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Comparison of Thermoplastic Filaments for 3D Printing in The Development of Ventilator During Ventilator Shortage Situation

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The ventilator shortage issue during the Covid-19 pandemic has become a challenge for the medical team in providing the necessary treatment for patients. Open-source ventilators were designed to curb this situation by providing the best minimal designs that can be shared and built within a short period of time. People's Ventilator Project was one of the comprehensive open-source ventilators (PVP) being shared that utilise the 3D printing technology. In this paper, different 3D printing filaments, which are PLA, PETG and ABS were being printed and investigated to identify the best filament that is most suitable to be used for ventilator parts. Two types of tests were used to compare the filaments which are the Disinfectant Test to ensure the material can withstand disinfectant used in healthcare facilities and the Failure Test to check the strength of each material. As the conclusion, PLA filament is considered as the best filament as it has the least printing issues and its capability of being printed at a circulating surrounding temperature.

Keywords: 3D printing; PLA; PETG; ABS

I. INTRODUCTION

During the COVID-19 pandemic period, conventional oxygen therapy had become insufficient to meet the oxygen needs of adult with COVID-19 (U.S. Department of Health and Human Services, 2022). The provision of positive pressure ventilation was highlighted as one solution to cater the requirements for a low-cost and quick-deployable ventilation system. The People's Ventilator Project (PVP) was one of the ventilator projects that can address the ventilator shortage situation. It is completely open-source ventilator and able to be rapidly deploy and was designed with less dependency on specialist of medical instruments to help in this circumstance (LaChance *et al.*, 2020). The PVP is a pressure-controlled and fully automated mechanical ventilator that can be built in a couple of days by a single person with no specialised tools or expertise necessary. The PVP project also applies the 3D printing technology which can be utilised in the development of custom-made ventilators to build customised components to ensure functional continuity between diverse or incompatible components within the ventilator. The objective of this study was to identify the optimal filament that can be used for Fused Deposition Modelling (FDM) based technology to print 3D printed parts for emergency ventilator based on disinfectant test and failure test conducted.

Fused Deposition Modelling (FDM) is the most widely used method in 3D printing technology. It is based on the principle of semi-melting plastic material in a heated nozzle and depositing semi-melted material fibre next to fibre in a horizontal plane as layer by layer. The most common material used in this method of printing is polymer. Pure polymer filament and composites filament are two types of polymer filament (Kristiawan *et al.*, 2021). The pure polymer filament is fully composed of polymer compounds, with no additional solutions added. Each form of pure polymer filament has unique mechanical and physical qualities. The inherent qualities of pure polymer cannot always satisfy the demand for mechanical properties in particular goods which leads to the production of composite polymer (Kristiawan *et al.*, 2021). In the realm of 3D printing, we have Polylactic Acid (PLA), Polythylene Terephthalate (PETG) and Acrylonitrile

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Butadiene Styrene (ABS) as commonly used composite thermoplastic polymers material (Tuncer, 2020).

PLA is a biodegradable thermoplastic filament that is popular in FDM. In developing a 3D printed product using PLA, a modest energy and temperature (starting melting point: 190˚C) are required as well as a moderately heated bed during deposition. PLA are generally synthesised using three common methods which are direct condensation polymerisation, azeotropic dehydrative condensation and polymerisation through lactide formation (Tuncer, 2020). PLA's raw material is lactic acid which is a chiral molecule with two optically active isomers: L-lactic acid and D-lactic acid which can be amorphous or semicrystalline depending on the molecular weight and amount of L, D or meso-lactide in the main chain, stereochemical structure (Tuncer, 2020).

PLA is classified as thermoplastic due to intrinsic elements influencing PLA flow properties. These properties include molecular weight distribution, branching degree, optical block length distribution and melting stability (Tuncer, 2020). In order to increase qualities of PLA, it can be combined with other polymers derived from renewable resources such as chitosan, starch, PHB or with petroleum-based polymers such as PVA, PCL and PEG. Besides, PLA produces pieces with better tensile strength but poorer ductility than other conventional materials. Additives are added to enhance the properties of PLA to cater other printing purposes that cannot be fulfilled by the standard PLA. Based on a research by (Auras, 2010), some additives have a significant contribution to the mechanical and physical properties of the material during printing.

PETG is a popular material in 3D printing because of its excellent chemical alkali resistance, transparency, gloss, low haze and outstanding printability among other advantages. Moreover, with the suitable print parameters, good layer adhesion and very low shrinkage qualities may be obtained (Valvez *et al*., 2022). At the same time, it is incredibly robust, allowing one to print things with remarkable impact performance that can work at high temperatures or in food-safe applications. All of these benefits make this material appropriate for both the culinary and medical industries. In the latter situation, its stiff structure allows it to withstand rigorous sterilising treatments, making it an ideal material for use in medical implants, pharmaceutical packaging and medical equipment (Valvez *et al*., 2022) . When PETG is bonded with carbon fibre, it produces an incredibly stiff and rigid material with a low weight. Due to their excellent ductility, impact resistance and greater strength than PLA-carbon fibre, such compounds shine in structural applications that must tolerate a wide range of end-use conditions (Devsingh *et al*., 2018).

ABS is made up of three monomer units which are Acrylonitrile, Butadiene and Styrene (SpecialChem, 2022). ABS is commonly used to make plastics such as LEGO bricks, wall sockets, interior decorative parts and more. Unfortunately, ABS is not biodegradable which has opened up new applications for materials such as recyclable ABS. This underlines the significance of researching ABS recycling as a mean of decreasing economic, environmental and energy challenges (Vishwakarma *et al*., 2017).

One study by the Department of Health and Human Services USA for infection control has been conducted to analyse the different FDM materials where the materials are visually inspected after being exposed to five types of sterilisation which are autoclave, flash autoclave, ethylene oxide gas, hydrogen peroxide gas plasma and gamma radiation (Production Automation Station, n.d.). Hydrogen peroxide sterilisation was discovered as the best solution to avoid 3D-printed deformations due to its low temperature and less concentration requirements (Selvaraj, 2008). Based on research by (Bathia, 2017) they claim that the material produced by an FDM 3D printer is sterile since it melts out of the extruder at a temperature of 200°C and above. This temperature is far beyond the steam sterilisation temperature which is 121°C. However, contamination on printing plate is highly possible and a complete sterile transfer of the object from 3D printing to the operating room cannot be assured. Typically, sterilisation processes and procedures are designed for this purpose.

Failure Test is important to determine a product's maximum strength and support ability. This will directly contribute into knowing if the product or material is suitable for our application. Table 1 is a tabulated comparison of filament's tensile, flexural and impact strength along with the extrusion and bed-plate temperature used. The process parameters that significantly influences the mechanical properties of FDM fabricated parts are layer thickness, raster width, infill percentage, raster angle, and build orientation. The table below shows the mechanical properties and printing characteristics of different FDM materials.

Table 1. Comparison of PLA, PETG, PEEK and ABS (Muhammed Algarni, 2023)

Properties	**PLA**	**ABS**	**PEEK**	**PETG**
Extrusion temperature (°C)	190-210	220-260	380-410	230-250
Bed platform Temp (°C)	25-80	90-110	90-150	60-80
Density (g/cm^3)	1.25	1.04	1.30	1.23
Tensile strength (MPa)	65	43	100	49
Flexural strength (MPa)	97	66	170	70
Izod impact strength (kJ/m^2)	4	19	7	7.6
Recyclability	Yes	Yes	Yes	Yes
Biodegradability	Yes	No	No	No
Fume toxicity	Very low	Medium	Low	Very low

Bending and Pull-Out Tensile Test are the common test used to test failures on 3D-printed objects (Alshammari *et al.*, 2021). These tests are usually aided by Universal Tensile Machine (UTM) to provide accurate measurements and readings. It works on the principle of elongation and deformation where these machines have hydraulic cylinders to create the force. Pull-out testing involves attaching an appropriate test rig, bolt, screw, rod or fixings which is then put under tension in the intention to create stress on the load or specimen. This procedure is usually done to determine the strength of the specimen and enables early diagnosis of underlying problems (Sadeghi & Sharma, n.d.). Pull-Out Tensile Test is normally done on concrete structures to assess bond between rebar and concrete. This idea was adapted from (Sadeghi & Sharma, n.d.) and innovatively applied to determine the maximum force needed to cause the 3D-printed design to fail.

II. MATERIALS AND METHOD

As stated in the aim, the goal of this research is to discover the best filament to produce 3D printing parts for the development of emergency ventilator. This chapter is divided into several sections. It begins with identifying which sections of the ventilator that should be 3D print and also identifying the printer and the filaments to be used. Subsequently, the filaments will be analysed to identify which filament is best used as for the development of emergency ventilator parts. The general methodology for this research is depicted in Figure 1.

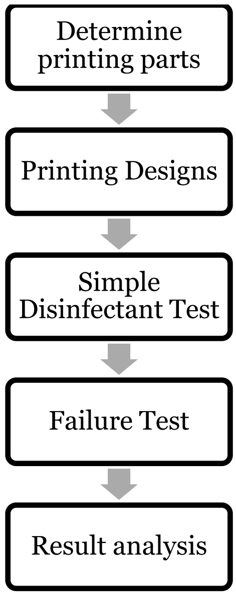


Figure 1. General Methodology

A. Selection of Parts, Printer and Filament

1. Parts for 3D printing

The parts of the emergency ventilator that were chosen to be 3D printed are L-Shape Bracket, Sensor atrium Manifold and One Side chassis as shown in Figure 2, Figure 3 and Figure 4. These three parts are chosen because of the variation in terms of size, shape and design complexity. Table 2 explains the function of the three different parts in the emergency ventilator.

Table 2. 3D printed parts function in emergency ventilator

3D Printed Parts	Function
L-Shape Bracket	Holds one of the heaviest components, which is the expiratory valve in place.
Sensor Atrium Manifold	Houses the oxygen sensor and “emergency breathing valve” and passes air from the proportional valve to the respiratory circuit
One Side Chassis	Provide support, protection and casing to the ventilation system

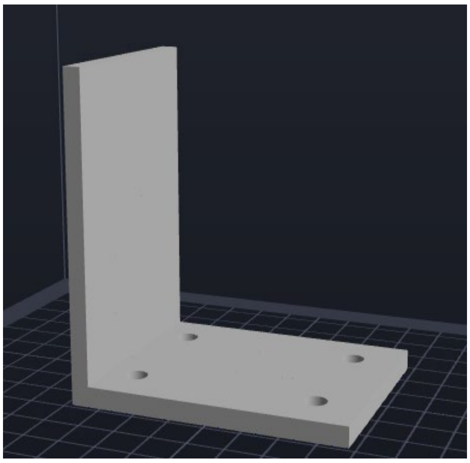


Figure 2. L-Shape Bracket

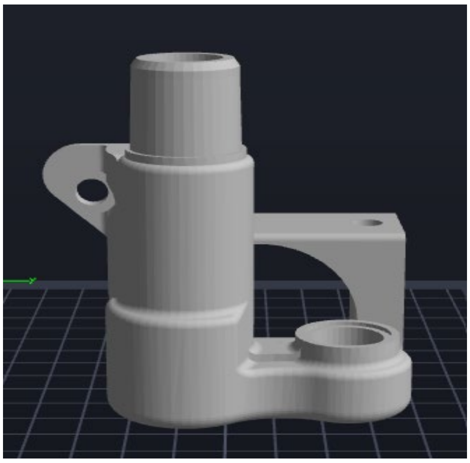


Figure 3. Sensor Atrium Manifold

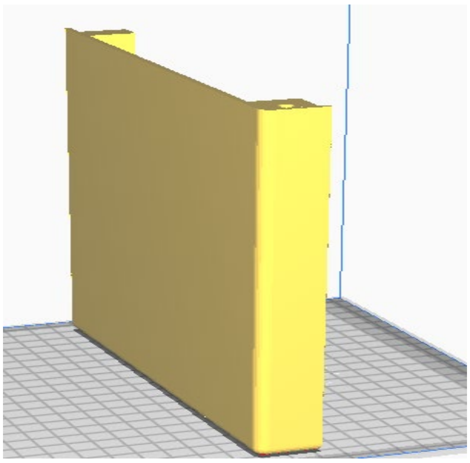


Figure 4. One Side Chassis

2. 3D printers

In this study, two 3D printers were used. The L-Shape bracket and the Sensor Atrium Manifold was printed using Flashforge Creator Pro 2 3D Printer. The One Side Chassis was printed using Twotrees Bluer 3D Printer because of its bigger dimension. The Flashprint and Cura Software were used to view the print time, conversion of file and for setting the parameter of 3D printers for Flashforge Creator Pro 2 and Twotrees Bluer, respectively.

Figure 5. Flashforge Creator Pro 2 3D Printer

Figure 6. Twotrees Bluer 3D Printer

3. *3D printing filaments*

The filaments used for this research are PLA, PETG and ABS. These filaments were obtained from 3D Gadget Malaysia. The filaments are proven to be certified with a high-quality (Triventor Solution, 2022). Below is a Table of Datasheet of filament PLA, PETG and ABS by (Triventor Solution, 2022)

Table 3. Datasheet for filament PLA, PETG and ABS (Triventor Solution, 2022)

	PLA	PETG	ABS
Diameter (mm)	1.755 +/- 0.02	1.755 +/- 0.02	1.755 +/- 0.02
Length (m)	335	335	335
Heated Bed Temperature	0-60	80-100	80-110
Printing Temperature	190-220	220-240	220-240
Net Weight (kg)	1.00	1.00	1.00
Price per kg (RM)	50.00	56.00	47.00

B. *Printing Designs*

The experimental procedure of printing the designs were illustrated in a flowchart as shown Figure 7. Explaining the flow chart further, the parts design in the form of .STL file were uploaded into SD cards and inserted into respective printers. Each printer is then loaded with PLA filament and the printing was then commenced. The printing process was then observed and analysed. After printing all the selected parts which are the L-shape Bracket, Sensor Atrium Manifold and Side One Chassis, the process is repeated for other filaments which are PETG and ABS.

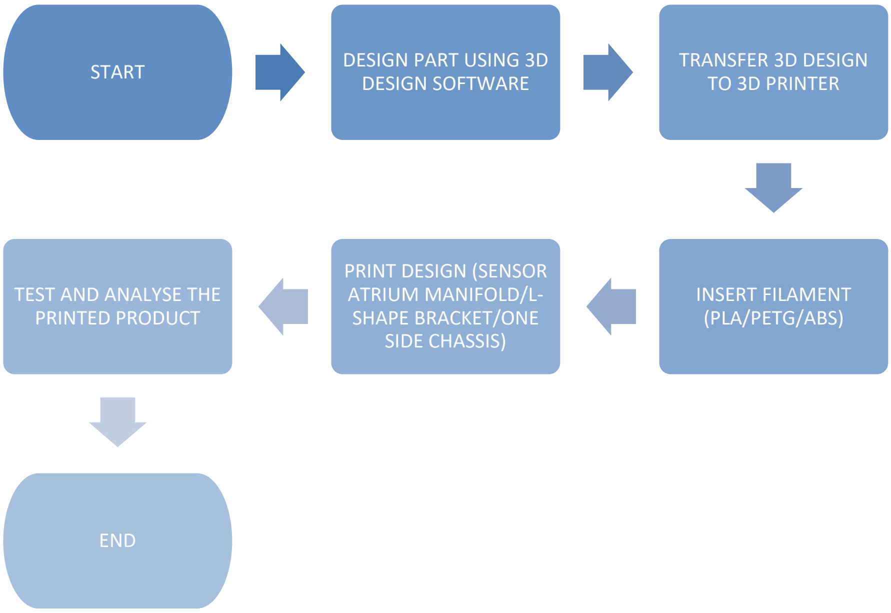


Figure 7. Flowchart of 3D Printing Procedure

C. Disinfectant Test

Sterilisation is a common procedure that is done to instruments, devices and other items that is used in healthcare or comes in direct contact with the bloodstream (Chains, 1999). Materials used should be permeable enough to withstand the concentration at the same time tightly woven enough to protect against the dust particles and microorganism.

After-printing designs Sensor Atrium Manifold, L-Shape Bracket and One Side Chassis, a simple disinfectant test by using a microfiber cloth to wipe the surface of printed designs to observe the changes that occur to the physical outlook of the design and the ability to withstand basic disinfectants that are commonly used to clean instruments.

Low percentage of 6% Hydrogen Peroxide was used as a disinfectant the 3D printed designs. Figure 8 shows the hydrogen peroxide used while Figure 9 and 10 show the disinfectant test on the 3D printed filaments.

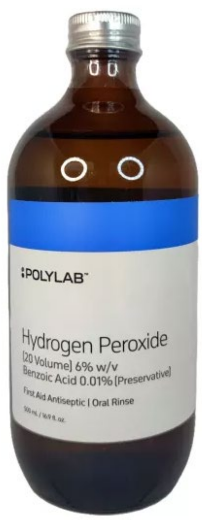


Figure 8. 6% Hydrogen Peroxide (Polylab)

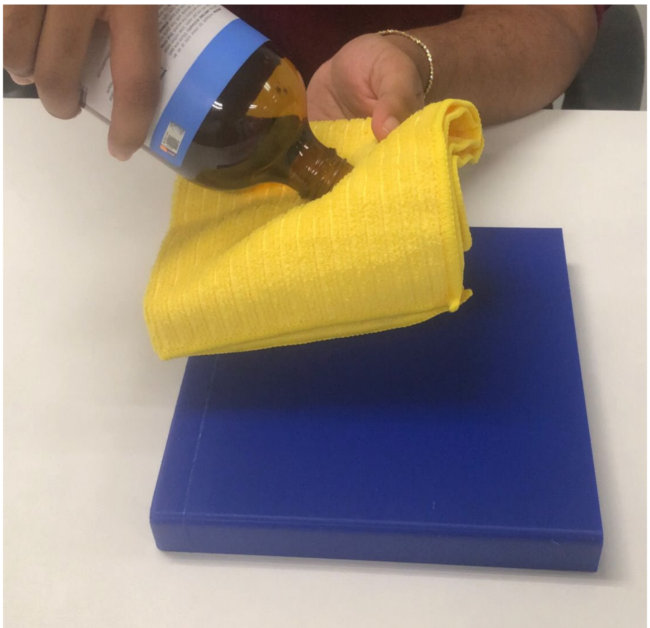


Figure 9. Applying Hydrogen Peroxide on microfiber cloth

Figure 10. Wiping the 3D Printed Designs with the microfiber cloth

D. Failure Test

Failure test was then done using a pull-out tensile test method. The pulling force was provided using human effort due to the unavailability of UTM equipment. This would also open doors for additional study that involves leveraging human effort as part of failure test.

As shown in Figure 11, 12 and 13, a steel beam, a gusset bracket, and screw was used to attach the 3D printed parts for the pull-out tensile test. A spring balance was then hooked to the gusset bracket to apply and record the pull force required to break the design. The value in the spring balance during the failure happens was tabulated and formulated.

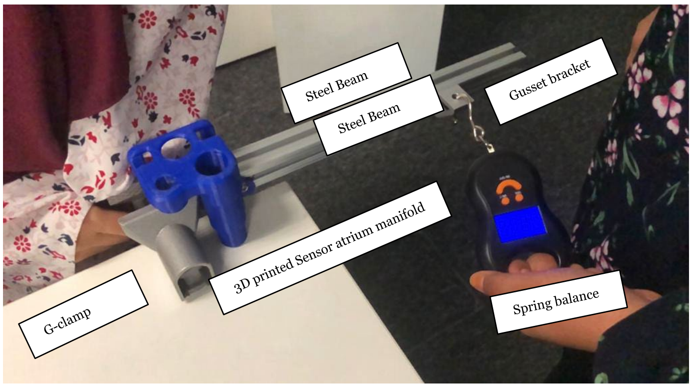


Figure 11. Failure test on Sensor Atrium Manifold

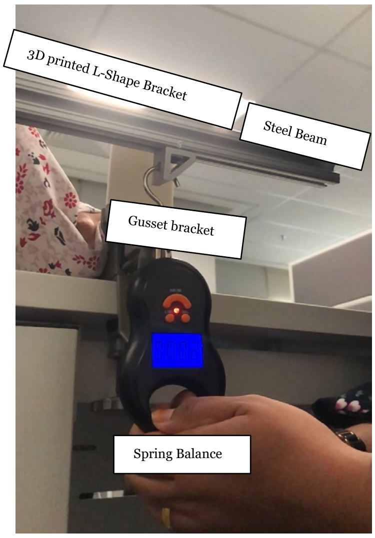


Figure 12. Failure test on L-Shape Bracket

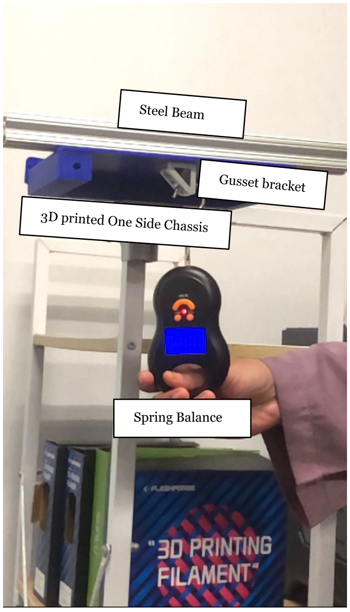


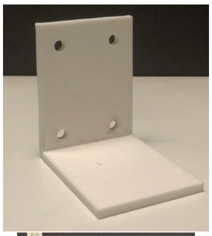
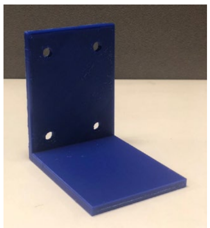
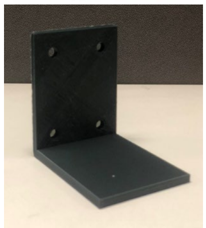
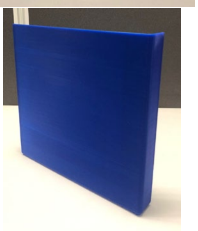
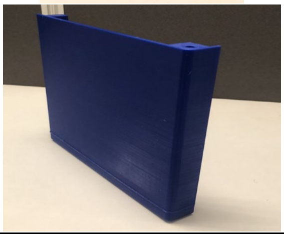
Figure 13. Failure test on One Side Chassis

III. RESULTS AND DISCUSSION

A. *Printing Design Outcome*

Table 4 below is an observation table done to visually analyse the 3D printed parts using PLA, PETG and ABS filaments. Printing process of Sensor Atrium Manifold and L-shape was relatively good for all three filaments used. However, the product of One Side Chassis that was made of ABS filament started warping and to crack upon cooling. Based on (Alshammari *et al.*, 2021), ABS is a thermoplastic that is very sensitive to the surrounding temperature which has a lot of tendency to warp. Since this part was printed using a non-enclosed printer which is the Two Trees Bluer printer, it could be deduced that the absence of enclosure led to ABS warping.

Table 4. Images of 3D printed parts based on filament type

	PLA	PETG	ABS
Sensor Atrium Manifold			
L-Shape Bracket			
One Side Chassis			

B. *Filament Comparison of Printed Designs*

Table 5. Printing analysis of 3D printed Sensor Atrium Manifold using different filament

	PLA	**PETG**	**ABS**
Amount of filament used (m)	16.49	13.64	16.49
Printing Speed (mm/s)	50.0	50.0	50.0
Support Requirement	Support enabled as linear raft with a width of 2.0mm	Support enabled as linear raft with a width of 2.0mm	Support enabled as linear raft with a width of 2.0mm
Printing and Bed Plate Temperature (°C)	Printing: 210.0 Bed Plate: 40.0	Printing: 240.0 Bed Plate: 70.0	Printing: 230.0 Bed Plate: 95.0
Print Time	5 hours 30 minutes	5 hours 13 minutes	5 hours 34 minutes
Print Dimensions (mm)	60.2 x 78.6 92.5	60.2 x 78.6 x 92.5	60.2 x 78.6 x 92.5
Product Weight (kg)	0.03	0.03	0.03
Printing Difficulty	Easy to print	Less easy than PLA due to stringing	Similar difficulty as PETG

Table 6. Printing analysis of 3D printed L-Shape Bracket using different filament

	PLA	PETG	ABS
Amount of filament used (m)	11.43	8.92	11.43
Printing Speed (mm/s)	50.0	50.0	50.0
Support Requirement	Support enabled as brim with a width of 4.0mm	Support enabled as brim with a width of 4.0mm	Support enabled as brim with a width of 4.0mm
Printing and Bed Plate Temperature (°C)	Printing: 210.0°C Bed Plate: 40.0°C	Printing: 240.0°C Bed Plate: 70.0°C	Printing: 230.0°C Bed Plate: 105.0°C
Print Time	3 hours	2 hours 55 minutes	3 hours 7 minutes
Print Dimensions (mm)	76.2 x 57.7 x 76.2	76.2 x 57.7 x 76.2	76.2 x 57.7 x 76.2
Product Weight (kg)	0.06	0.06	0.06
Printing Difficulty	Easy to print	Less easy than PLA due to stringing	Similar difficulty as PETG

Table 7. Printing analysis of 3D printed One Side Chassis using different filament

	PLA	PETG	ABS
Amount of filament used (m)	81.11	79.21	81.11
Printing Speed (mm/s)	50.0	50.0	50.0
Support Requirement	Support enabled as brim with a width of 4.0mm	Support enabled as brim with a width of 4.0mm	Support enabled as brim with a width of 4.0mm
Printing and Bed Plate Temperature (°C)	Printing: 210.0°C Bed Plate: 40.0°C	Printing: 240.0°C Bed Plate: 70.0°C	Printing: 230.0°C Bed Plate: 105.0°C
Print Time	1 day 5 hours 28 minutes	1 day 5 hours 20 minutes	1 day 5 hours 28 minutes
Print Dimensions (mm)	205.0 x 25.3 x 200.0	205.0 x 25.3 x 200.0	205.0 x 25.3 x 200.0
Product Weight (kg)	0.125	0.125	0.125
Printing Difficulty	Easy to print	Less easy than PLA due to stringing	Difficult print due to the size of print and printer having less enclosure

As per the experiment, each filament had variety of properties that both benefited and affected the 3D printed design. The printing speed was kept at a constant of 50 mm/s to ensure the manipulated variables can be clearly observed. Printing extrusion and bed plate temperature are set according to the datasheet provided to ensure the optimal melting and printing temperature of the filaments. PLA has an extrusion temperature of 210.0°C with a bed plate temperature of 40.0°C. PETG on the other hand requires temperature of 240.0°C with bed plate at 70.0°C. ABS requires 230.0°C for extrusion and 105.0°C for bed plate.

PLA does not require a high temperature to melt the filament hence making it one of the easiest materials to print. A slightly heated bed plate gives a better PLA print results as adhesion on the plate of better (O'Neil, 2022.). Due to its low temperature, PETG on the other hand require a higher extrusion temperature to allow better flow and layer adhesion. PETG, however, does not require a heated bed plate like ABS, a heated plate will ensure the extruded filament sticks the bed plate. ABS demand a higher nozzle temperature for extrusion since it has a higher melting point and glass transition temperature than PLA. Additionally, a heated printed bed and preferably an enclosure is needed since ABS is prone to warping as it cools down. Higher bed plate temperature is set to avoid the warping from becoming too severe (O'Neil, 2022.).

In a glance, the results table and images show that PETG requires a lesser printing time and filament compared to PLA and ABS. Brim support was provided while printing L-Shape Bracket and One Side Chassis to improve bed adhesion and prevent warping. It can also be considered as skirting that does not touch the edge of the printed part. Sensor Atrium

Manifold on the other hand used linear raft support due to its irregular shape. Brim support is directly connected to the first layer of the print and not separated by any space while raft adds a 3D printed base beneath the actual print (O'Conell, 2022).

Challenges were faced during printing of the One Side Chassis using PETG and ABS filament. PETG filament had too much of stringing that caused uneven printing layers and clogged extruder. This issue was able to be solved by introducing a layer fan that was directed to the printed part to cool down the plastic as it comes out from the hot end. The ABS filament on the other hand begin to crack half way through printing due to warping. This situation was caused resulting from the lack of enclosure for the Twotrees Bluer 3D Printer. The absence of enclosure for the 3D printer makes it harder to control the surrounding temperature of the filament right after printing hence contribute to the poor quality of the ABS filament using this type of printer.

C. *Effects of Disinfectant*

Testing of the filament with disinfectant solution is an important process to ensure the filament chosen to be used for printing of emergency ventilators are easy manageable and does not corrode when it comes to contact with disinfectant that is commonly for disinfection in the healthcare sectors. Hydrogen Peroxide concentration is used from a range of 3% to 6% for disinfections. Based on (Centre of Disease Control and Prevention, n.d.), hydrogen peroxide starts the process of microbial inactivation by exposing all the load's surfaces to the sterilant. Upon observation for 24 hours, the 3D printed designs do not corrode or have any physical changes as shown in Figure 14.

Figure 14. 3D Printed designs after 24 hours of applying disinfectant solution

D. *3D Printed Parts Failure Point*

This part of the experiment focuses on the amount of force that was needed to fail the design. In order to calculate the force, the principle of the Newton's Second Law of Motion was used.

$$F = ma \quad (1)$$

F = Force required to fail the 3D design (N)
m = Spring balance weight when 3D design fails (kg)
a = gravitational acceleration (m/s-2)

External acceleration is neglected to avoid parallax error and due to the acceleration being too small. Adapting from (The Physics Classroom, 1996), acceleration of an object is inversely proportional to the mass. As the mass that acts upon the object increases, the acceleration decreases.

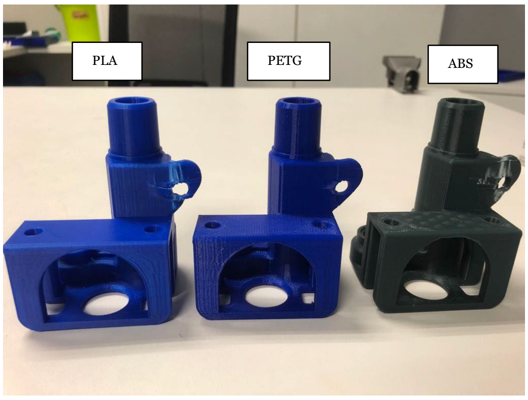


Figure 15. Sensor Atrium Manifold after Failure Test

Table 8. Sensor Atrium Manifold Failure Test Results

Material	PLA	PETG	ABS
Applied Weight	1.15 kg	0.69 kg	1.0 kg
Applied Force	11.28 N	6.762 N	9.8 N
Deformation Type	Ductile	Ductile	Ductile

The Sensor Atrium Manifold has a very complex design that ensures long-term strength. All 3 PLA, PETG and ABS printed Sensor Atrium Manifold weigh equally at 0.03 kg. The tensile test on this particular design was focused on the high screw utilisation area to see the robustness of it. As per the image and table above, these designs did not break instead it bend and stretched out showing that it possess the properties of being highly ductile. A maximum of 11.28 N was needed to fail PLA while minimum of 6.762 N was required to fail PETG. It can be seen that PLA is the strongest followed by ABS then PETG.

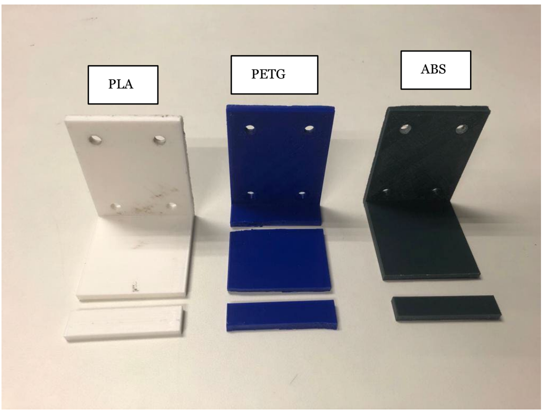


Figure 16. L-Shape Bracket after Failure Test

Table 9. L-Shape Bracket Failure Test Result

	PLA	**PETG**	**ABS**
Applied Weight	12.50 kg	8.885 kg	4.5 kg
Applied Force	122.5 N	87.07 N	44.1 N
Deformation Type	Brittle	Brittle	Brittle

The L-Shape Bracket is a simpler design that acts as a bracket for join bolts. All 3 PLA, PETG and ABS printed Sensor Atrium Manifold weigh equally at 0.06 kg. The tensile test on this design was focused mid-section of the bracket to ensure its strength. As per the image and table above, these prints broke and did not bend and stretched out like the Sensor Atrium Manifold showing that these 3D prints have brittle properties too. A maximum of 122.5N was needed to fail PLA while minimum of 44.1N was required to fail ABS. PLA is once again proven to be stronger that PETG and ABS.

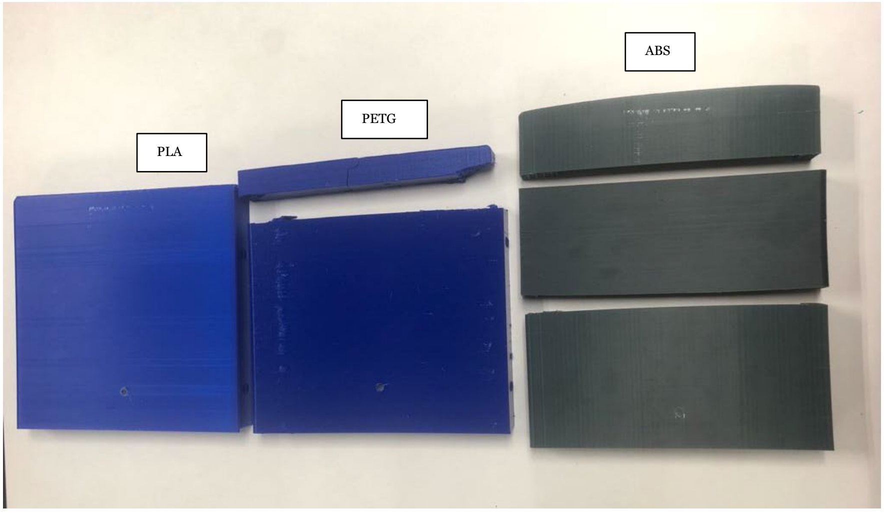


Figure 17. One Side Chassis after Failure Test

Table 10. One Side Chassis Failure Test Results

	PLA	PETG	ABS
Applied Weight	13.5 kg	11.25 kg	9.2 kg
Applied Force	132.3 N	110.25 N	90.16 N
Deformation Type	No Deformation	Brittle	Wrapped

The One Side Chassis was hard to break given its size and initial deformities during printing of ABS. All 3 PLA, PETG and ABS printed One Side Chassis weigh equally at 0.125 kg. The tensile test on this particular design was focused on the breaking the chassis due to its function of being the protective cover for the emergency ventilator. As per the image and table above, PLA Chassis did not break at all. The maximum of 132.3N was applied on the PLA design but it was strong enough to withstand that load. The PETG Chassis on the other hand broke ta a force of 110.25 N proving that it is not as strong as PLA. ABS Chassis was the easiest to fail. It only required force of 90.16 N. This lack of strength of ABS filament is also due to the warping of the design during printing.

IV. CONCLUSION

In conclusion, based on the objective of the experiment, PLA is considered to be the best material to be used as a filament for developing emergency ventilator parts. This is due to the low level of difficulty in printing it and its capability of working at a circulating surrounding temperature. Adding on to that are the advantages that comes along which is lack of warping and stringing during the printing process. PLA is also environmentally friendly, biodegradable and low-cost. When compared, PLA has the highest mechanical strength as well which is an added benefit when implemented into the emergency ventilator.

The limitations that were encountered during this study is the difficulty to maintain the surrounding temperature that affected the printing of ABS printed filament. The tendency for parallax error was high during the experiments due human effort or force used.

As a future improvement, it is suggested to create and enclosed area to aid the ABS filament-based printing. Disinfection test and bending test are propose to ensure these filaments can withstand disinfectant process and sudden falls.

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