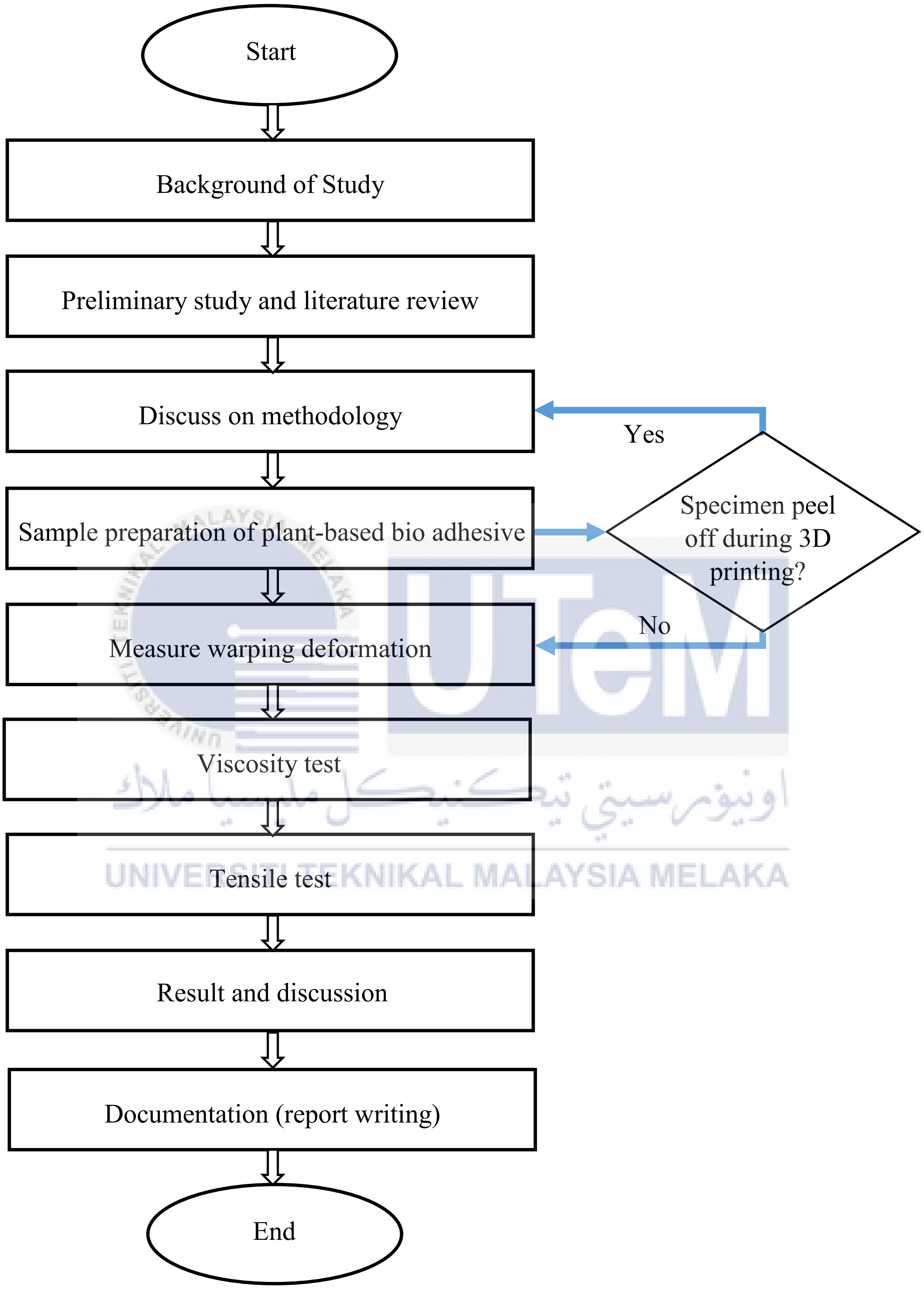


Figure 3.1 Project flow Chart

3.3 Sample Preparation

Two types of sample are used in this project which are Chinese yam (Dioscorea Oppositifolia) and orange sweet potato (Ipomoea Batatas). This two sample undergoes the same preparation method to obtain its starch or powder which are then to be used as an adhesive for 3D printer. Therefore, this sample preparation is divided into two different parts which are starch preparation and adhesive preparation.

3.3.1 Starch Preparation

1kg of orange sweet potatoes were wash, peeled, washed again with distilled water and grated into fine slices by using grater. Two methods can be used to produce fine slices either by grating or blending. If blending method was used, the potatoes are cut into small pieces and add into the blender together with lukewarm water. The blending process was used in short burst to prevent heating of the starch. Hence, the slurry was filtered or strained using a muslin cloth into a large container and the filtrate was left to settle.

Blending method is slightly similar to grating process where fine slices were soaked with a lukewarm water into a container and was left to settle for 4 hours to allow all the starch from the potatoes dissolved into the water. After 4 hours, the sliced potatoes were separated using a sieve leaving only the water and was left for 12 hours for sedimentation process to occur.

Figure 3.2 Grate into fine slices

Figure 3.3 Soaking into lukewarm water

Figure 3.4 Separating starch water and fine slices

The sliced potatoes can be wash multiple times to completely extract all the starch from it which will increase the amount of starch at the end of the process. After 12 hours, the water is decanted leaving the sediment (starch) that was at the bottom of the container. Hence, the starch was washed few times using distilled water to remove impurities from the starch and finally dried under brilliant sunshine for approximately 4 hours. Before the powdery starch was stored in an air tight container to prevent contamination from surrounding, it was separated using sieve to obtain only fine powders as only fine powder will be used in making bio-based adhesive. The same procedure was repeated to prepare Chinese yam starch.

Figure 3.5 Powderly starch

Figure 3.6 Fine powder

3.3.2 Adhesive Preparation

The orange sweet potato-based adhesive will be prepared using distilled water, sodium borate (borax) and hydrochloric acid (HCL). 10g of dry sweet potato starch (Ipomoea batatas) was dissolved in 84ml of 0.01M of HCL where HCL act as a gelatinization modifier. The mixture is then mixed until there was complete dissolution using a magnetic stirrer at 60 rpm. Next, the solution was heated up continuously with the aid of magnetic stirrer where the rotation speed is increased gradually as the concentration increase to obtain uniform gel.

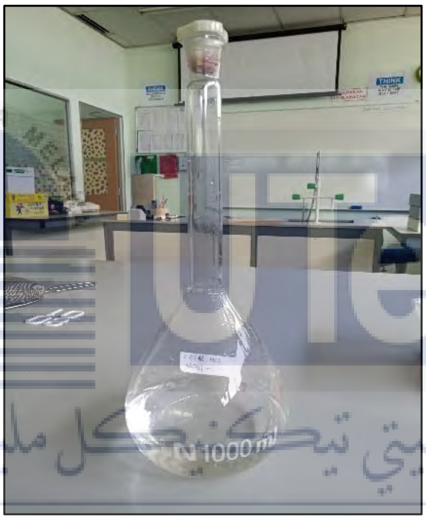


Figure 3.7 Hydrochloric acid

Figure 3.8 Magnetic stirrer

Figure 3.9 Gel

The gel was allowed to cool at room temperature. Finally, 20ml of the gel was transferred into different beaker and 0.17g of borax was added and stirred at 80ºC, with the aid of water bath to obtain a constant temperature. The adhesive obtained was preheated before applying on the 3D printer platform. Same procedure was repeated for starch obtained from Chinese yam.

Figure 3.10 Weighing sodium borate

Figure 3.11 Water bath

3.3.3 Viscosity Test

To determine the viscosity level of a certain adhesive, a viscosity test is required by using viscometer. Same spindle will be used for both samples of adhesive made with different temperature in order to determine the trend of viscosity in the sample as temperature increases. In this process, water bath was used to ensure the temperature is not lost to the surrounding during the measuring process.

Figure 3.12 Viscometer

3.4 Printing Process

Two types of process are involved for specimen printing which are PLA and ABS using FDM printer. Along the printing process, for PLA, the platform was used in two different conditions which are with heat bed at 60ºC and without heat bed also the nozzle temperature is set to 195ºC while for ABS material, 240 ºC nozzle temperature with 100 ºC heat bed temperature will be use. Without heat bed will also be tested for ABS material.

Since, the main idea of this project is to reduce warping and material cost, the parameters are set to 13% infill density with no additional support structure and 0.2mm layer thickness using 1.75mm filament thickness. Specimen with dimension 100mm x 30mm x 5mm was used for printing for both PLA and ABS.

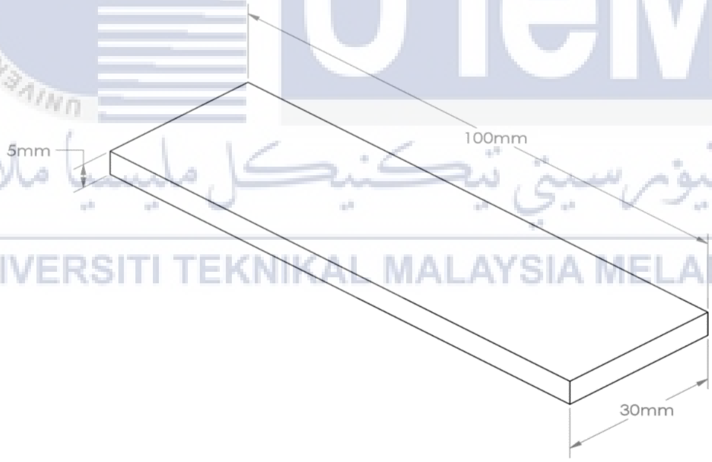


Figure 3.13 Specimen dimension

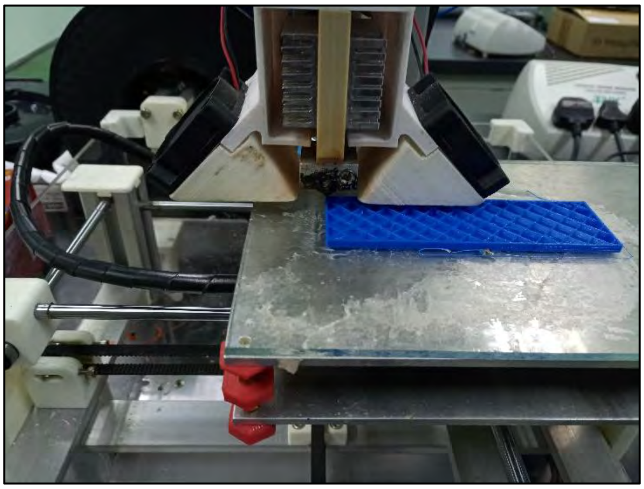


Figure 3.14 Specimen printing process

3.4.1 Method of Applying Adhesive on 3D Printer Platform

Applying glue on 3D printer platform plays an important role before printing because if the glue applied on the platform are too thick, it will interrupt the printing process as the height between the nozzle and platform is only 0.2mm. Therefore, uniform adhesive spreading is required. To apply on the platform, a brush or any flat tools is required to evenly spread the adhesive diagonally starting at the edge of the platform from left to right and another layer from right to left. This ensure the adhesive to properly bond between the platform and specimen.

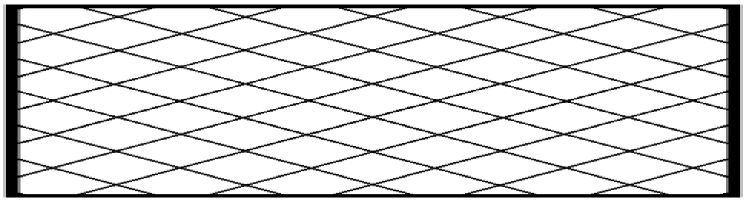


Figure 3.15 Diagonal direction

3.5 Warping Deformation

Warping deformation occurs when the vertexes of the specimen curled upwards due to change in temperature on the specimen. Warping can be reduced by providing good adhesive at base of the specimen. In this research, warping deformation is measure using a vernier caliper by placing the specimen on a flat glass plate to obtain its depth and compare with the original specimen. There is various way to measure the warping deformation of a specimen other than using vernier caliper which are by using vernier height gauge or 3D scanner. Each vertex is labelled with 1, 2, 3 and 4 to avoid confusion during measuring and the deflection collected using vernier caliper were recorded in a table form for comparison.

Figure 3.16 Measuring warping deformation

3.6 Tensile Test

Different sample produces different strength of adhesive. Thus, tensile test is required to compare which adhesive has the greatest criteria. In 3D printing, the strength of adhesive between the platform and the first layer of printing plays an important role in reducing warping and avoiding specimen from peeling away. Therefore, tensile test will be conducted using ASTM D2095 to determine the maximum ultimate strength of the adhesive before failure begins or before the adhesive losses its strength from the platform.

3 samples will be tested under tensile test which are Dioscorea Oppositifolia-based adhesive, ipomoea batatas-based adhesive and glue stick. The specimen is printed on a glass pane with the specimen dimension of 13mm x 13mm x 5mm using PLA as its material. 2 tons epoxy was used to permanently stick the upper part of the specimen and bottom part of glass platform to a square solid steel with dimension of 12.7mm x 12.7mm x 40mm and 5.5mm diameter hole. Next, both solid steels are attached to a shaft which will be connected to the tensile machine. An Instron 8872 machine with control panel is used to conduct tensile test experiment.

Figure 3.17 Instron 8872

Figure 3.18 2 tons epoxy

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Sample Preparation

Procedure of preparing adhesive was guided by ASTM standard. The mixture of both sweet potato and yam-based adhesive consist of hydrochloric acid and sodium borate with ratio of one gram of powder to 8.4ml of hydrochloric acid. The preparation of both starches started by grating, soaking and drying under brilliant sunshine. The starch obtained was sieved to separate between fine and course structures. In this experiment, 10g of sweet potato starch and 84ml of 0.01 mol hydrochloric acid will be used by measuring using weighing scale and measuring cylinder respectively. The mixture is then mixed together in a beaker with the aid of magnetic stirrer to ensure there was a complete dissolution

Next, heat the solution with a continuous stirring using magnetic stirrer to obtain a uniform gel and allow it to cool at room temperature. Once, it is cooled, with the help of thermometer, heat 20ml of gel again up to 80ºC and add 0.17g of sodium borate. The ratio between the gel to sodium borate is 1ml to 0.0084g respectively. The solution is then stirred for 10 to 15 minutes under a constant temperature with the aid of water bath to obtain even mixing and the sweet potato-based adhesive is ready for testing. The same procedure is repeated for Chinese yam-based adhesive.

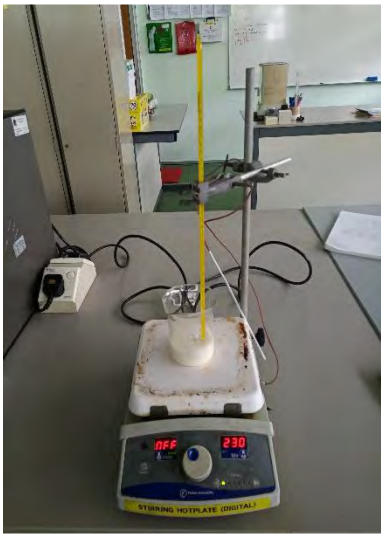


Figure 4.1 Heating solution until turns into uniform gel

Figure 4.2 Sweet potato-based adhesive

Table 4.1 Ratio of sweet potato and Chinese yam-based adhesive

Adhesive	Starch weight (g)	Hydrochloric acid (ml)	Sodium Borate (g)
Sweet potato	10	84	0.17
Chinese yam	10	84	0.17

4.2 Warping Deformation

Warping deformation is a common problem in 3D printing where the first layer of the specimen printed on the platform curl or bend upwards due to the lack of adhesiveness between the platform and specimen. The adhesive decreases overtime as the glue used tend to dry off causing the first layer to stick temporarily and warp or peel off from the platform. In this research, warping deformation using bio-based adhesive will be tested and analyzed to find out whether can it replace synthetic adhesive and is it suitable to be used for 3D printing process. Warping deformation is measure from four different vertexes, labelled 1, 2, 3, and 4. Figure below shows the warping deformation measuring process and the printed specimen using sweet potato and Chinese yam as an adhesive.

Figure 4.3 Measuring the thickness of specimen

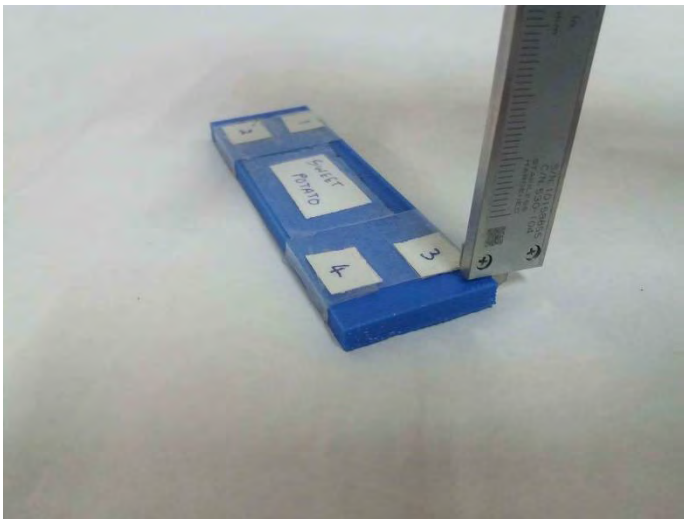


Figure 4.4 Measuring the depth of the specimen

Figure 4.5 Printed specimen using bio-based adhesive

4.2.1 Sweet Potato Adhesive

PLA with heat bed (60˚C) (Sweet Potato)

Table 4.2 Sweet potato warping deformation using PLA with heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	0.05	0.10	0.35	0.00	0.13
100_30_5 (b)	0.15	0.10	0.05	0.10	0.10
100_30_5 (c)	0.40	0.10	0.10	0.00	0.15

PLA without heat bed (Sweet Potato)

Table 4.3 Sweet potato warping deformation using PLA without heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	0.25	0.10	0.30	0.27	0.23
100_30_5 (b)	0.10	0.40	0.17	0.21	0.22
100_30_5 (c)	0.25	0.30	0.20	0.21	0.24

ABS with heat bed (100˚C) (Sweet Potato)

Table 4.4 Sweet potato warping deformation using PLA without heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	0.10	0.05	0.13	0.08	0.09
100_30_5 (b)	0.11	0.09	0.13	0.07	0.10
100_30_5 (c)	0.05	0.20	0.15	0.08	0.12

ABS without heat bed (Sweet Potato)

Table 4.5 Sweet potato warping deformation using PLA without heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	-	-	-	-	-
100_30_5 (b)	-	-	-	-	-
100_30_5 (c)	-	-	-	-	-

4.2.2 Chinese Yam Adhesive

PLA with heat bed (60˚C) (Chinese yam)

Table 4.6 Chinese Yam warping deformation using PLA with heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	0.05	0.45	0.05	0.15	0.18
100_30_5 (b)	0.05	0.30	0.05	0.25	0.16
100_30_5 (c)	0.15	0.10	0.30	0.20	0.19

PLA without heat bed (Chinese yam)

Table 4.7 Chinese Yam warping deformation using PLA without heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	0.26	0.30	0.30	0.34	0.30
100_30_5 (b)	0.10	0.12	0.29	0.65	0.29
100_30_5 (c)	0.13	0.19	0.40	0.60	0.33

ABS with heat bed (100˚C) (Chinese yam)

Table 4.8 Chinese yam warping deformation using PLA without heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	0.15	0.18	0.14	0.13	0.15
100_30_5 (b)	0.00	0.15	0.25	0.12	0.13
100_30_5 (c)	0.16	0.13	0.17	0.10	0.14

ABS without heat bed (Chinese yam)

Table 4.9 Chinese yam warping deformation using PLA without heat bed

Specimen	1 (mm)	2 (mm)	3 (mm)	4 (mm)	Average (mm)
100_30_5 (a)	-	-	-	-	-
100_30_5 (b)	-	-	-	-	-
100_30_5 (c)	-	-	-	-	-

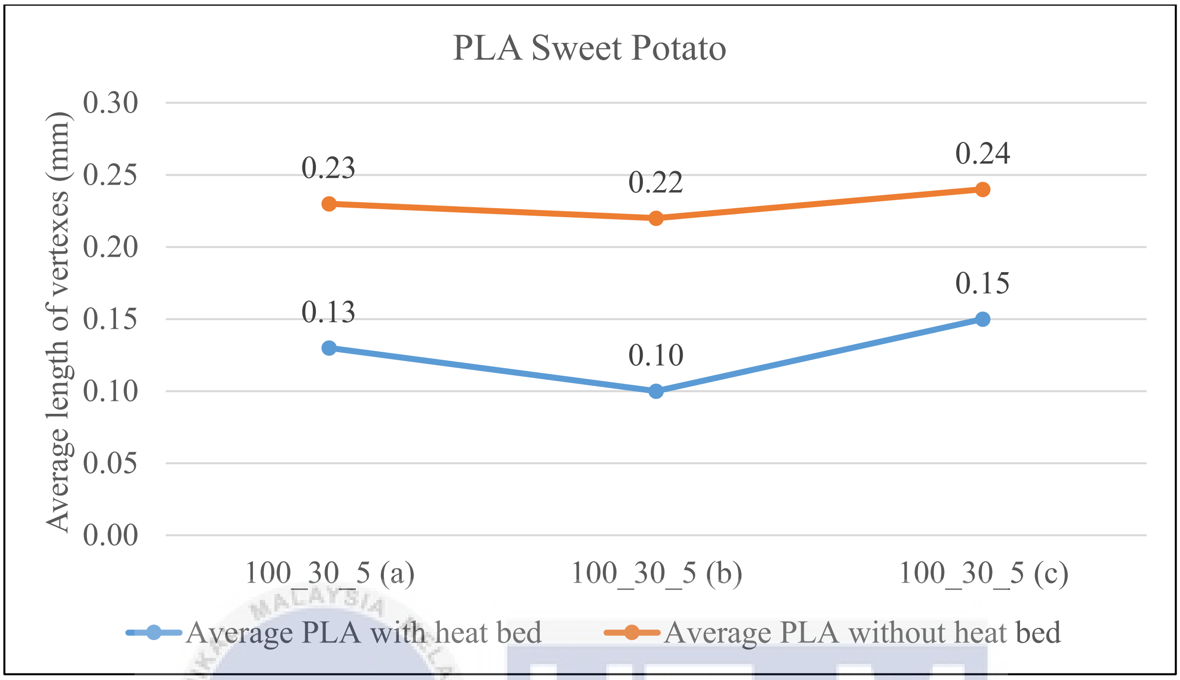


Figure 4.6 Average PLA warping deformation for sweet potato adhesive

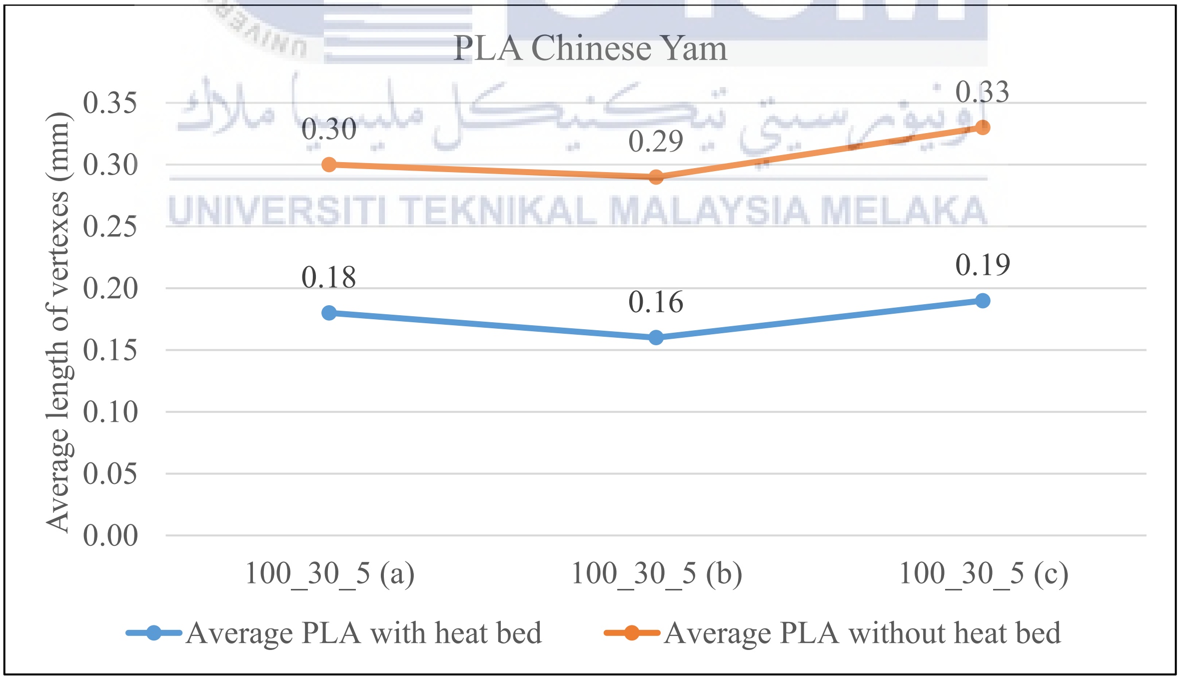


Figure 4.7 Average PLA warping deformation for Chinese yam adhesive

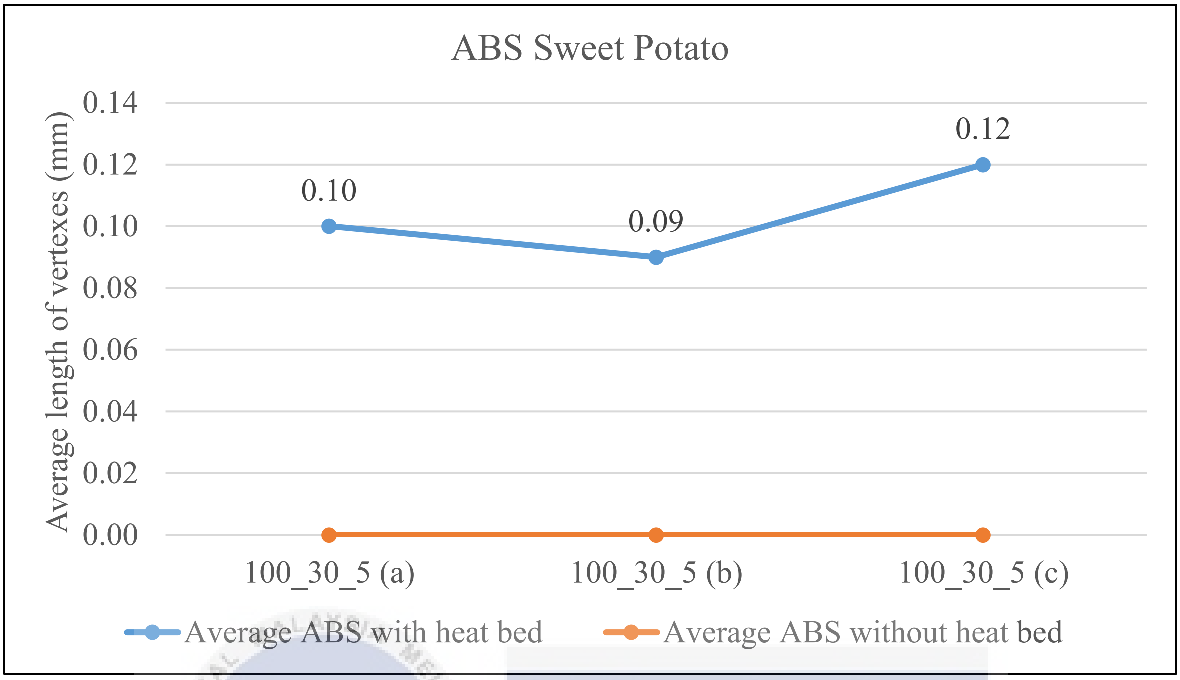


Figure 4.8 Average ABS warping deformation for sweet potato adhesive

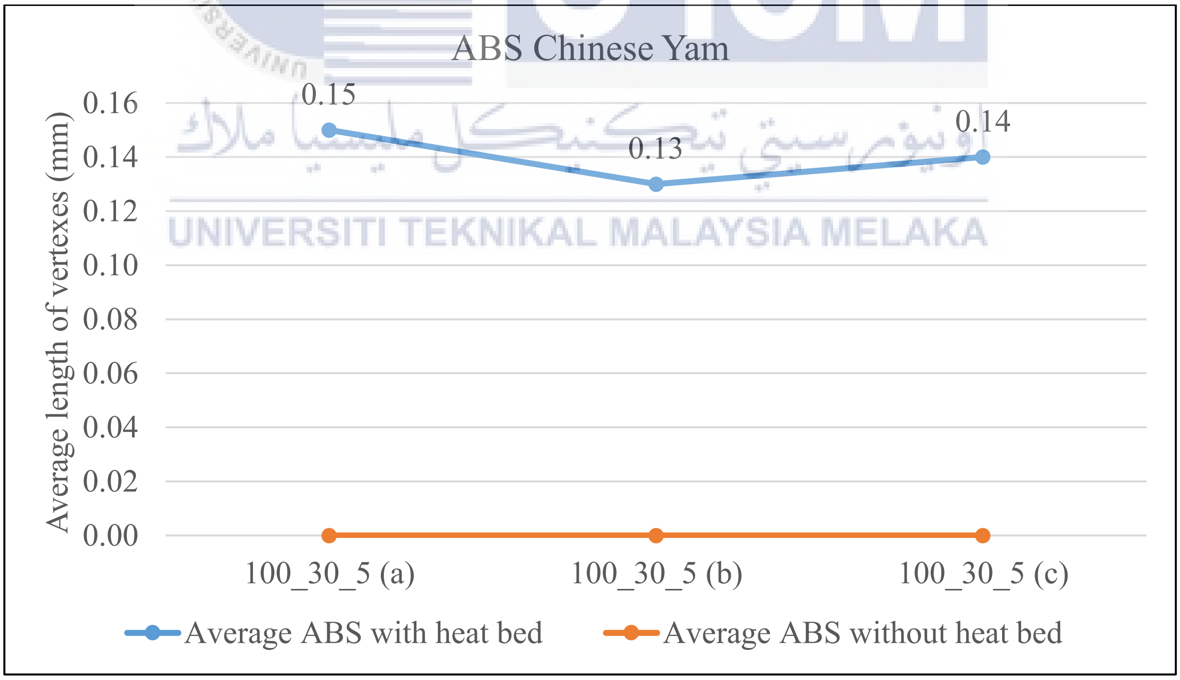


Figure 4.9 Average ABS warping deformation for Chinese yam adhesive

Table above shows the result of different vertex length on each specimen 1, 2, 3 and 4 which was measured using a vernier calliper. Each test was printed three times to obtain average results. In order to do comparison of vertex length between two different adhesives and different types of filament used, the specimen is fixed to only one dimension which is 100mm x 30mm x 5mm. Various test was conducted which are PLA and ABS filament with and without heat bed to test the strength of adhesive to the first layer in an open source 3D printer.

Based on the graph plotted, it clearly shows a significant difference between PLA and ABS materials in terms of warping deformation, For PLA, it can be observed that print with heat bed at 60°C provides stronger bonding between the base and the first layer which reduces warping where the average reading is around 0.13mm and 0.18mm for sweet potato and Chinese yam respectively as compared to printing without heat bed where the average for sweet potato and Chinese yam are around 0.23mm and 0.31mm. Meanwhile for ABS filament, the warping is less on heated bed at 100°C which proves that ABS filament has the strongest bonding which greatly reduce warping during printing but the major drawback is it can't be printed without heat bed as the specimen will tend to peel of eventually approximately at layer height of 17 out of 25 layers in total. This causes all the experiment printed without heat bed to fail and no data could be recorded.

Figure 4.10 Warping deformation without adhesive

Figure 4.11 Warping deformation with adhesive

According to most of the findings, low cost 3D printers are not able perform a complete printing process when ABS filament without heat bed is used because ABS tends to shrink before there is enough height in the part to stabilise it. Shrinkage occur during printing because of two main reasons which are poor support and uneven temperature. Since no support is required while printing as the main objective of this project is to test its warping deformation, uneven temperature is the main factor that affecting specimen to shrink and warp.

The term uneven temperature means, temperature drops from very high to low in few seconds where the nozzle which is at 240ºC will change the ABS filament properties to semi molten and print on the printer platform. Usually the platform will be heated up to 100ºC to control its temperature to prevent rapid cooling but since its printed without heat bed, the semi molten filament will be cooldown to room temperature and by the time the printer develops a new layer, the edges of the specimen will shrink due to contraction and causes the specimen to eventually peel off from the platform overtime. According to Figure 4.12, it shows that the middle area has the lowest temperature thus when it contracts or shrink, the edges of the specimen will tend to move inwards causing it to lift upwards from the printer platform

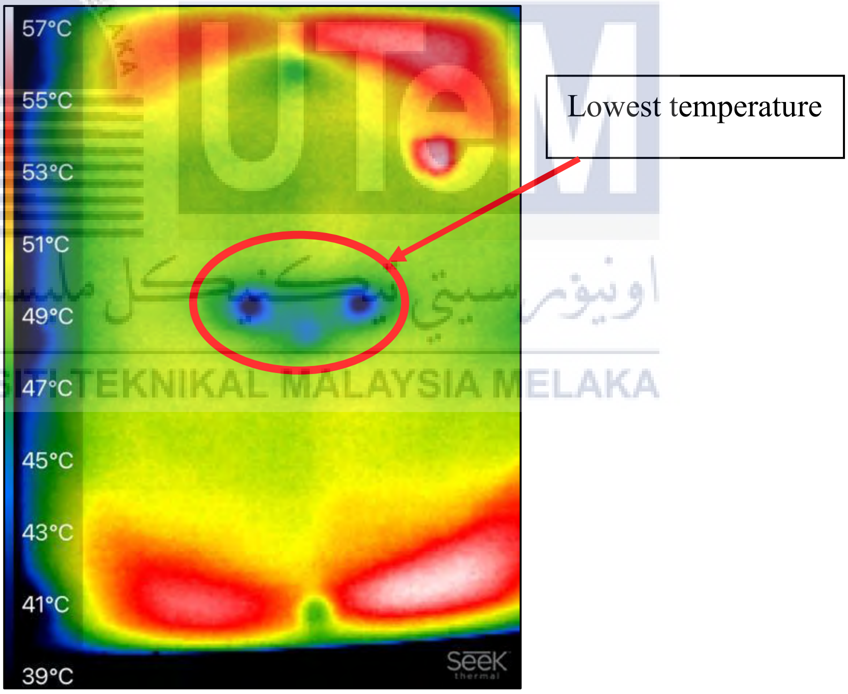


Figure 4.12 Heat distribution on sample printed specimen (3D Prints Warping or Curling)

Table 4.10 Warping deformation for specimen of UHU glue stick (Layer Adhesion Investigation of 3D Printer Platform)

Specimen	I (mm)	II (mm)	III (mm)	IV (mm)	Average (mm)
UHU glue stick	0.00	1.00	050	0.50	0.50

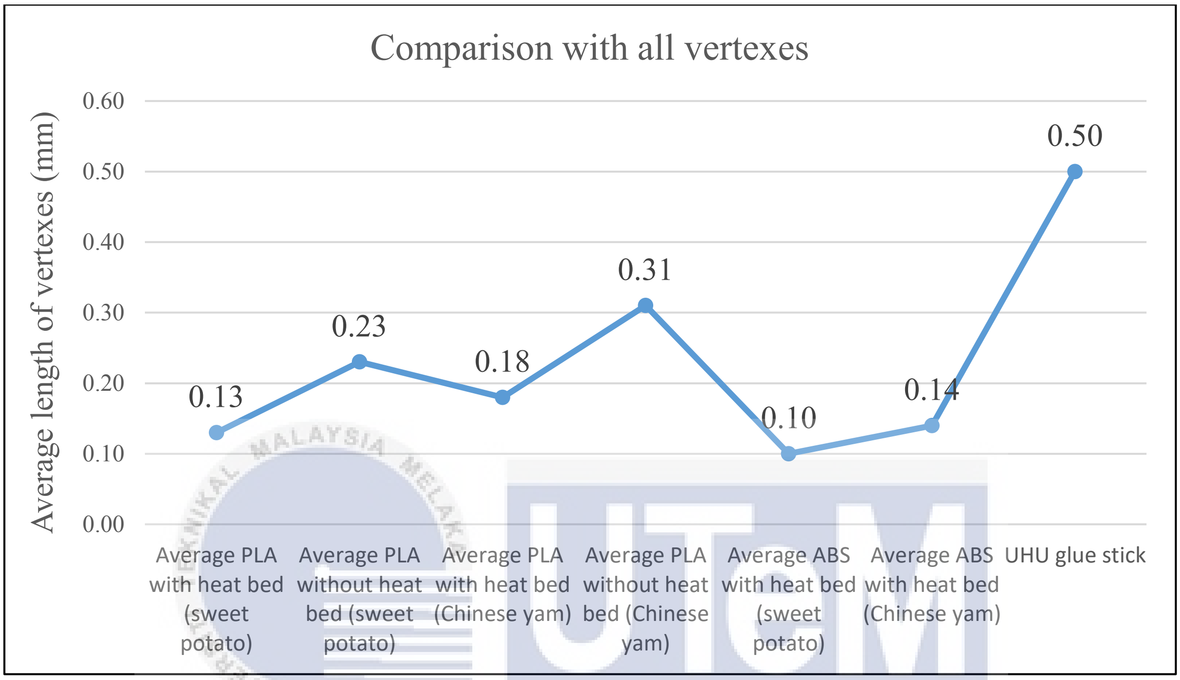


Figure 4.13 Average warping deformation for sweet potato, Chinese yam and UHU glue stick

Comparing to all the results obtained with UHU glue stick, specimen printed with orange sweet potato and Chinese yam obtain the lowest length of vertex as compared to UHU glue stick. Taking the average lowest value for both adhesive without heat bed, the length is 0.23mm and 0.31mm for sweet potato and Chinese yam respectively as compared to UHU glue stick which is 0.50mm.

Although the results for without heat bed have higher deflection compared to with heat bed, but it still can be used for 3D printing as the deflection difference are not significant thus, not affecting the specimen dimension. Therefore, both adhesive, sweet potato and Chinese yam can be applied on the 3D printer platform without turning on the heat bed hence, reducing the energy power consumption. The same test was conducted without turning on heat bed and no adhesive on the printer platform and the deflection is very high causing the dimension of the specimen to differ from actual design and in worst case causing it to peel off from the 3D printer platform. This proves that both adhesives have higher bonding strength which could greatly reduce warping deformation and suitable to be used on a low-cost 3D printer.

4.3 Viscosity Test

For viscosity test, both bio-based adhesive was tested to observe the property of fluids which describes a liquid resistance to flow and its internal friction. Different temperature was tested using a water bath that is linked directly to viscometer to study the properties of adhesive when expose to heat. A Brookfield Viscometer will be use to conduct this test by using the same spindle throughout the test which is Spindle 64. The manipulated variable will be temperature with 20ºC, 40ºC and 60ºC while the responding variables are the spindle speed which are 5rpm, 10rpm, 15rpm, 20rpm, 25rpm and 30rpm.

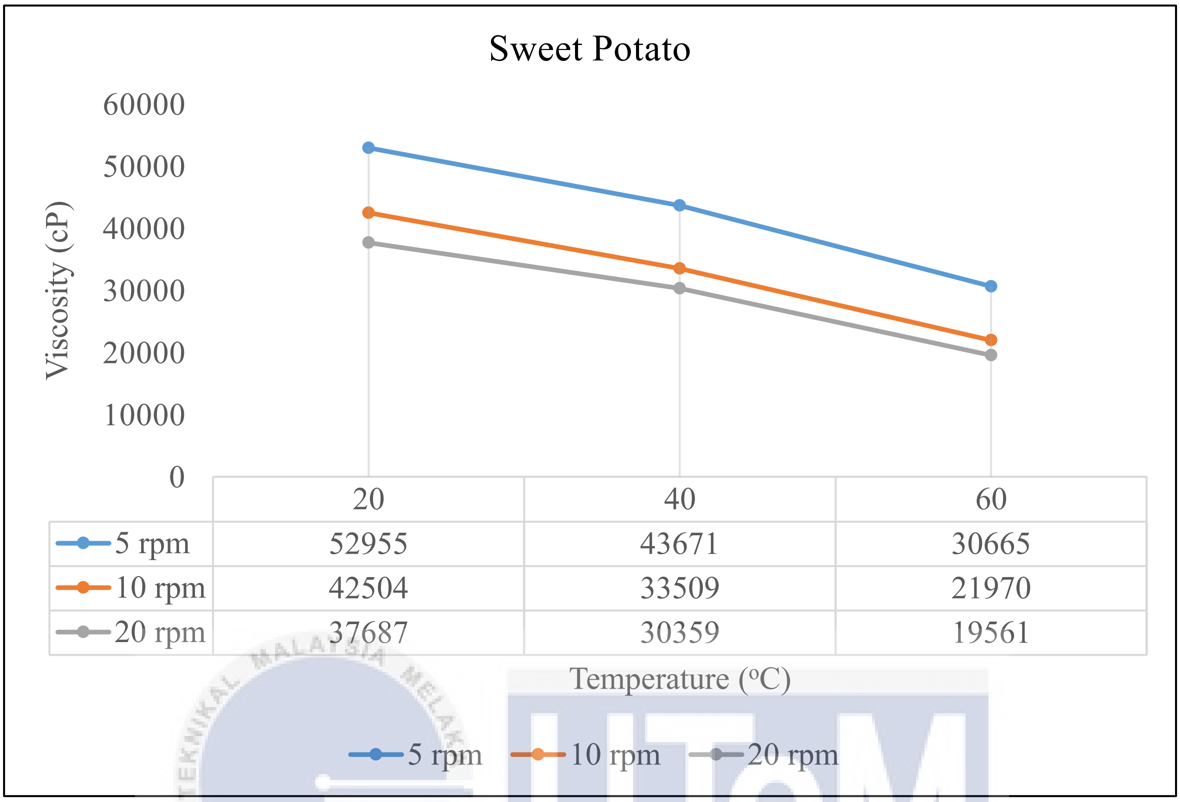
According to the user manual of Brookfield Viscometer, every spindle has their own spindle speed range. If the material is reading higher than a Full-Scale Range, an error will display hence, reducing the spindle speed or changing the spindle will avoid this error. Since the spindle size is the fixed variable, reducing the speed to 5rpm, 10rpm and 20rpm will obtain the optimum results.

Figure 4.14 Water bath and viscometer

Figure 4.15 Spindle 64

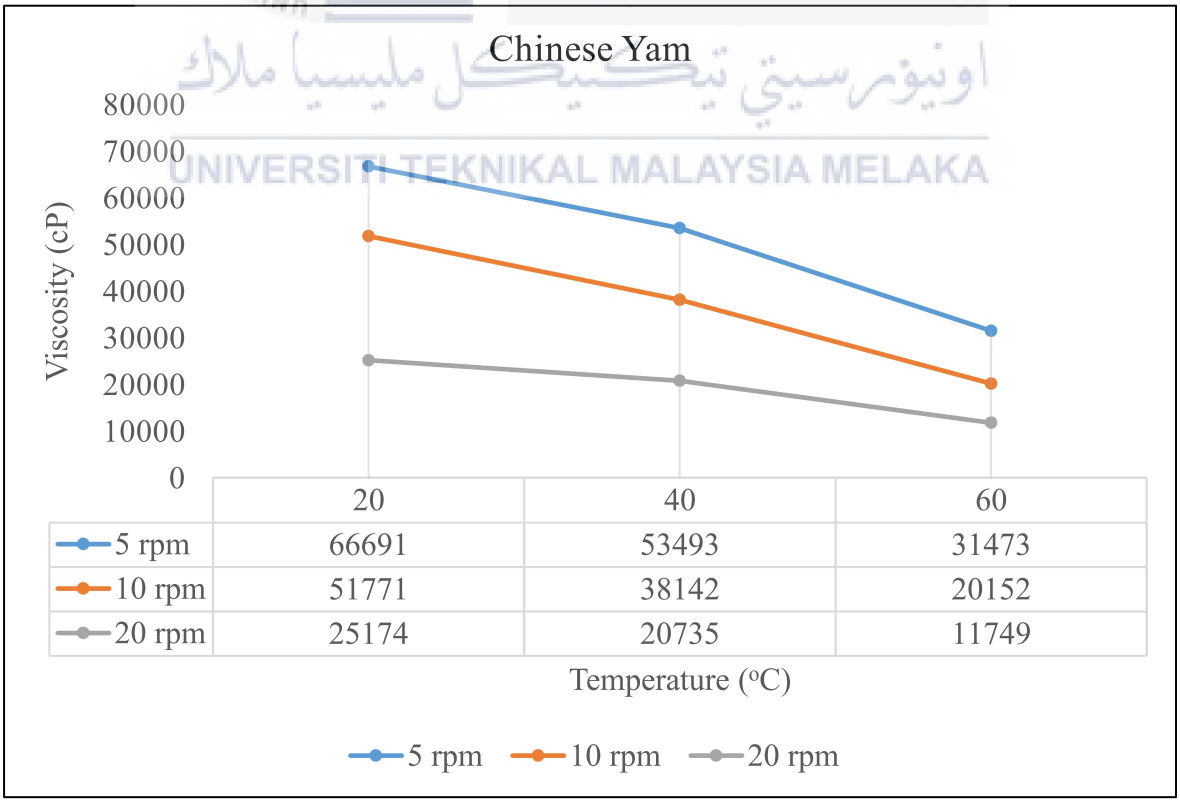
Figure 4.16 Viscometer

4.3.1 Sweet Potato and Chinese Yam Adhesive



	20	40	60
5 rpm	52955	43671	30665
10 rpm	42504	33509	21970
20 rpm	37687	30359	19561

Figure 4.17 Viscosity test for sweet potato



	20	40	60
5 rpm	66691	53493	31473
10 rpm	51771	38142	20152
20 rpm	25174	20735	11749

Figure 4.18 Viscosity test for Chinese yam

By referring to Appendix from B1 to C3, both viscosity test for sweet potato and Chinese yam graph are plotted based on data collected. Based on Figure 4.17 and 4.18, the relationship between viscosity and temperature are inversely proportional which means the higher the viscosity the lower the temperature. This is because, increase in temperature causes an increase in molecular interchange as molecules tends to move faster in higher temperature resulting in lower internal friction. Besides, in liquid, the viscosity is considered as atomic bonding therefore, higher temperature will cause the bond to break apart and allow the molecule to move freely hence decreasing its viscosity.

Chinese yam has higher viscosity at lower temperature in all three different spindle speed compared to sweet potato where the average reading is 66691cP, 51771cP and 25174cP for 5 rpm, 10 rpm and 20 rpm respectively. However, as the temperature increase to 60°C, Chinese yam has lower viscosity reading for spindle speed at 10 rpm and 20 rpm compared to sweet potato which is 20152cP and 11749cP. Therefore, from the results obtained, it clearly shows that Chinese yam tends to break its molecule faster as the temperature increases. Although the viscosity obtained is lower, but the adhesive can still be used to reduce warping deformation during 3D printing as the molecules does not break completely at 60°C thus providing a strong bonding between the platform and first layer of the specimen. Furthermore, since both adhesive, sweet potato and Chinese yam have promising results within the temperature range, it is suitable to replace current synthetic adhesive that is in the market now.

4.4 Tensile test

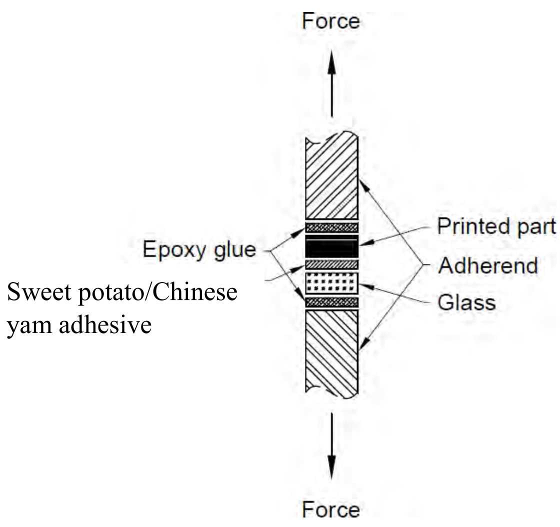


Figure 4.19 Tensile test setup

Tensile test was conducted to analyse the strength of orange sweet potato and Chinese yam adhesive in compare to UHU glue stick (Layer Adhesion Investigation of 3D Printer Platform). 3 samples were prepared for each adhesive in order to obtain average results. All the test was tested with ASTM D2095 using an Instron machine, a Universal Tensile Machine Dynamics 8872 (UTM Dynamics 8872) with speed of 1mm per minute as a fixed variable, types of adhesive as manipulated variables and maximum load, tensile stress at maximum load and extension at maximum load will as the responding variables.

Table 4.11 Tensile test results for sweet potato, Chinese yam and UHU glue stick

Types of adhesive	**Maximum Load (N)**	**Tensile stress at maximum load (MPa)**	**Extension at maximum load (mm)**	**Ranking of best adhesive**
Sweet potato 1	10.7149	0.0857	0.4254	2
Sweet potato 2	2.6443	0.0212	0.0609	6
Sweet potato 3	8.6431	0.0536	0.0260	3
Chinese yam 1	0.9916	0.0079	0.0301	7
Chinese yam 2	4.7166	0.0292	0.2782	5
Chinese yam 3	7.8251	0.0485	0.8388	4
UHU glue stick	19.9490	0.1596	1.0356	1

Table 4.12 Tensile test results for sweet potato, Chinese yam and UHU glue stick in percentage

Types of adhesive	Maximum Load (N)	Tensile stress at maximum load (MPa)	Extension at maximum load (mm)	Ranking of best adhesive
Sweet potato 1	46%	46%	59%	2
Sweet potato 2	87%	87%	94%	6
Sweet potato 3	57%	66%	97%	3
Chinese yam 1	95%	95%	97%	7
Chinese yam 2	76%	82%	73%	5
Chinese yam 3	61%	70%	19%	4
UHU glue stick	Reference			1

Data from Table 4.11 are converted in percentage to Table 4.12 for better understanding. Percentage error was calculated with the reference of glue stick as this experiment are comparing bio-based adhesive with synthetic adhesive. The formula to calculate percentage error is as shown

$$\text{Percentage error (\%)} = \frac{\text{Theoretical value} - \text{Experimental value}}{\text{Theoretical value}} \times 100 \tag{4.1}$$

where theoretical value is value taken from UHU glue stick and experimental value if from sweet potato and Chinese yam.

$$\text{Percentage error (\%)} = \frac{19.9490 - 10.7149}{19.9490} \times 100 \tag{4.2}$$

Percentage error = 46 %

From Table 4.11, UHU glue stick has the highest strength and extension which is 19.9490 N and 1.0356 mm as compared to other adhesives. The value of maximum load means at the strength of 19.9490 N, the adhesive will lose its strength from the glass platform thus tearing apart. 19.9490 N load is need to tear apart UHU adhesive from glass platform at a constant speed of 1 mm per minute. Referring to Table 4.12, taking the lowest percentage error value for both adhesive, sweet potato and Chinese yam have percentage error of 46 % and 61 % respectively. Sweet potato has better strength as compared to Chinese yam but both of the adhesive values are quite low when compared to synthetic adhesive, UHU. This is because during the 3D printing process on a glass platform before tensile test was conducted, the adhesive layer may tend to dry because of the use of heat bed thus resulting in low bonding strength causing the adhesive to tear apart quicker.

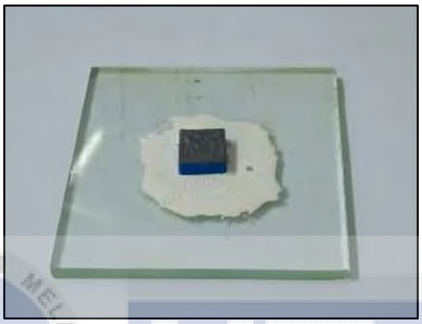


Figure 4.20 Specimen printed on a glass platform

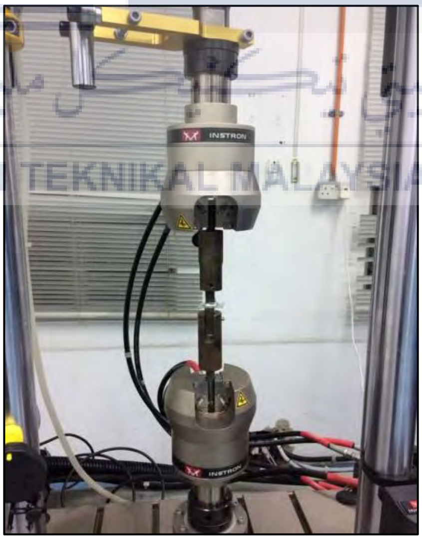


Figure 4.21 Tensile testing process

4.4.1 Graphical Results of Tensile Test

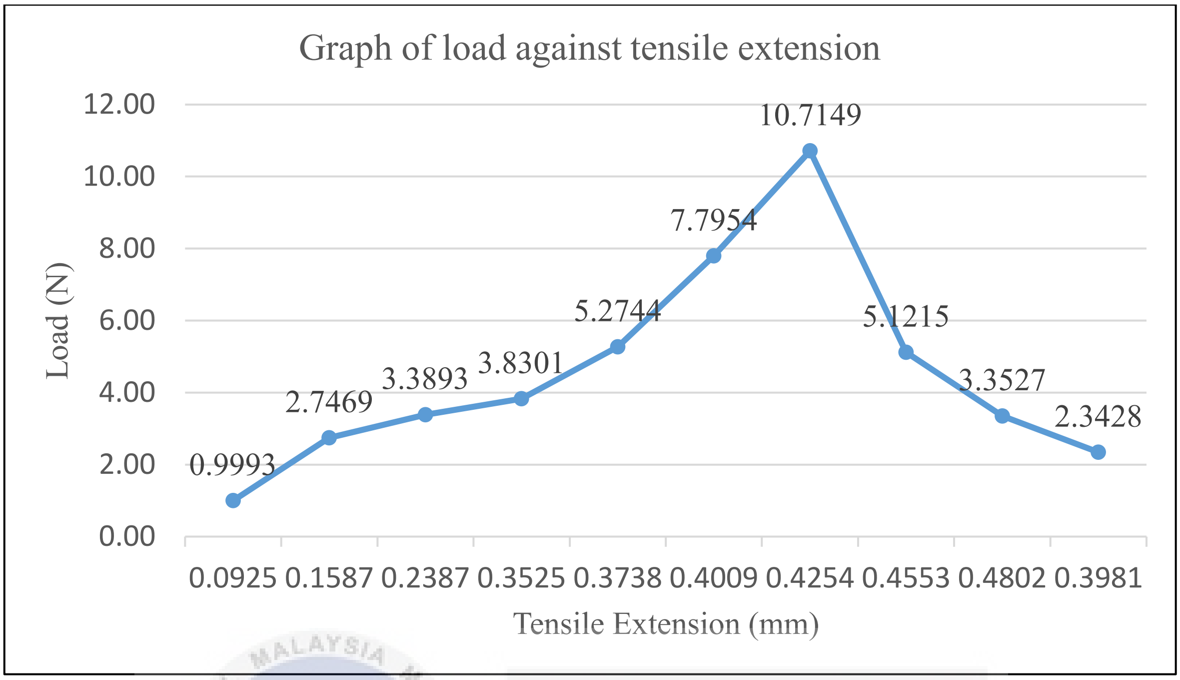


Figure 4.22 Graph of sweet potato 1

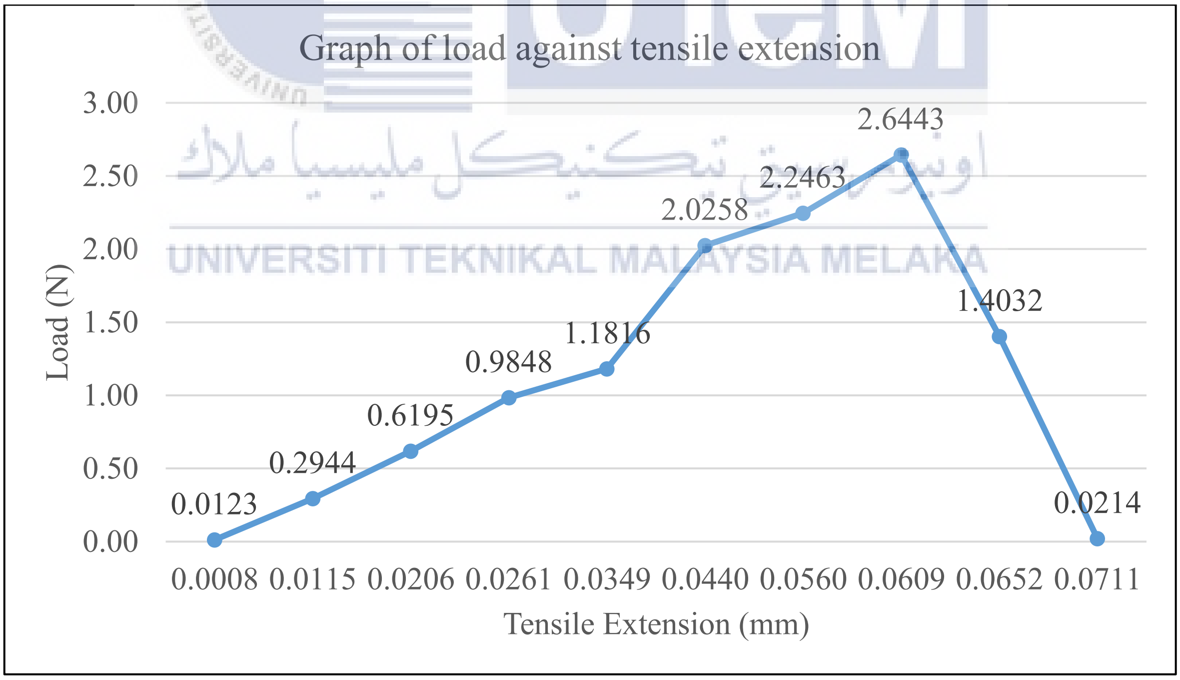


Figure 4.23 Graph of sweet potato 2

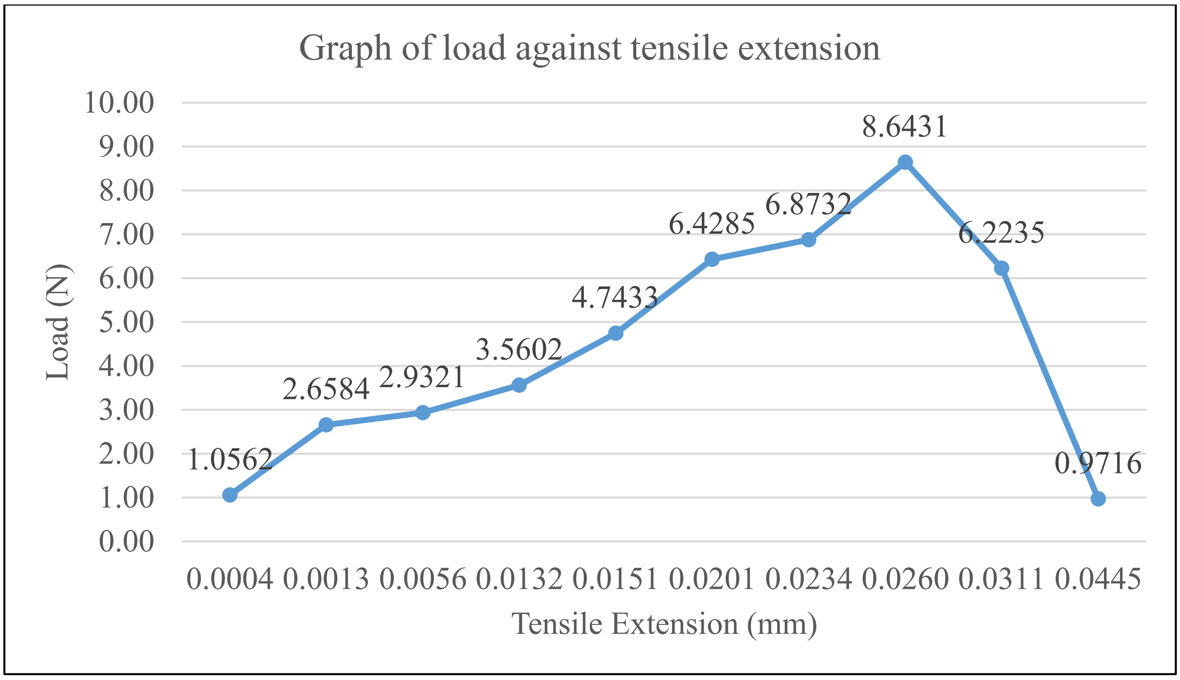


Figure 4.24 Graph of sweet potato 3

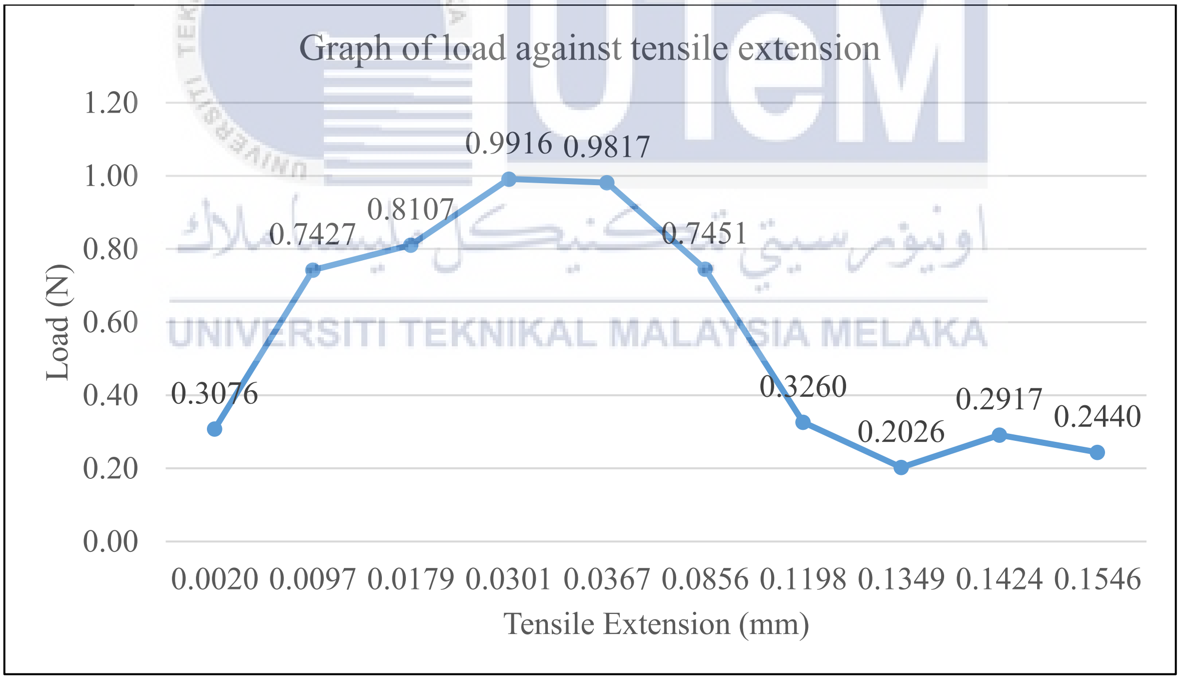


Figure 4.25 Graph of Chinese yam 1

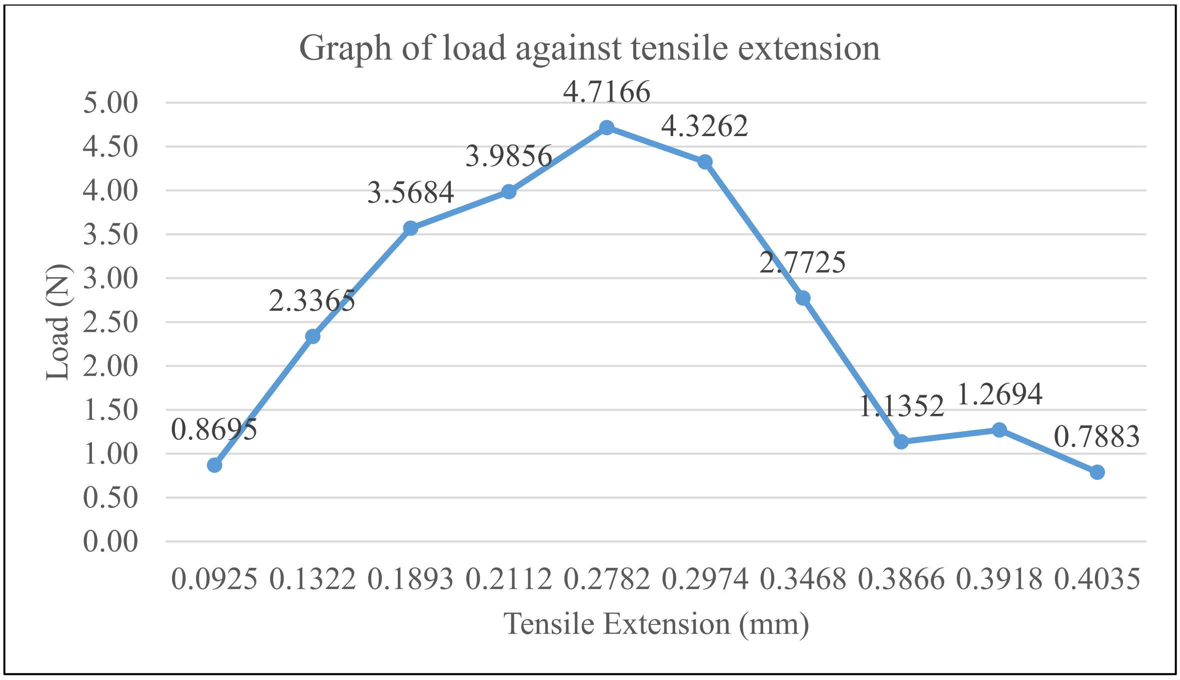


Figure 4.26 Graph of Chinese yam 2

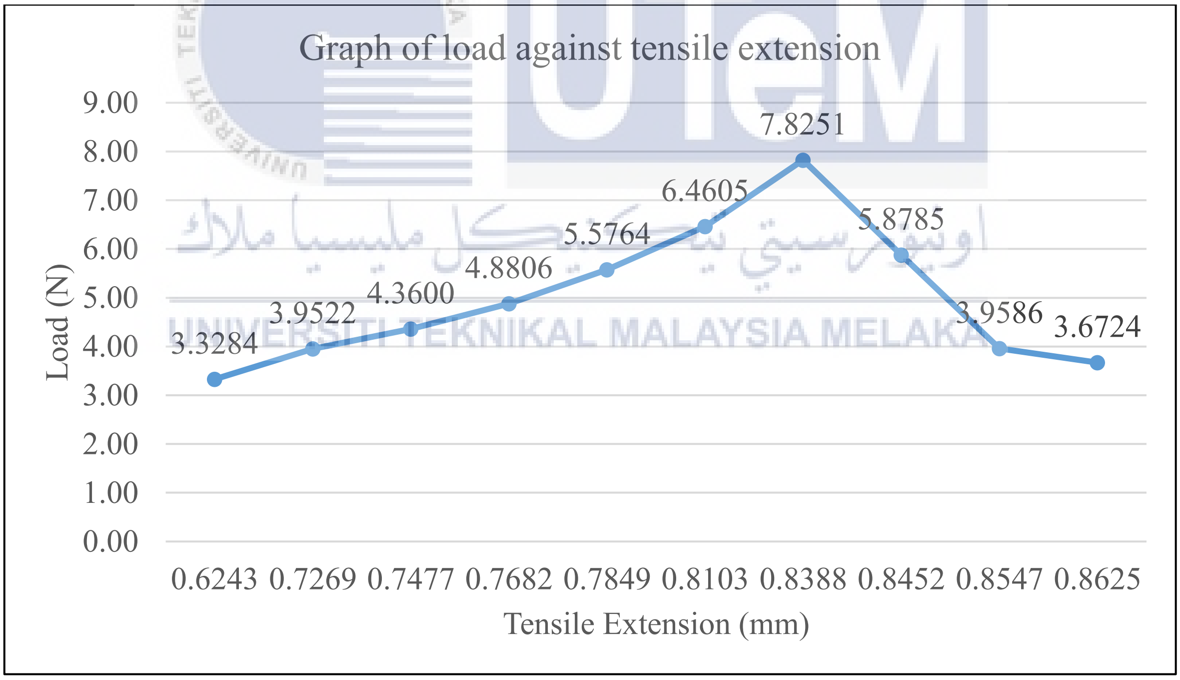


Figure 4.27 Graph of Chinese yam 3

Based on all of the graph obtained, each adhesive shows its respective maximum load value which means, adhesive will tear apart from glass platform when it reaches the maximum load. Based on the data obtained from (Layer Adhesion Investigation of 3D Printer Platform), UHU glue stick has the highest value of maximum load which is 19.9490 N followed by sweet potato 1, sweet potato 3, Chinese yam 3, Chinese yam 2, sweet potato 2 and Chinese yam 1 where the maximum value is 10.7149 N, 8.6431 N, 7.8251 N, 4.7166 N, 2.6443 N and 0.9916 N respectively. From the data collected, sweet potato has the highest strength compared to Chinese yam where the highest value for sweet potato and Chinese yam is 10.7149 N and 7.8251 N respectively. Although the value is lower than UHU glue stick, this bio-based adhesive can still be applicable and greatly reduce warping deformation in an open source 3D printer.

CHAPTER 5

CONCLUSION

5.1 Summary

Based on the results obtained, it clearly shows that both orange sweet potato and Chinese yam are able to act as an adhesive for 3D printing usage. The methods on producing adhesive are based on Gumus et al. (2014) journal as his journal focuses more on sweet potato and Chinese yam. Furthermore, the method on preparing adhesive based on Gumus et al. (2014) journal is much simpler as it only requires hydrochloric acid and sodium borate compared to other journals where approximately 4 chemicals need to be use such as sodium peroxide, sodium hydroxide, sodium thiosulfate and ferrous sulfate heptahydrate. According to the first objectives, after the 3D printing process using both adhesives, with and without heat bed, sweet potato and Chinese yam adhesive was recorded with the lowest vertex length as compared to UHU glue stick in both PLA and ABS material. This shows that both of this adhesive are applicable in 3D printing industry because the difference in warping deformation are not noticeable as the deflection vary by very small value.

Furthermore, the new mixture of plant-based bio-based bio adhesive which is the second objective is tested using viscosity test with 5 rpm, 10 rpm and 20 rpm where the viscosity of sweet potato and Chinese yam decreases over time when the temperature increase. This clearly shows that both of the adhesive has stronger bonding properties when the temperature is low and is suitable to use for 3D printing process without heat bed. As for the final objective, by conducting tensile test, UHU glue stick has the strongest force before it begins to tear apart from glass platform. Although sweet potato and Chinese yam adhesive unable to provide higher or similar maximum load when compared to UHU glue stick where the maximum load is 10.7149 N and 7.8251 N respectively, it still able to show promising results by reducing the warping deformation of a specimen during 3D printing process thus all the objectives have been achieved.

5.2 Future Research

In the upcoming research, various types of plant-based bio-adhesive can be discovered and the research can not only be on what have been done before but can be applied on food 3D printing with much more environment friendly and safe for anyone to use without restricting human age.

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APPENDICES

Appendix A

TASK NAME	DURATION WEEK													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Introduction														
- Identify objectives and scope														
Litreture Review														
- Rapid prototyping														
- Adhesive														
- Warping and tensile test														
Bio based adhesive preparation														
Improve and optimise solution														
Report Preparation														
Presentation														

TASK NAME	DURATION WEEK													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Study the preparation of bio based adhesive														
Measuring warping deformation														
Tensile test														
Suggestion for improvement														
Report Preparation														
Presentation														

APPENDIX B1

Temperature (ºC)	Percentage (%)	Viscosity (cP)
20	44.1	52789
	44.5	53149
	44.7	53389
	44.3	53149
	44.0	53029
	44.4	52789
	44.8	52289
	44.3	53029
	44.7	53029
	44.3	52909
40	36.2	44031
	36.2	43791
	35.8	43791
	35.9	43551
	36.2	43311
	36.3	43431
	36.2	43911
	36.1	43791
	36.1	43671
	36.0	43431
60	24.0	30013
	23.9	31124
	26.7	30008
	24.5	31018
	26.0	31117
	26.8	30008
	24.0	30129
	23.8	31024
	24.4	31096
	23.5	31114

APPENDIX B2

Temperature (ºC)	Percentage (%)	Viscosity (cP)
20	71.5	44031
	71.6	44211
	70.8	43971
	71.1	43791
	70.3	43581
	70.0	41391
	71.2	41031
	70.6	41271
	69.4	41031
	68.9	40731
40	55.1	33293
	54.0	33713
	55.2	33773
	55.1	33713
	54.9	33713
	54.5	33293
	53.9	33653
	54.7	33413
	54.3	33113
	54.2	33413
60	43.2	23114
	42.1	22007
	40.8	20014
	42.3	21963
	41.5	23080
	42.9	22996
	41.5	21173
	42.3	22181
	43.1	20096
	40.5	23076

APPENDIX B3

Temperature (ºC)	Percentage (%)	Viscosity (cP)
20	75.1	38192
	74.4	37892
	75.0	37592
	74.0	38042
	74.7	37942
	73.6	37192
	74.5	37842
	73.9	37392
	74.1	37192
	73.8	37592
40	60.1	30593
	60.1	30643
	60.5	30244
	59.5	30593
	60.2	30344
	60.4	30194
	60.0	30294
	60.5	30244
	59.5	30344
	60.0	30099
60	34.5	19376
	36.7	20076
	37.8	21154
	38.1	19425
	35.2	18317
	36.1	20056
	38.9	21113
	39.1	18416
	35.5	18555
	39.2	19117

APPENDIX C1

Temperature (°C)	Percentage (%)	Viscosity (cP)
20	54.0	68025
	57.4	68865
	53.2	66126
	54.6	66826
	56.1	65136
	54.8	68505
	53.3	64506
	55.1	65986
	55.8	65866
	53.5	67066
40	40.9	57908
	39.9	56728
	40.5	54228
	41.8	54228
	41.6	53009
	40.4	52529
	41.2	53329
	42.6	50989
	42.3	51349
	41.5	50629
60	25.6	31393
	26.4	31613
	26.6	32873
	26.0	30473
	25.0	31673
	26.9	31313
	26.1	31313
	25.6	32033
	26.2	31073
	26.6	30973

APPENDIX C2

Temperature (ºC)	Percentage (%)	Viscosity (cP)
20	79.4	55128
	76.2	52129
	78.5	52309
	76.7	51469
	75.3	51109
	77.2	52009
	75.1	51649
	81.9	49130
	83.2	47150
	80.0	55630
40	42.9	37194
	42.6	37015
	44.3	39094
	44.1	39154
	44.0	39172
	43.9	38334
	45.2	38014
	44.6	37834
	45.0	38074
	45.2	37539
60	32.9	20396
	33.6	20217
	32.1	19616
	34.0	20456
	33.0	20356
	32.0	19616
	34.0	20516
	33.2	20756
	32.3	19556
	34.4	20036

APPENDIX C3

Temperature (ºC)	Percentage (%)	Viscosity (cP)
20	79.6	25765
	81.9	25105
	80.3	25854
	81.2	25105
	80.7	25435
	81.2	24989
	81.5	25195
	82.6	24775
	82.2	25045
	82.9	24475
40	67.6	20306
	67.1	20486
	67.7	20786
	67.4	20986
	66.5	21034
	66.9	21205
	66.3	20816
	66.0	20699
	66.2	20666
	65.7	20366
60	37.8	11698
	37.3	11578
	37.4	11608
	37.5	11428
	37.7	11638
	38.3	11757
	38.0	12027
	39.1	11997
	39.2	11817
	39.0	11937