TENSILE AND BENDING TESTING OF 3D PRINTED MATERIALS FOR SCOLIOSIS BRACE

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Executive Summary:

This work investigates the mechanical properties of 3D printed polymers namely Polylactic Acid (PLA) and Polypropylene (PP), which underwent the process of tensile and bending testing. The PP material is utilized in the production of scoliosis braces as shown in Figure 1. 3D printing has evolved in recent years and it has become widely used in several engineering applications for its numerous advantages summarized in this document. The purpose of this work is to determine the most suitable material for 3D printing scoliosis braces, which one can use as a reference to gain insights as it applies to other parts involving 3D printed PLA and PP materials in general.

When tensile testing, the PLA and PP samples are printed in two orientations – on their side and upright. The nozzles used to print the PLA samples are 0.4 mm and 0.6 mm. The samples are tested and the results are compared and evaluated. The other 3D printing parameter examined in this work is infill density, specifically 50% and 100%. This parameter is used to identify which setting significantly affects the weight of mechanical parts, cost, and production speed. PP samples show great flexibility, as some of the samples are stretched without breaking. The upright 3D printed orientation PP samples have higher Ultimate Tensile Strength and Young's Modulus than side 3D printed orientation samples.

This experiment shows that for the side printed 3D samples, the PLA dominates in terms of tensile strength compared to the upright print orientation. The samples printed with the bigger nozzle have a higher tensile strength. The 100% infill density has more than double the strength compared to 50% infill density. This document shows the breaking loads during the bending test of PLA samples and the bending loads of PP samples.

When bending testing PLA samples, side printed samples clamped on the wide side show the highest strength, while side printed samples clamped on the short side illustrate predictable breaking load. Upright printed samples show unpredictable strength evident by some samples being able to hold big loads before breaking whereas some break at small loads. For PP bending testing, 3D printed samples made of Ultimaker and Formfutura filaments are compared which resulted in a slight difference of deflections in different loads. There are three design criteria for scoliosis brace material such as strength, flexibility and impact resistivity. This project focuses only on testing the strength and flexibility of material by tensile and bending testing.

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Dedication

I dedicate this project thesis report to my Lord and Savior Jesus Christ, whom I got all my strength and everything I need, and to my family who is always there to support me.

I. Introduction

This research project consists of two parts. One is tensile testing of two different plastic materials namely PLA and PP. This work extends a previous research study conducted by another experimenter, Mr. Rahul Malik's Master's project report entitled, "Tensile Testing of 3D Printed Materials for Scoliosis Brace" [1]. The second part is bending testing of the same materials to determine their mechanical properties under the application of bending forces.

The previous study focused on different materials to explore the most suitable material to utilize for 3D printing scoliosis brace at different printing orientations, including side print and upright print.

In contrast, in this work, PP is tested as a new possible material for printing scoliosis braces, as shown in Figure 1 because it is more flexible and softer. These properties of PP might be a promising solution for the patients that might experience discomfort when wearing scoliosis braces.

In 3D printing, different nozzle sizes can be used to print any design parts, which significantly changes the strength of the printed output. The previous project did not focus on the effects of 3D printing settings for the strength of materials, but in this experiment, some important settings are explored to uncover the effects of the 3D printed parts. This project tested different nozzle sizes such as 0.4 mm and 0.6 mm nozzle diameters. In 3D printing, 0.6 nozzle has several advantages including up to two times faster printing duration, better durability, and lower risk of jams. However, there are some disadvantages as well, such as a lack of aesthetic surface details when printing small parts, and difficult to remove supports [2].

3D printing has captured the interest of different industries, research, and academics. It has also evolved in recent years and becomes widely utilized in several engineering applications because of its several advantages. Recently, producing high print quality by faster and low-cost techniques have been developed [3]. This technology could potentially lower the production costs and increase the overall efficiency of the manufacturing sector [3]. This also allows for prototypes to be easily produced by current designers and innovators. In many cases, the design and fabrication periods of some products are reduced from weeks to a few hours [3]. Because of the numerous advantages that this technology offers, 3D printing is now seriously considered to produce materials for many applications in construction, dentistry, medicine, electronics, automotive, robotics, military, oceanography, aerospace, and more. Recently, one interesting 3D printing innovation includes a 3D-printed Femtosatellite launching device that has won the design competition sponsored by Mouser Electronics as shown in Figure 2 below. The goal of the competition was to design a useful device that allows astronauts to conduct 3D printing in the International Space Station [3].

In this project, I did new things such as tensile testing of side and upright printed samples from 0.4mm diameter nozzle, tensile testing of side and upright printed from 0.6mm diameter nozzle, tensile testing of 100% and 50 % infill density side and upright prints of PLA material, and tensile testing of side and upright printed PP samples. Also, I performed bending testing of side and upright printed PLA samples with two different setups to find the load to break the samples and bending testing of PP to check the deflections for different loads.

Figure 1: 3-D-printed scoliosis brace [4]

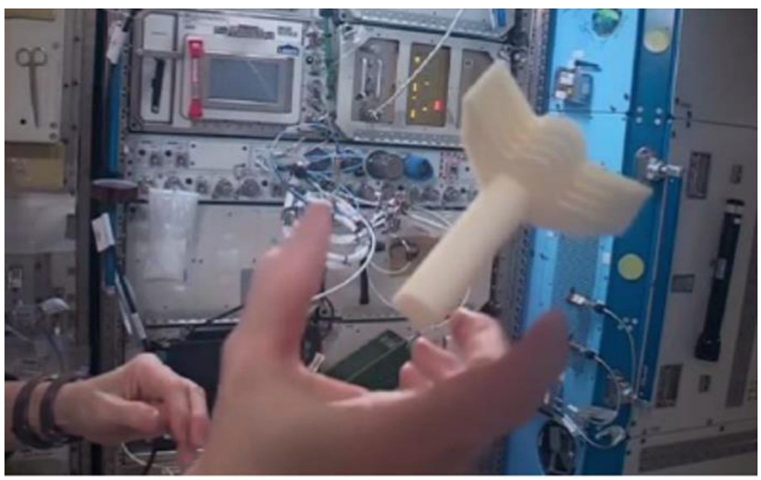


Figure 2: Femtosatellite launching [2]

Tensile testing is a significant qualification test as it provides crucial information on different materials' properties, such as modulus of elasticity, tensile strength, elastic limit, proportional limit, elongation, reduction area, yield point, yield strength, and several other tensile properties [5]. This testing is also called a tension test, which is an essential and well-known type of mechanical testing. A tensile or pulling force applied to the material that measures the sample's response to the stress. This process determines the strength of the materials and the maximum elongation that it can reach until the specimen fails [6] [7]. The MTI tensile machine is used to provide the parameters stated above.

As the purpose of this material testing is to get the most suitable material for scoliosis brace, bending testing is critical testing to investigate the 3D printed samples of PLA and PP behavior during the application of bending loads. In this experiment, there are three different bending test set-ups – two for PLA material and one for PP.

II. Background

A part of the tensile experiment in this document is executed by following the steps provided by previous Master student, Rahul Malik's Master's project report entitled, "Tensile Testing of 3D Printed Materials for Scoliosis Brace"[1]. This document serves as a start of exploring another avenue to determine and validate material strength through the process of bending testing. Mr. Malik's report focuses on evaluating the tensile strength of PLA, ABS, Nylon, and HDGlass (PETG). He concludes that PLA is the best material for scoliosis braces as it shows the highest Young's modulus and Ultimate tensile strength compared to the others. In light of this information, the 3D printing parameters of PLA are explored further to obtain the optimal strength of this material.

Another testing modality briefly examined in this experiment is bending testing for PLA that involves a 0.4 mm nozzle diameter with 100% infill density. This is to determine the strength of this type of material when undergoing a bending load. The results, analysis, and recommendations are also provided in this document.

The steps involved in experimenting are illustrated in this document as a reference for the next person to continue the recommended steps that might be important for the optimization of the current results. The experimental results are updated in conjunction with current innovations to keep up with the current technology; however, as innovation is constantly progressing there is a promising possibility for future optimization of the results. For this reason, it is recommended to the next experimenter to update the results accordingly and to continue working on finding a better engineering design.

In this project, tensile testing and bending testing are conducted for PLA and PP polymers. For future work, compressive testing and impact testing can be explored as well. Another 3D printing parameter that warrants further exploration is the different effects of infill density. One can manipulate this parameter as this has a directly proportional relationship with the material strength. Specifically, as the percentage of infill density decreases, the strength also decreases. However, it is also important to consider that decreasing the infill percentage also decreases printing time and cost. Another recommendation is to explore the effects of the numerous infill patterns available in Cura as it is believed that as the pattern changes the strength also changes accordingly.

As the material being tested is for scoliosis braces, the comfort of the patient as it relates to the flexibility of the material and the overall design is also worth exploring as it plays a significant role in whether or not a patient chooses scoliosis braces or other remedies. Some remedies for scoliosis have been explored by different inventors. The pain that is supposedly caused by wearing scoliosis braces has been used by an advertisement as a drawback and encourages the consumers to try the products they are advertising instead. One advertisement states, "Full-time bracing often causes more problems for the person wearing it, such as pain that didn't exist before, breathing problems, and weakened muscles. It hasn't been consistently proven to prevent scoliosis surgery, either." [8]. The braces are aimed to help manage and prevent the progression of patient's scoliosis, therefore the materials utilized for the production of braces play a significant role in ensuring patient comfort and the possible prescription of braces. Another recommendation pertains to the production of 3D printed scoliosis braces with composite materials and exploring the characteristics of the design, including comfort, safety, flexibility, durability, performance, cost, and more.

3D Printing (Additive Manufacturing)

3D Printing

3D printing is a process to produce objects by adding selected materials together that were necessary following digital 3D model guidance. This technology is significant, for instance, as it allows the ability to construct complex geometric structures matched to the patient's anatomy or surgeon's requirement. The technology also offers wide applications in medicine, ranging from surgical planning tools to custom surgical devices. The translation of 3D printing in health care has been enhanced recently under the guidance of the regulatory agency [9].

This advance manufacturing process is based on a 3D CAD drawing model. The model is further manipulated by the use of slicer software, like Cura, which generates G-codes that are required to command the motors of 3D printer machines.

3D Printing Process

A 3D printer is a machine that employs x, y, z robotic stage together with other deposition technology to print a three-dimensional model from CAD software. The model can be created from different CAD software such as SolidWorks, AutoCAD, and more. The CAD model is processed again using slicer software such as Cura to generate G-codes needed for the 3D printer. This code is similar to the code used for CNC Machine that will drive the deposition material to build a desired designed part. The recent innovation of this technology uses different filament materials, which are mostly polymers but in few cases metals, ceramics, and non-metals [1].

Advantages

There are several advantages in 3D printing such as easy prototype production, waste reduction, specialized tooling not required, feasible small production batches, quick design modifications, design customization and more[1].

3D printing has several advantages that facilitate the personalized design of basically any practical engineering designs are as follow [1]:

- Not needing specialized tools and equipment that in turn reduces production time and cost.
- Small production batches are feasible and economical.
- Ability to modify the design as needed within a short period.
- Easy to produce prototype products.
- Waste reduction.
- Shorter lead times for easy supply chain and lower inventories.
- Design customization.

Disadvantages

- Limited Materials

In 3D printing, the parts are build layer by layer from the ground up and although this technology has been intensely studied the materials available to be used for printing have remained limited. One printing material that is commonly utilized is plastic due to its abundance, availability, pliability, and versatility as it can be melted down and deposited one layer after another to form a final product. The types of plastic material do vary in strength when exposed to different temperatures so they cannot be tested accurately. In addition to plastic, metal, glass, and gold are also utilized by some developers and designers, but these products are not available commercially just yet [10].

- Questionable Accuracy

3D printing technology is mainly a prototyping technology that is dedicated to producing test parts with precise dimensions to allow engineers and designers to obtain an accurate approximation on the feasibility of a part. Although 3D printers have been intensely studied with significant advances made as a result, many of the materials like plastic still comes with accuracy issues. Specifically, several materials still have either +/- 0.1 mm room for error [10].

- Manufacturing Limitations

3D printing is a convenient technology for producing prototype parts as it provides an economical avenue to make one-run parts without having to create tooling. Parts are usually made within hours wherein specific design and engineering modifications of the specific parts are possible via a CAD file after analysis of the part. On the other hand, in manufacturing, 3D printing technology is not a realistic option due to the length of printing time. For instance, in the manufacturing process like thermoforming and stamping where parts are usually produced within minutes and not hours [10].

- Size

In 3D printing, the parts produced are also limited in size, for instance, the most inexpensive 3D printing machines that are commonly utilized are small in size that fits on a desktop. The 3D printers that are capable of producing larger parts are more costly and not economically feasible for commercial companies. The fabrication of large parts required larger 3D printing machines and in turn, larger chambers which mean higher cost and the longer time it takes to create [10].

Applications

3D printing technologies are gaining popularity in engineering research, construction industries, medical field; however, less adapted in manufacturing industries as 3D printing technologies costs higher than injection molding [1].

Due to its design customization, and fast design modification, AM becomes more versatile in the biomedical field for custom-shaped orthopedic, tissue scaffolds, dental implants and medical equipment [1].

3D Printing Technologies

In 3D printing of plastics, there are several available techniques in 3D printing with several specific advantages and drawbacks depending on the applications. For this project, the most popular technique called Fused Deposition Modelling (FDM) is utilized [11]. This technique is widely used as it is found to be the most suitable for the application, affordable, user friendly, and durable. Another technique called 3DP is also explored to determine its potential advantages as tabulated in Table 1 below.

Table 1: Summary of Advantages and Disadvantages of FDM and 3DP [12]

Technique	State of starting materials	Typical polymer materials	Working principle	Advantages	Disadvantages
FDM	Filament	Thermoplastics, such as PC, ABS, PLA, and nylon	Extrusion and deposition	Low cost, good strength, multi material capability	Anisotropy, nozzle clogging
3DP	Powder	Any materials can be supplied as powder, binder needed	Drop-on demand binder printing	Low cost, multimaterial capability, easy removal of support powder	Clogging of binder jet, binder contamination

Fused Deposition Modeling (FDM)

FDM printers are commonly used for producing polymer composites. The most commonly utilized material for printing are thermoplastics like PC, ABS, and PLA because of its low melting temperature. Figure 3 depicts the mechanism at which FDM printers operate by controlled extrusion of thermoplastic filaments. Specifically, these printers melt the filaments into a semi-liquid state nozzle and then extruded layer by layer onto the platform where the layers are fused and left to solidify into the final parts. FDM printers contain printing parameters including layer thickness, printing orientation, raster width, raster angle, and air gap that one can manipulate or alter to control the quality of the printed parts [12]. Utilizing FDM printers has several disadvantages including the following:

- the composite materials have to be in filament form to enable the extrusion making it difficult to homogenously disperse reinforcements[1]
- materials to be used for printing are limited to thermoplastic polymers with the appropriate melt viscosity
- molten viscosity needs to be high enough to sufficiently provide structural support and low enough to allow the extrusion process

- complete removal of the structural support utilized when printing can be challenging

Using FDM printers also offer some advantages including the following [12]:

- low cost
- high speed
- simplicity
- potential to enable deposition of different materials simultaneously
- has multiple extrusion nozzles for loading different materials making printed parts multi-functional with designed composition

FDM Printing Procedure:

First, the 3D model designed from CAD must be converted to a format that is compatible with an FDM 3D printer such as Cad to STL or OBJ file. Next, build preparation software and 3D printer hosts such as netfabb, Cura or Simplify3D that positions and slices the 3D file, and analyzes a path to extrude thermoplastics filaments and any need support material. Lastly, transfer the file to the 3D printer and start the printing process.

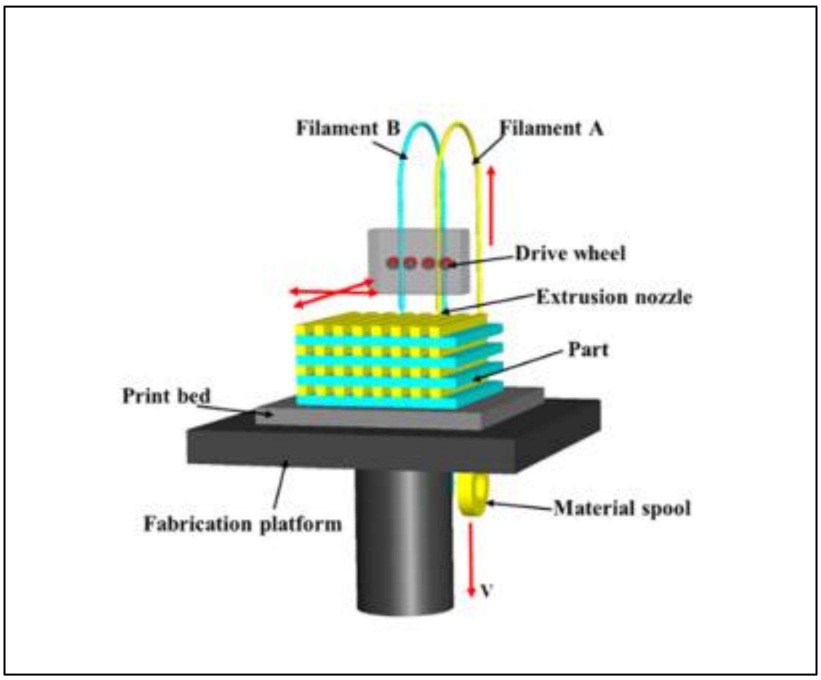


Figure 3: FDM 3D Printing [13]

Three-Dimensional Packaging (3DP)

Another printing technology known as powder-liquid 3D developed at the Massachusetts Institute of Technology (MIT) in 1993 as a rapid prototyping technology depicted in Figure 4. Firstly, powders are spread on the build platform, which is then selectively joined into patterned layers by depositing a liquid binder through an inkjet printhead that can move in XeY direction. Secondly, when the desired 2D pattern is created, the build platform lowers and the subsequent layer of powder is spread. This process is repeated until an unbounded powder should be removed to get the final product. The internal structure of the parts can be controlled by modifying the amount of binder deposited. Some factors that contribute to the quality of the final products include powder size, binder viscosity, the interaction between binder and powder, and deposition speed of the binder [12].

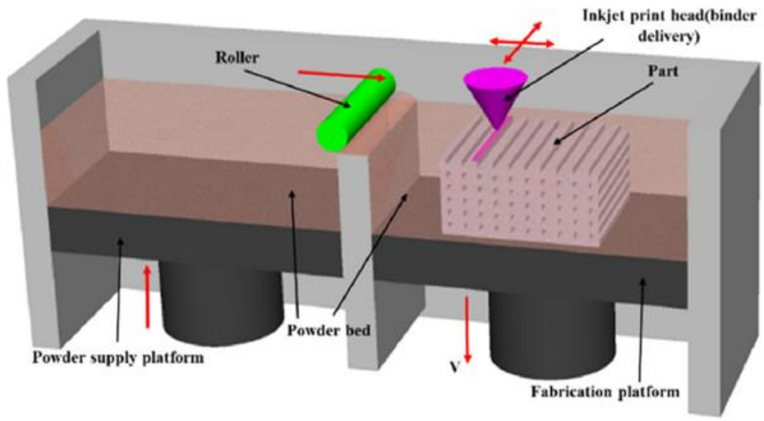


Figure 4: 3DP Printing [13]

The materials tested in this experiment are Polylactic acid (PLA) and Polypropylene:

Polylactic Acid (PLA)

PLA is a biodegradable hydrolyzable aliphatic semicrystalline polyester that is produced via direct condensation reaction of its monomer, lactic acid, as the oligomer followed by ring-opening polymerization of the cyclic lactide dimer [7]. PLA is a natural and biodegradable organic substance present in the bodies of animals, plants, and microbes, thus needs to be industrially prepared through lactic acid polymerization. The lactic acid monomers utilized for the synthesis of polylactic acid are derived from genetically altered corn grains [14].

Polypropylene (PP)

PP is a semi-crystalline polymer produced by propylene homopolymerization or copolymerization with a small amount of ethylene comonomer through either in liquid propylene or gas phase reaction [15]. Polypropylene is known to be an excellent material for producing certain spinal orthotic designs. It has been utilized for the pelvic girdle of the Milwaukee Brace, scoliosis jackets, and flexion jackets. Polypropylene is also utilized for the non-operative management of spinal deformity and post-operative care. This material offers highly desirable properties including being lightweight, comfortable, superior durability, and relatively easy to fabricate [16].

Table 2: Specific properties of Polylactic acid (PLA) [1]

S No	Property	Value
1	Technical Name	Polylactic acid(PLA)
2	Chemical Formula	(C3H4O2) n
3	Tensile Strength	50-70 MPa
4	Melting Temperature	180-220 °C
5	Density	1.24 g/cm3

Table 3: Specific properties of Polypropylene [17][18]

	Property	Value
1	Technical name	Polypropylene
2	Chemical Formula	(C3H6)n
3	Tensile Strength	32 MPa (4700 PSI)
4	Melting Temperature	130°C (266°F)
5	Density	946 kg/m³

III. Design Experiment

Design of samples

In this research project, the mechanical properties of the 3D printed materials of PLA and PP are explored. The results are revealed and conclusions drawn on the mechanical properties of these two materials. In general, the tensile testing of plastics is done as per the ASTM D638 standard. This standard is industrially utilized and a critical test technique. Tensile testing employs standard "dumbbell" or "dogbone" formed specimens [1].

Purpose of using Dog Bone

The rationale of using dog bone is to confine the deformation to the narrow center region to reduce the possibility of fracture at the end of the specimen [1]. The MTI 10K machine has a pre-load feature to make sure that the sample is already in that stable state and free from a movement that can affect the accuracy of the test result. For materials with small displacement about 5mm, Extensometer is required for accurate displacement measurement.

Fabrication of Samples and Materials

The same process of fabrication of specimens is performed as the previous experiment with the specimen printed inside print and upright print. PLA and PP are the materials printed for testing.

3D Printing Process Parameters:

3D Printing parameters of specimens including Layer Height, Shell Thickness, Fill Density, Print Speed and Temperature

Material	Layer Height (mm)	Shell Thickness (mm)	Fill Density (%)	Print Speed (mm/s)	Temperature (C)
PLA	0.2	0.8	100/50	50	210
PP	0.2	0.8	100	20	230

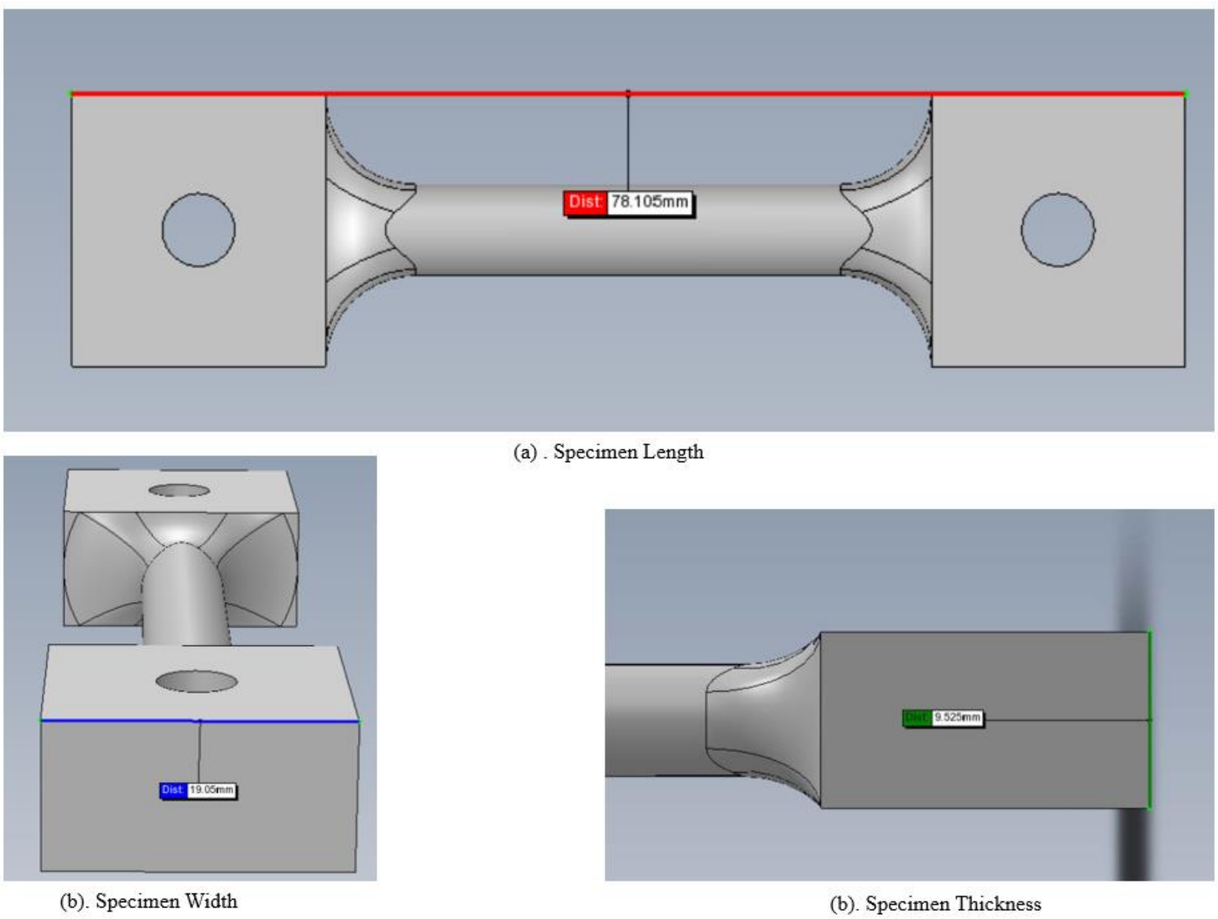


Figure 5: Design Sample [8]

Figure 6: Specimen model viewed in Cura platform

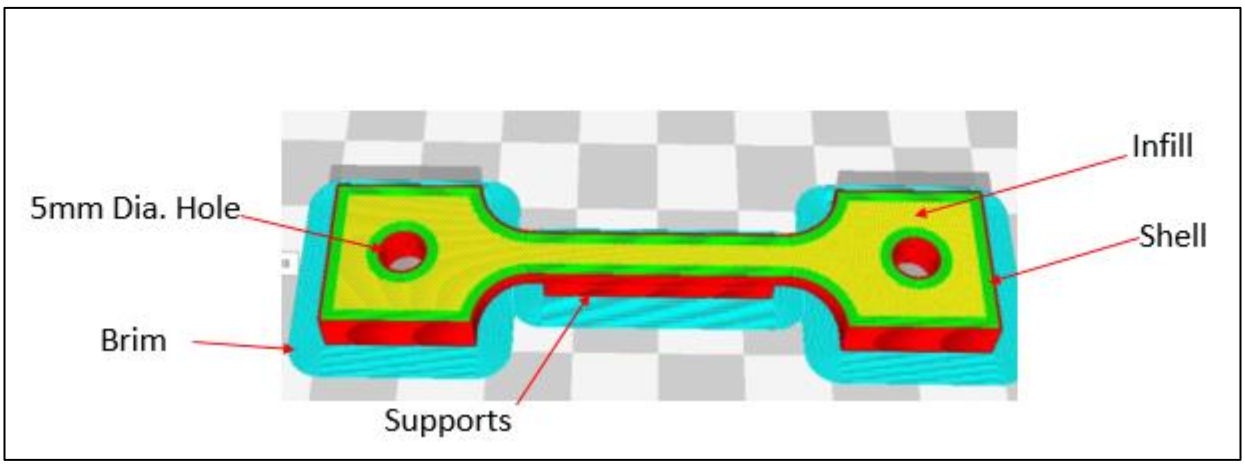


Figure 7: Side Printing [8]

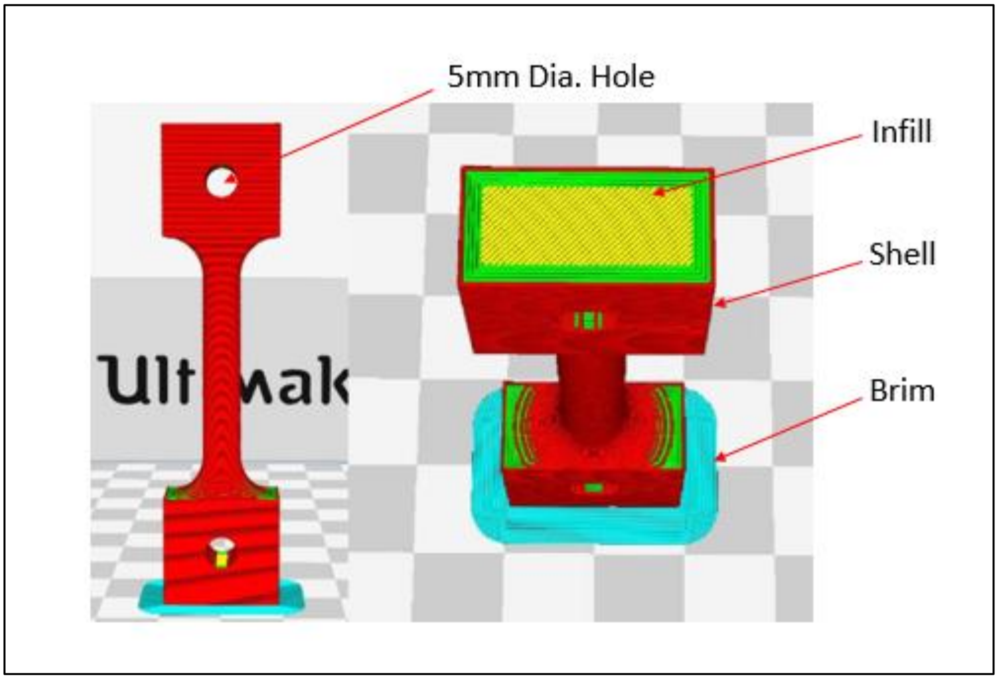


Figure 8: Upright Printing [8]

IV. Tensile Testing

A. Testing Process

In all engineering materials, the tensile test is a vital qualification test [1]. Tensile testing is a destructive test process that reveals information on the mechanical properties of a specific material including tensile, yield strength, and ductility of a material. This testing technique measures the force required to break a specimen and the extent of specimen elongation to its breaking point. This test also provides the specimen’s tensile strength at yield and break, tensile modulus, tensile strain, elongation, and percent elongation at yield and elongation [19].

List of printing parameters to be evaluated and compared in tensile testing of 3D printed samples

- PLA, side versus upright printed samples of 0.4 mm nozzle diameter
- PLA, side versus upright printed samples of 0.6 mm nozzle diameter
- PLA, 0.4 versus 0.6 mm nozzle diameters printed samples
- PLA, 50% versus 100% infill density using 0.4mm nozzle diameter
- PP, side versus upright printed samples using 0.6mm nozzle diameter

Tensile Testing Procedure:

- Sample’s diameter measurement

Figure 9: Measuring the diameter of the samples

The average diameter of the samples that underwent tensile testing were 6.28 mm as measured using Vernier scale. Figure 9 shows how the diameter of the samples was measured using a Vernier scale. The diameter of samples was entered into the MTI machine to be used for the mechanical properties calculation.

- Sample mounting to MTI-10k Machine

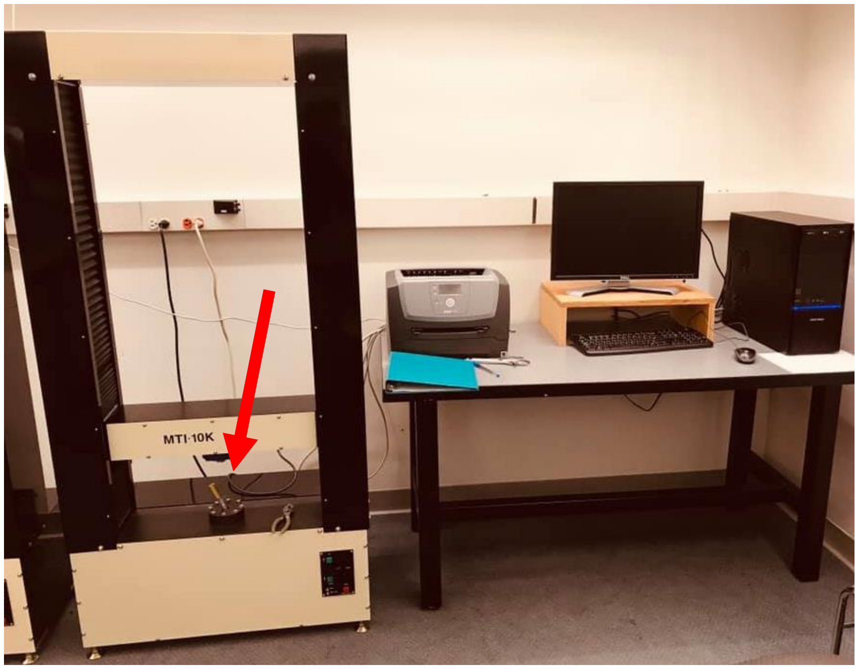


Figure 10: MTI-10K Machine

Figure 10 depicts the MTI- 10K machine used for tensile testing. The computer on the right side of the image is where the tensile testing parameters are entered. The left side of the image shows the red arrow where the samples are mounted. Figure 11 shows the samples before testing (left) and after testing (right).

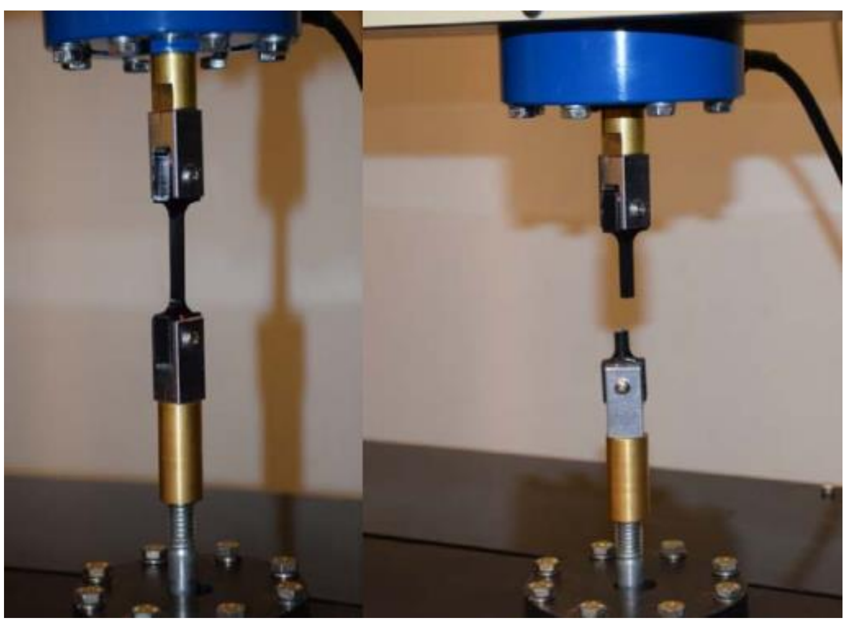


Figure 11: Tensile Testing of the samples [1]

Polylactic Acid (PLA) Tensile Testing

- Mounting of extensometer

For small displacement materials such as PLA, about 5 mm, the instrumentation called extensometer is required as per MTI manufacturer's recommendation for more accurate results, depicted in Figure 12 and Figure 13. Figure 12 shows the position of the clamp before the test, while Figure 13 is after the test.

Figure 12: Extensometer attached before testing

Figure 13: Extensometer position after the fracturing of the specimen

List of samples printed and tested:

Table 4: Summary of 3D Printed Samples for Tensile Testing

Number	Material	Print Orientation	Nozzle Size (mm)	Infill (%)	Quantity of specimen
1	PLA	Side Print	0.4	100	7
2	PLA	Upright	0.4	100	7
3	PLA	Side Print	0.6	100	6
4	PLA	Upright	0.6	100	7
5	PP	Side Print	0.6	100	7
6	PP	Upright	0.6	100	6
7	PLA	Side Print	0.4	50	7
8	PLA	Upright	0.4	50	7
				Total Samples Tested	54

Table 4 shows the summary of 3D printed samples that are tested using the MTI 10K machine and the values of the mechanical properties per item are illustrated in the testing results section.

B. Testing Results, Comparison, and Discussion

1) PLA, Side versus Upright printed Samples of 0.4 mm nozzle diameter

In this part of the testing, there are 14 3D printed samples. The printed samples are all PLA material, layer height of 0.2mm, shell thickness of 0.8mm, infill density of 100%, a print speed of 50mm/s, and a temperature of 210 C as shown in Table 5. The samples are divided into 2 groups, which contain seven samples per group. Seven samples are side printed, while the other seven are upright printed. All the samples underwent tensile testing using the MTI 10K machine as shown in Figure 10. The results of the testing are tabulated in Table 6 for side printed and Table 7 for upright printed.

Table 5: Printing parameters for print orientation comparison of 0.4 mm nozzle diameter.

Material	Layer Height (mm)	Shell Thickness (mm)	Fill Density (%)	Print Speed (mm/s)	Temperature (C)
PLA	0.2	0.8	100	50	210

The most common nozzle size being used for this type of 3D printer is 0.4mm diameter because of the surface details for small designed parts. PLA material is tested by the parameters shown in Table 5 for nozzle size 0.4mm.

- **Side printed PLA 3D samples**

Material	**Print Orientation**	**Nozzle Size (mm)**	**Infill Density (%)**
PLA	Side	0.4	100

Table 6: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation for all Side printed materials for 0.4 nozzle size

Specimen #	Mat’l	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation
0.4_S-100-1	PLA	2547.04	1462.08	46.61	0.4	4.01	Side
0.4_S-100-2	PLA	2537.69	1437.92	46.13	0.4	6.74	Side
0.4_S-100-3	PLA	2508.23	1467.38	46.33	0.4	6.18	Side
0.4_S-100-4	PLA	2532.41	1496.57	48.01	0.4	4.74	Side
0.4_S-100-5	PLA	3181.84	1617.63	51.08	0.4	5.27	Side
0.4_S-100-6	PLA	3197.69	1535.09	48.47	0.4	5.09	Side
0.4_S-100-7	PLA	2976.57	1514.97	47.84	0.4	5.52	Side

Table 6 shows specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, print orientation for all side printed material for 0.4 nozzle size. There are seven samples tested in this setting as shown in the first column on the left side. The material for this setting is PLA.

The average value of Young's modulus is 2783.07 MPa with a maximum value of 3197.69 MPa and a minimum of 2508.23 MPa, respectively. The average rupture force is 1617.63 N; a maximum is 1617.63 N, and the minimum is 1437.92 N. The average ultimate stress is 47.78 MPa; the maximum is 51.08 MPa, and the minimum is 46.13 MPa.

- ❖ **Upright printed PLA 3D samples**

Material	Print Orientation	Nozzle Size (mm)	Infill (%)
PLA	Upright	0.4	100

Table 7: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation for all Upright printed materials for 0.4 nozzle size

Specimen #	Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation
0.4-U-1	PLA	3104.31	921.63	31.54	0.4	3.48	Upright
0.4-U-2	PLA	2847.19	1125.37	37.52	0.4	4.01	Upright
0.4-U-3	PLA	3214.71	989.99	31.36	0.4	3.48	Upright
0.4-U-4	PLA	3469.85	1076.15	35.64	0.4	3.48	Upright
0.4-U-5	PLA	2633.30	1321.74	41.34	0.4	3.30	Upright
0.4-U-6	PLA	2785.26	1164.92	36.1	0.4	3.68	Upright
0.4-U-7	PLA	2643.33	1112.11	34.04	0.4	2.94	Upright

Table 7 shows specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, print orientation for all Upright printed material for 0.4 nozzle size. Similar to side printed samples, there are seven samples tested in this setting as shown in the first column on the left side. The material for this setting is PLA.

The average value of Young's modulus is 2956.85 MPa with a maximum value of 3469.85 and a minimum of 2633.3 MPa, respectively. The average is 1101.70 N; the maximum rupture force is 1321.74 N, and the minimum is 921.63 N. The average is ultimate stress is 35.36 MPa; a maximum is 41.34 MPa, and the minimum is 31.36 MPa.

❖ Graphs comparison of Side and Upright 3D printed samples of 0.4 nozzle diameter

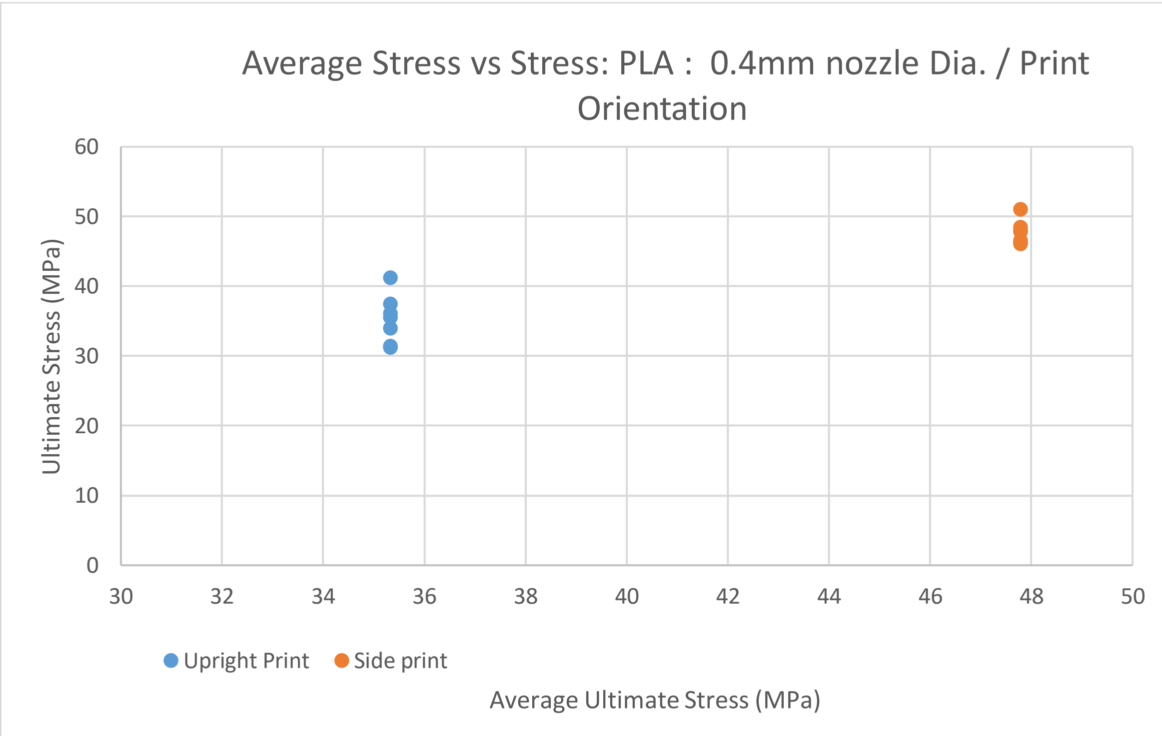


Figure 14: Ultimate Tensile Stress for 0.4 mm Nozzle Diameter for Side Vs Upright Printed

Figure 14 shows the difference of ultimate tensile stresses for side printed and upright printed samples for 0.4 nozzles with 100% infill density. There were 14 samples tested 7 for side printed and 7 for upright printed. Side printed samples have higher values than upright printed. The results show that the average, the maximum, the minimum values differences between side and upright printed are 12.42 MPa, 9.74 Mpa, 14.77 Mpa, respectively. The graphs show that the print orientation has a greater impact on the ultimate tensile strength of 3D printed PLA in nozzle size 0.4mm diameter.

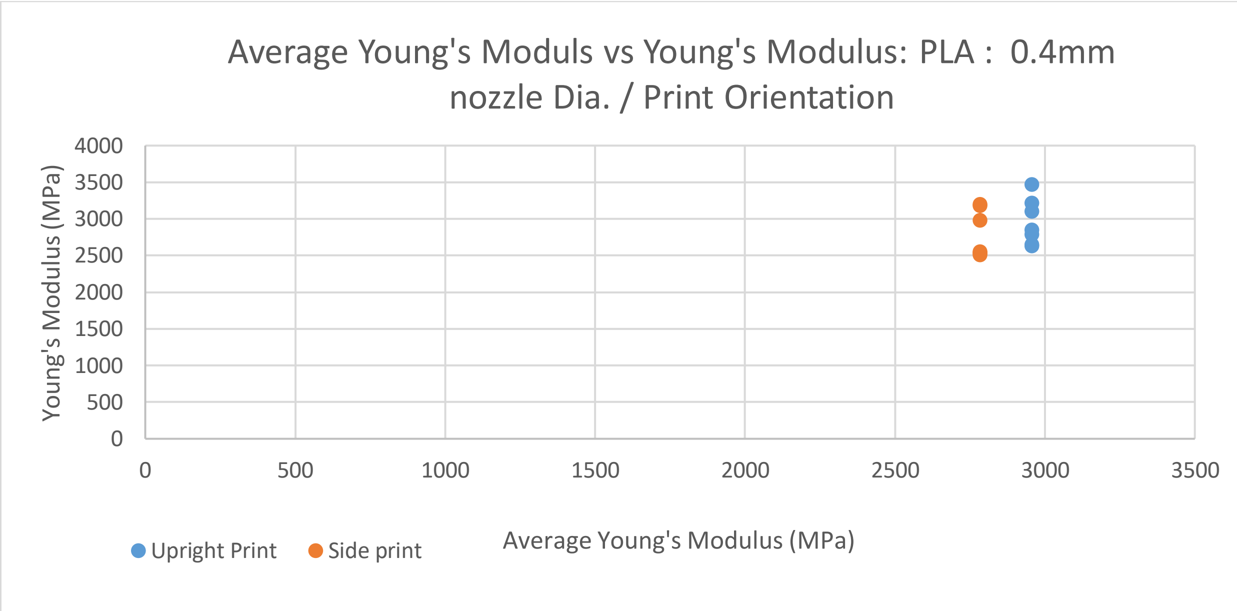


Figure 15: PLA, Young's Modulus for 0.4 mm Nozzle Diameter for Side Vs Upright Printed

Figure 15 illustrates the values of Young's modulus of both side and upright printed 3D samples. The results show that the average, a maximum, a minimum values differences between side and upright printed are 321.24 MPa, 272.16 Mpa, 125.07 Mpa, respectively. The difference values are for upright to side printed as upright printed show higher values than side printed. The results illustrate that the print orientation for a 0.4mm nozzle cannot be used as a basis for obtaining optimum Young's modulus values.

2) PLA, Side versus Upright printed Samples of 0.6 mm nozzle diameter

Table 8: Printing Parameters for print orientation comparison of 0.6 mm nozzle diameter

Material	Layer Height (mm)	Shell Thickness (mm)	Fill Density (%)	Print Speed (mm/s)	Temperature (C)
PLA	0.2	0.8	100	50	210

Table 8 shows the printing parameters that both side and upright printed shared for comparison for 0.6 mm nozzle used for PLA 3D printed samples.

- **Side printed PLA 3D samples 0.6 mm nozzle diameter**

Material	Print Orientation	Nozzle Size (mm)	Infill (%)
PLA	Side Print	0.6	100

Table 9: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation for all Side printed materials for 0.6 nozzle size

Specimen #	Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation
0.6_ S-100-1	PLA	3129.96	1777.32	56.12	0.6	5.65	Side
0.6_ S-100-2	PLA	3100.30	1795.13	55.80	0.6	5.45	Side
0.6_ S-100-3	PLA	3071.09	1761.90	55.63	0.6	6.19	Side
0.6_ S-100-4	PLA	2817.96	1796.25	54.63	0.6	4.38	Side
0.6_ S-100-5	PLA	2865.90	1816.08	54.56	0.6	4.91	Side
0.6_ S-100-6	PLA	2844.27	1785.84	55.34	0.6	4.92	Side

Table 9 shows specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, print orientation for all side printed material for 0.6 nozzle size. There are six samples tested in this setting as shown in the first column on the left side. The material for this setting is PLA.

The average value of Young's modulus is 2971.58 MPa with the maximum value of 3129.96 MPa, and a minimum of 2817.96 MPa, respectively. The average rupture force is 1788.75 N; the maximum is 1816.08 N, and the minimum is 1761.90 N. The average ultimate stress is 55.35 MPa; the maximum is 56.12, and the minimum is 54.56 MPa.

- **Upright printed PLA 3D samples of 0.6 mm nozzle diameter**

Material	Print Orientation	Nozzle Size (mm)	Infill (%)
PLA	Upright	0.6	100

Table 10: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation for all Upright printed materials for 0.6 nozzle size

Specimen #	Mat'l	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation

0.6_U-1	PLA	2751.03	1338.85	41.49	0.6	3.81	Upright
0.6_U-2	PLA	2415.53	1342.68	41.74	0.6	3.84	Upright
0.6_U-3	PLA	2515.82	1182.84	36.54	0.6	3.48	Upright
0.6 U-4	PLA	2382.91	1013.00	30.53	0.6	2.77	Upright
0.6_U-5	PLA	2653.37	1348.06	41.77	0.6	3.49	Upright
0.6_U-6	PLA	2484.86	1363.80	42.39	0.6	4.20	Upright
0.6_U-7	PLA	2520.70	1272.01	39.42	0.6	3.30	Upright

Table 10 shows specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, print orientation for all upright printed material for 0.6 nozzle size. There are seven samples tested in this setting as shown in the first column on the left side. The material for this setting is PLA.

The average value of Young's modulus is 2532.03 MPa with a maximum value of 2751.03 and a minimum of 2382.91 MPa, respectively. The average rupture force is 1265.89 N; the maximum is 1363.80 N, and the minimum is 1013.00 N. The average ultimate stress is 39.13 MPa; a maximum is 42.39 MPa, and the minimum is 30.53 MPa.

- ❖ Graphs comparison of Side and Upright 3D printed samples of 0.6 nozzle diameter printed 100% infill density

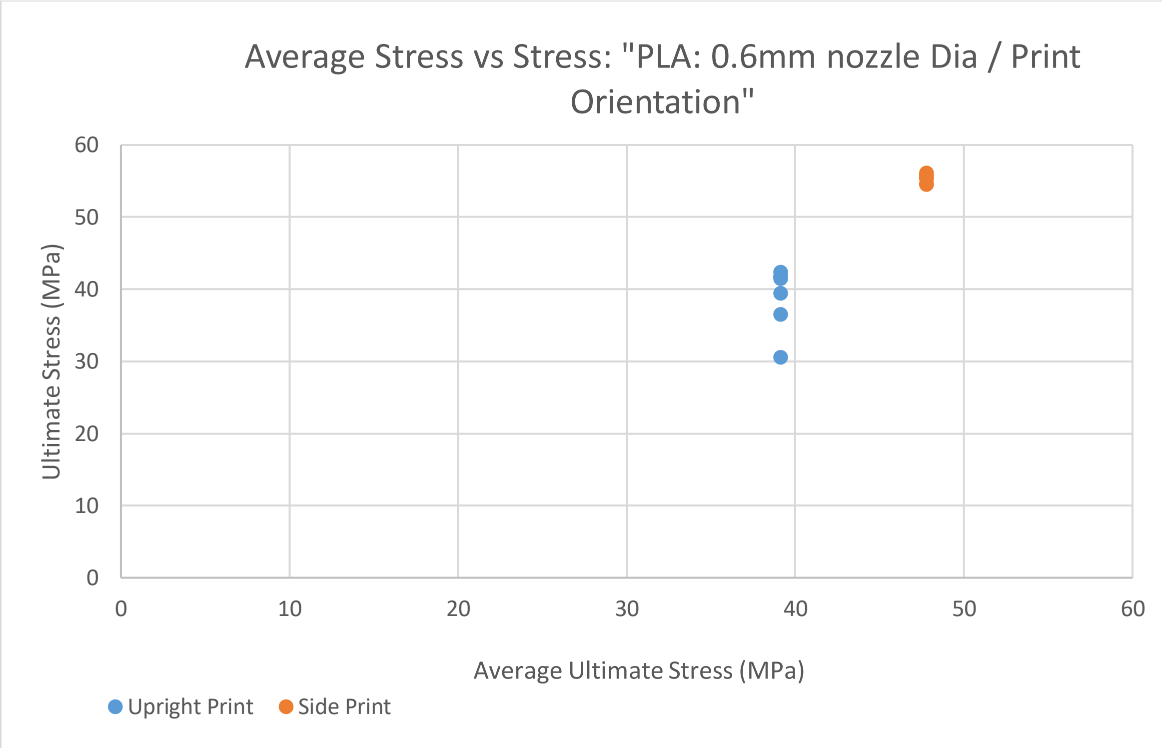


Figure 16: Ultimate Tensile Stress for 0.6 mm Nozzle Diameter for Side Vs Upright Printed

Figure 16 depicts the comparison of side printed and upright printed samples for ultimate tensile stress for 0.6 mm diameter nozzle. The side printed shows higher values compared to the Upright printed samples.

The results show that the average, maximum, minimum values differences between side and upright printed are 16.22 MPa, 13.73 Mpa, 24.03 Mpa, respectively. The graph shows that there are consistently higher values of ultimate tensile stress of side printed compared to upright printed in 0.6mm nozzle diameter.

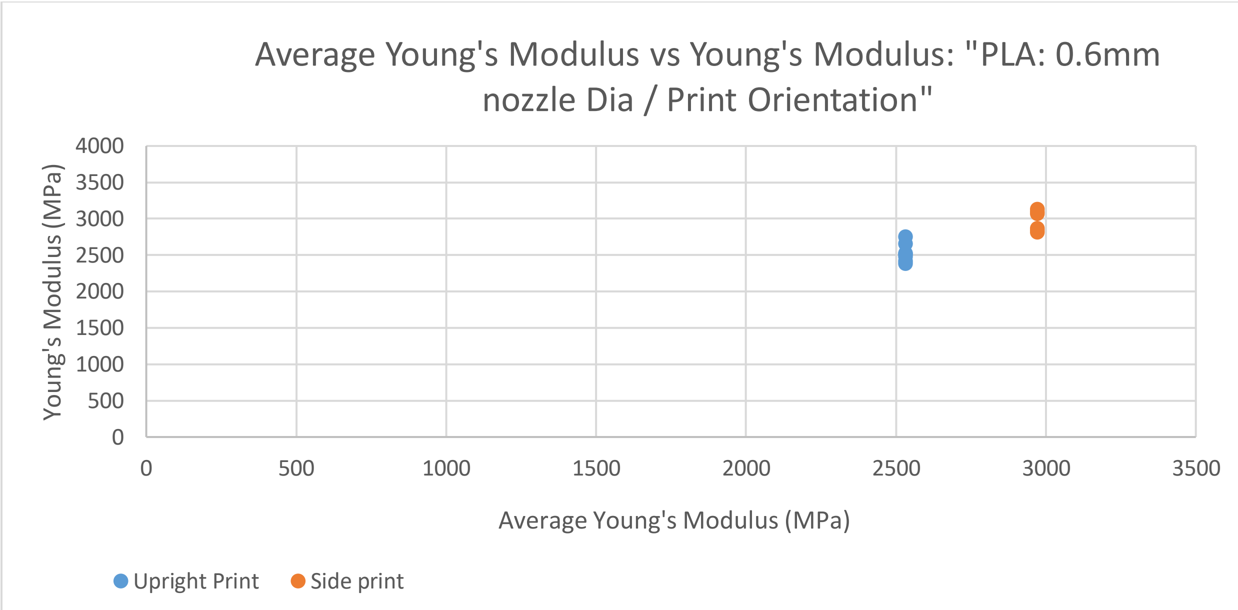


Figure 17: Young’s modulus of 0.6 mm Nozzle Diameter for Side Vs Upright PLA 3D printed samples

Figure 17 depicts Young’s modulus values for 0.6 mm diameter nozzle for side and upright printed samples, which shows six samples with consistent higher values for side printed over the seven upright samples.

The results show that the average, maximum, minimum values differences between side and upright printed are 439.55 MPa, 378.93 Mpa, 435.05 Mpa, respectively. The graph shows that there are consistently higher values of side printed compared to upright printed in 0.6mm nozzle diameter.

3) PLA, 0.4 versus 0.6 mm nozzle diameters printed samples

From the results of 0.4mm diameter and 0.6mm diameter nozzles, the two comparisons are combined and compared in Figure 18 and Figure 19. Figure 18 depicts the Ultimate stresses of four groups of samples.

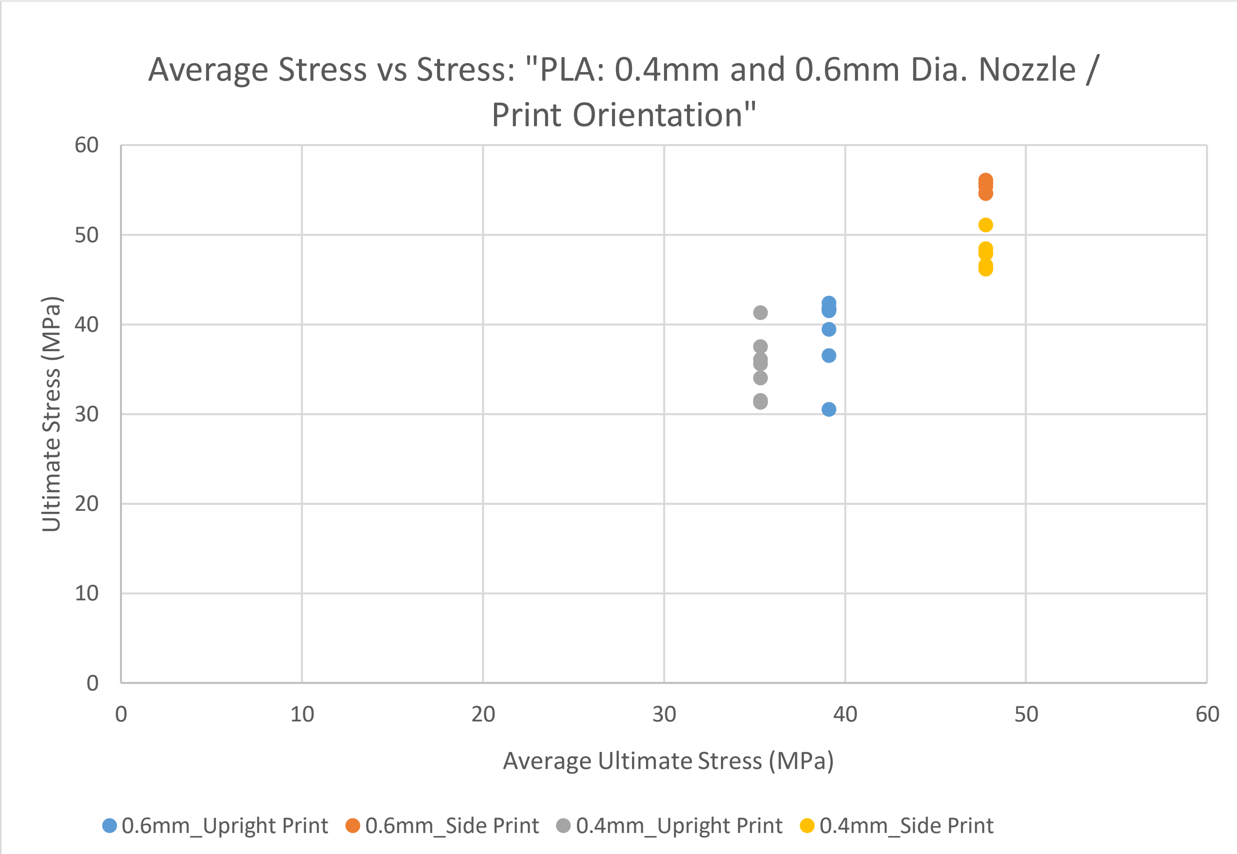


Figure 18: PLA, Ultimate Tensile Stress for 0.4 and 0.6 mm Nozzle Diameter for Side Vs Upright Printed

Figure 18 depicts the comparison of side printed and upright printed samples for ultimate tensile stress for 0.6 mm and 0.4 mm diameter nozzles. The side printed samples show higher values compared to the Upright printed samples for both 0.4 mm and 0.6 mm nozzle sizes.

Samples printed from 0.6 mm diameter with side printed orientation have higher ultimate tensile strength than 0.4 mm nozzle diameter with an average, maximum, minimum differences of 7.57 Mpa, 5.04 Mpa, and 8.43 Mpa, respectively. This means that the bigger nozzle has higher ultimate tensile strength if the print orientation is sideway.

Samples printed from 0.6mm diameter with upright printed orientation have different values of average, maximum, minimum, of 3.76 Mpa, 1.05 Mpa, -0.83 Mpa, respectively, compared to 0.4mm diameter nozzle upright printed orientation. This means that the size of the nozzle does not have a great impact on the ultimate strength of the upright printed orientation samples.

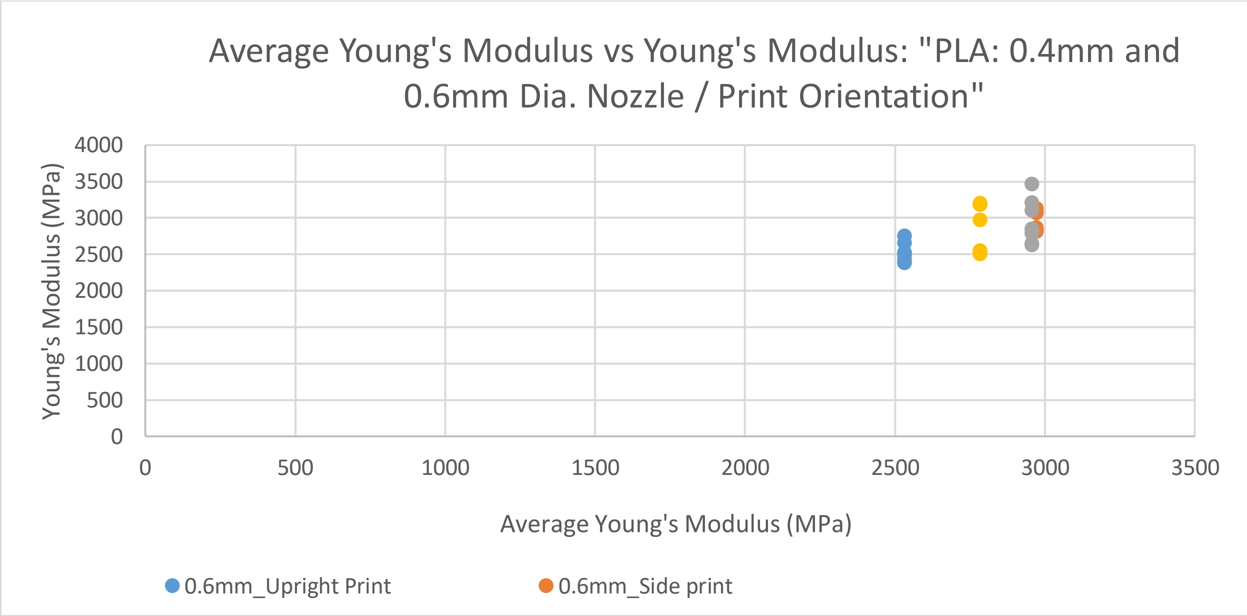


Figure 19: Young's Modulus for 0.4 and 0.6 nozzles 3D printed Materials for both side printed and upright printed PLA samples

Figure 19 shows the comparison of side printed and upright printed samples for Young's modulus for 0.6 mm and 0.4 mm diameter nozzles.

Samples printed from 0.6 mm diameter with side printed orientation have higher Young's modulus than 0.4 mm nozzle diameter, of an average, maximum, minimum differences of 188.51Mpa, -67.73 Mpa, and 309.73 Mpa, respectively. This means that the size of the nozzle cannot be a basis to maximize or minimize Young's modulus of PLA 3D printed parts for side print orientation.

In terms of upright print orientation, Young's modulus differences of samples printed from 0.6mm diameter nozzle to 0.4 mm nozzle diameter, are an average, maximum and minimum of -424.82 Mpa, -718.82 Mpa, -435.05 Mpa, respectively. The negative values indicate that the samples printed from 0.4mm nozzle in an upright orientation have higher values than samples printed from 0.6mm nozzle diameter nozzle. Based on the result as shown in the graphs above, in upright orientation printing, the bigger the nozzle the lower the value of Young's modulus of the 3D printed samples.

4) PLA, 50% versus 100% infill density using 0.4mm nozzle diameter

- **50% Infill Density of 0.4 mm diameter nozzle side printed PLA samples**

Table 11: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation, diameter, and infill density for all side printed materials for 0.4 nozzle size.

Specimen #	Mat'l	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Print Orientation	Diameter (mm)	Infill Density (%)
0.4-S-50-1	PLA	1105.33	720.74	22.76	0.4	Side	6.35	50
0.4-S-50-2	PLA	1207.52	742.98	23.46	0.4	Side	6.35	50
0.4-S-50-3	PLA	1163.82	606.22	19.14	0.4	Side	6.35	50
0.4-S-50-4	PLA	947.57	723.08	22.76	0.4	Side	6.36	50
0.4-S-50-5	PLA	1180.06	640.23	20.28	0.4	Side	6.34	50
0.4-S-50-6	PLA	1247.25	667.58	21.62	0.4	Side	6.27	50
0.4-S-50-7	PLA	1113.49	637.12	19.68	0.4	Side	6.42	50

Table 11 shows specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, print orientation for the upright printed specimens for 0.4 nozzle size. There are seven samples tested in this setting as shown in the first column on the left side. The material for this setting is PLA.

The average value of Young's modulus is 1137.86 MPa with a maximum value of 1247.25 and a minimum of 947.57 MPa, respectively. The average rupture force is 676.85 N; a maximum is 742.98 N, and the minimum is 606.22 N. The average ultimate stress is 21.39 MPa; a maximum is 23.46 MPa, and the minimum is 19.14 MPa.

Table 12: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation, Diameter, and Infill density for all upright printed materials for 0.4 nozzle size.

Specimen #	**Material**	**Young's Modulus (N/mm^2)**	**Rupture Force (N)**	**Ultimate Stress (N/mm^2)**	**Nozzle Size (mm)**	**Print Orientation**	**Sample Diameter (mm)**	**Infill Density (%)**
0.4-U-50-1	PLA	896.31	99.18	3.59	0.4	Upright	6.41	50
0.4-U-50-2	PLA	-44.44	125.97	4.59	0.4	Upright	6.40	50
0.4-U-50-4	PLA	1331.08	145.00	5.18	0.4	Upright	6.42	50
0.4-U-50-5	PLA	847.49	95.37	3.43	0.4	Upright	6.5	50
0.4-U-50-6	PLA	905.77	115.06	4.19	0.4	Upright	6.41	50
0.4-U-50-8	PLA	1104.5	148.43	5.34	0.4	Upright	6.40	50
0.4-U-50-9	PLA	1237.39	218.34	7.88	0.4	Upright	6.41	50

Table 12 shows the specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, the print orientation of upright printed material for 0.4 mm nozzle size. There are seven samples tested in this setting as shown in the first column on the left side. The material for this setting is PLA.

The average value of Young's modulus is 896.87 MPa with a maximum value of 1331.08 and a minimum of -44.44 MPa, respectively. The average rupture force is 135.34 N; a maximum is 218.34 N, and the minimum is 95.37 N. The average ultimate stress is 4.89 MPa; a maximum is 7.88 MPa, and the minimum is 3.43 MPa.

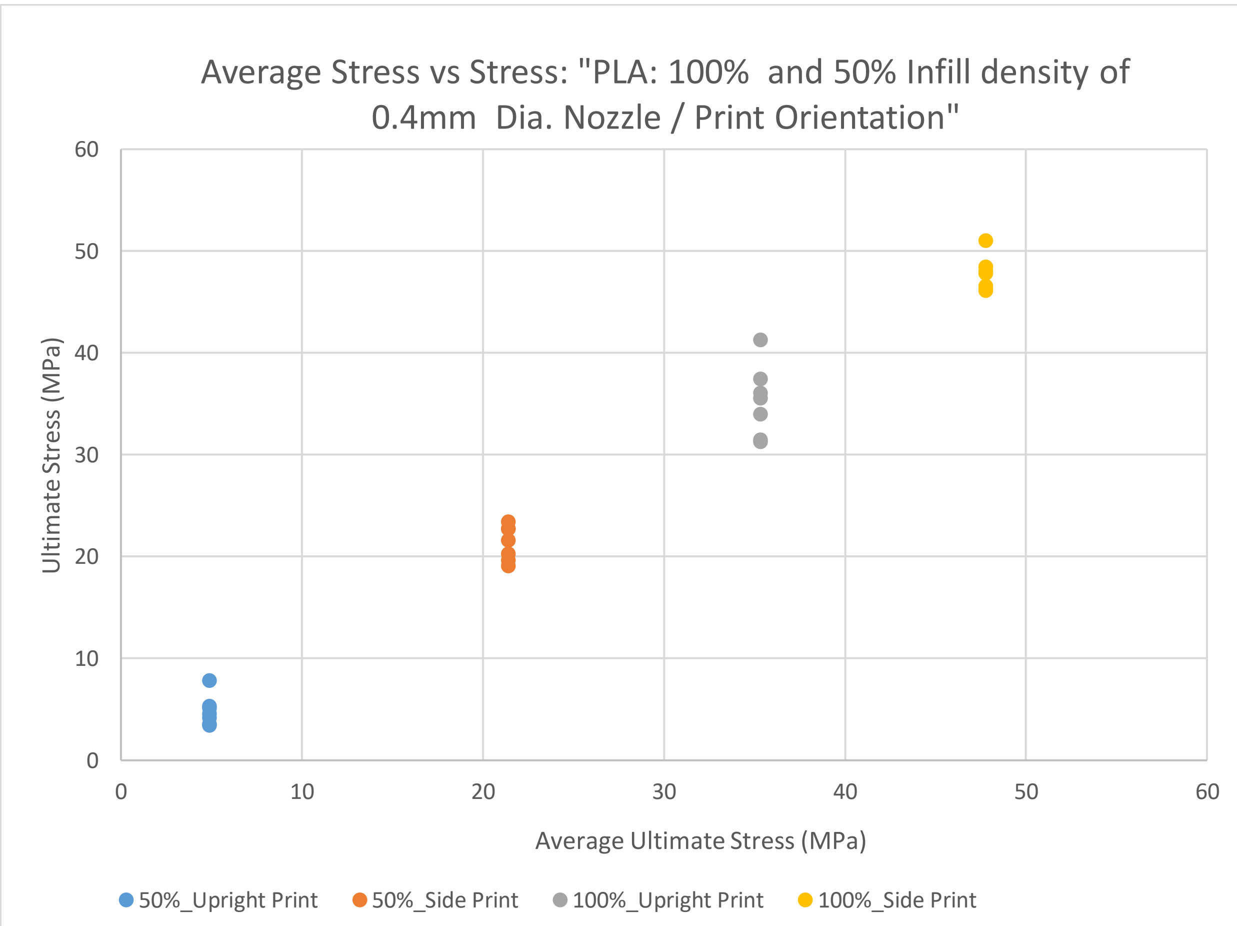


Figure 20: PLA, Ultimate Tensile Stress for 0.4 mm Nozzle Diameter for 100% and 50% infill density

Figure 20 illustrates the comparison of Ultimate Tensile stress of 100% infill density to 50% infill density for PLA printed from 0.4mm nozzle diameter.

100% infill density, side printed samples have average, maximum, minimum difference of 26.40 Mpa, 27.62 Mpa, 26.99 Mpa, respectively, over 50% infill density side printed samples. The values show that the 100% infill density samples have more than double in ultimate tensile stress over the 50% infill density.

100% infill density, upright printed samples have an average, maximum, minimum average of 30.48 Mpa, 33.46 Mpa, 27.93 Mpa, respectively. 100% infill density samples have 4 to 8 times higher values than 50% infill density in upright printed orientation in terms of ultimate tensile stress.

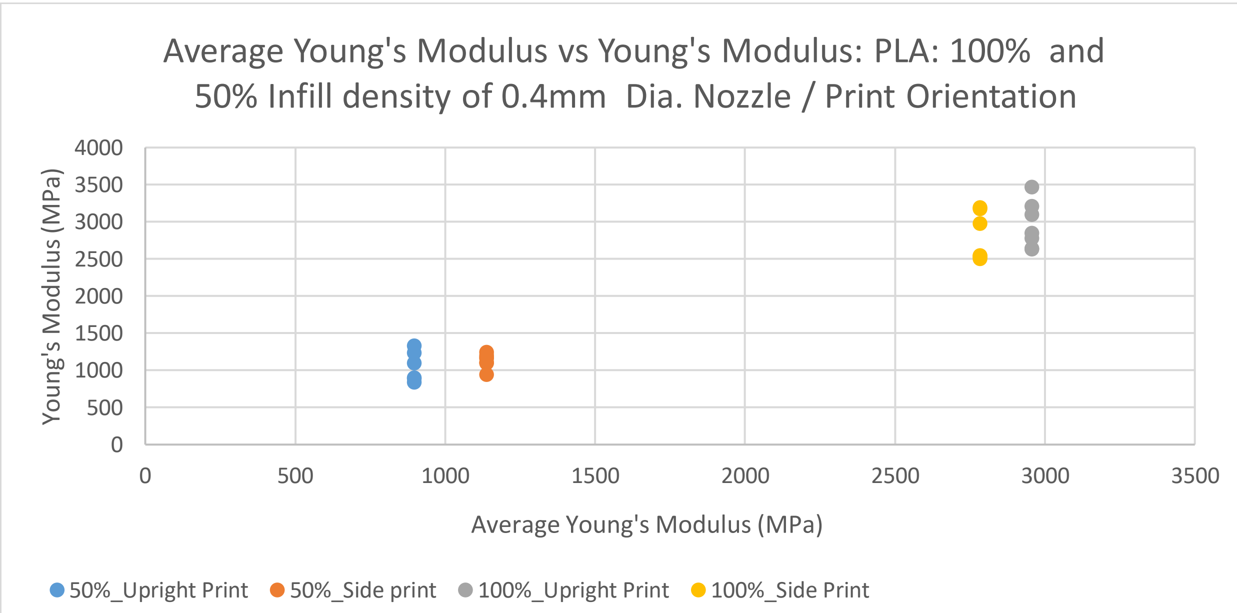


Figure 21: PLA, Young's Modulus for 0.4 mm Nozzle Diameter for 100% Vs 50% infill density

Figure 21 depicts Young's modulus comparison of 100% infill density and 50% infill density for nozzle size 0.4mm for PLA samples. The values of Young's modulus for both side and upright printed in 100% infill are more than double compared to the 50% infill density.

5) PP, Side versus upright printed using 0.6mm nozzle diameter

❖ **PP material side printed by 0.6mm diameter nozzle**

Table 13: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation, diameter for all side printed materials for 0.6 nozzle size

Specimen #	Mat'l	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation
0.6_PP-S-1	PP	68.77	382.13	12.42	0.6	37.98	Side

0.6_PP-S-2	PP	46.25	343.34	11.34	0.6	38.41	Side
0.6_PP-S-3	PP	43.97	338.86	11.19	0.6	38.56	Side
0.6_PP-S-4	PP	71.27	380.73	12.53	0.6	38.42	Side
0.6_PP-S-5	PP	54.85	349.12	11.56	0.6	38.09	Side
0.6_PP-S-6	PP	67.14	422.51	13.01	0.6	38.53	Side
0.6_PP-S-7	PP	58.49	384.84	12.5	0.6	39.08	Side

Table 13 shows the specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, the print orientation of side printed material for 0.6 nozzle size. There are seven samples tested in this setting as shown in the first column on the left side. The material for this setting is Polypropylene (PP).

The average value of Young's modulus is 58.68 MPa with a maximum value of 71.27 and a minimum of 43.97 MPa, respectively. The average rupture force is 371.65 N; the maximum is 422.51 N, and the minimum is 338.86 N. The average ultimate stress is 12.08 MPa; the maximum is 13.01 MPa, and the minimum is 11.19 MPa.

- **PP material upright printed by 0.6mm diameter nozzle**

Table 14: Specimen #, Material, Young's modulus, Rupture Force, Ultimate Stress, Nozzle Size, Displacement, Print orientation, diameter, and infill density for all side printed materials for 0.6 nozzle size.

Specimen #	Mat'l	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation
0.6_PP-U-1	PP	85.46	402.75	13.09	0.6	38.26	Upright
0.6_PP-U-2	PP	83.8	382.54	12.67	0.6	38.37	Upright
0.6_PP-U-3	PP	86.5	390.82	12.94	0.6	38.85	Upright
0.6_PP-U-5	PP	76.46	393.39	12.74	0.6	34.80	Upright
0.6_PP-U-6	PP	88.77	378.22	12.33	0.6	30.43	Upright
0.6_PP-U-7	PP	62.7	379.7	12.46	0.6	38.42	Upright

Table 14 shows the specimen number, material, Young's modulus, rupture force, ultimate stress, nozzle size, displacement, the print orientation of upright printed material for 0.6 mm nozzle size. There are six samples tested in this setting as shown in the first column on the left side. The material for this setting is Polypropylene (PP).

The average value of Young's modulus is 80.62 MPa with a maximum value of 88.77 and a minimum of 62.70 MPa, respectively. The average rupture force is 387.90 N; the maximum is 402.75 N, and the minimum is 378.22 N. The average ultimate stress is 12.71 MPa; the maximum is 13.09 MPa, and the minimum is 12.33 MPa.

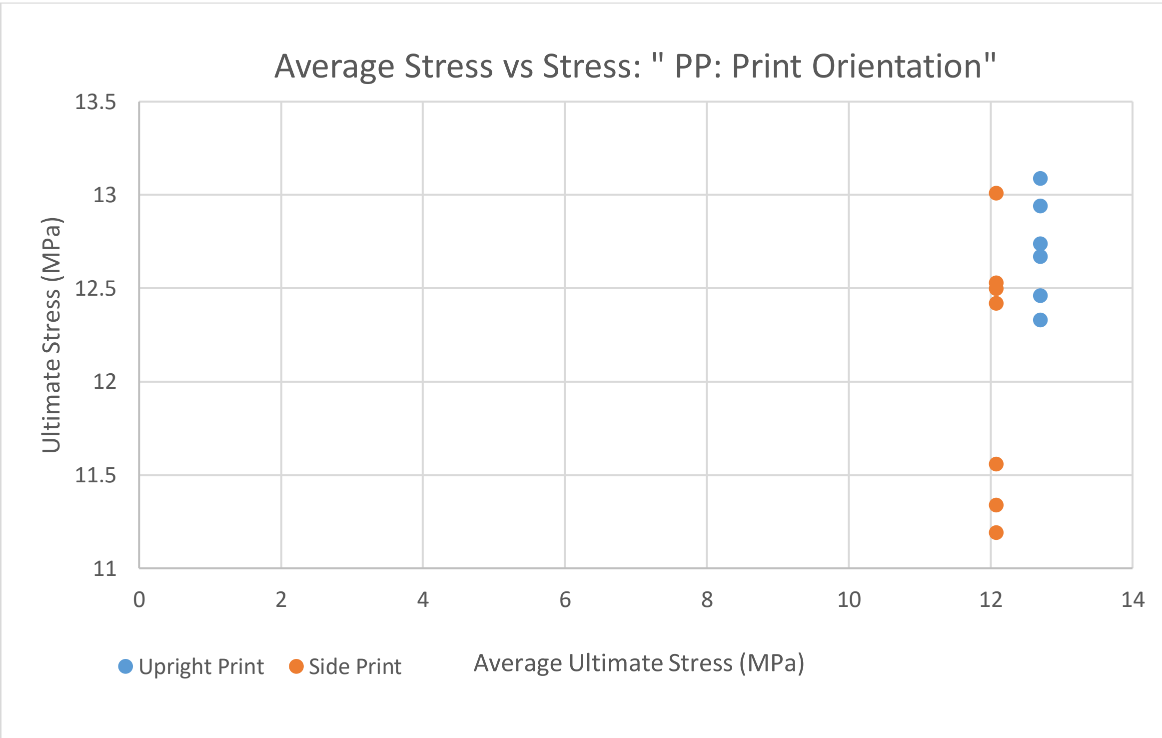


Figure 22: PP, Ultimate Tensile Stress for 0.6 mm Nozzle Diameter for Side Vs Upright Printed

Figure 22 depicts the comparison of side printed and upright printed samples for ultimate tensile stress for 0.6 mm diameter nozzle for PP material. The side printed shows lower values compared to the Upright printed samples.

The results show that the average, maximum, minimum values differences between side and upright printed are -0.63 MPa, -0.08 Mpa, -1.14 Mpa, respectively. The negative values mean that upright printed samples have higher values over side printed samples as shown in the graph above with consistently lower values of side printed compared to upright printed in 0.6mm nozzle diameter. This is the opposite compared to the PLA material in which side printed samples have consistently higher values compared to upright printed samples.

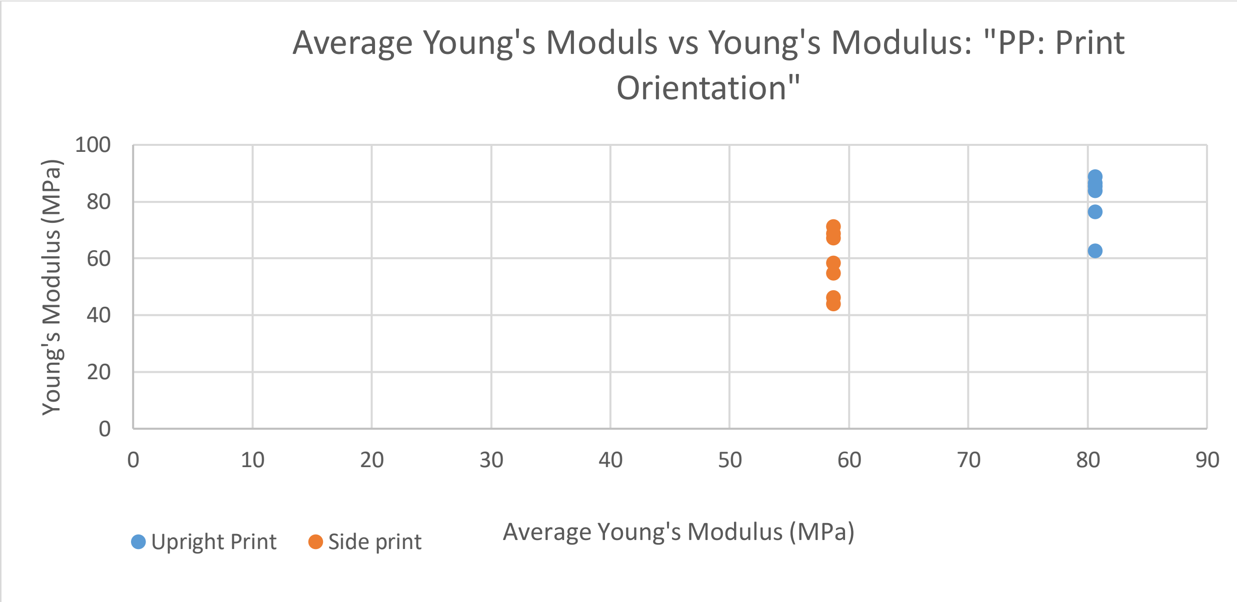


Figure 23: PP, Young's Modulus for 0.6 mm Nozzle Diameter for Side Vs Upright Printed

Figure 23 depicts the comparison of side printed and upright printed samples for Young's Modulus for 0.6 mm diameter nozzle for PP material. The side printed shows lower values compared to the Upright printed samples.

The results show that the average, maximum, minimum values differences between side and upright printed are -21.94 MPa, -17.50 Mpa, -18.73 Mpa, respectively. The negative values mean that upright printed samples have higher values over side printed samples as shown in the graph above with consistently lower values of side printed compared to upright printed in 0.6mm nozzle diameter. This is opposite to the PLA material in which side printed samples have consistently higher values compared to upright printed samples.

C. Tensile Testing Summary

The experiment summary is listed below for easier comparison.

Tensile Testing findings:

- PLA, side printed specimens show higher values compared to upright printed in many aspects
- PLA, Bigger nozzle has higher Ultimate tensile stress
- PLA, Bigger nozzle has a lower Young's modulus
- 100% infill density has more than double the strength than 50%
- PP, Upright has higher Ultimate Tensile Stress
- PP, Upright print has higher Young's Modulus

Comparison summary:

- PLA, 0.4 mm nozzle, (Side Vs Upright)→(UTS=Side is higher), (YM=Upright is higher)
- PLA, 0.6 mm nozzle, (Side Vs Upright)→(UTS=Side is higher), (YM=Side is higher)
- PLA (0.4mm Versus 0.6mm Diameter Nozzle) → (UTS=0.6mm is higher (Side and Upright); (YM= 0.6mm higher a little (side); 0.4mm is higher in upright)
- PLA (50% Versus 100% Infill) →100% infill strength is more than double
- PLA (Upright Versus Side prints) → Side prints have higher strength.
- PP (Side Versus Upright print); upright prints are slightly stronger

V. Bending (Flexural) Testing

Bending or flexural testing is utilized to measure the required force in bending a beam of plastic material, to measure the resistance to flexing or the material's stiffness. Flex modulus is a measure used to indicate the degree at which the material can flex before any permanent deformation [20]. There are two bending testing procedures conducted in this experiment – one for PLA and one for PP. The PLA samples that underwent bending testing have a similar configuration to the samples that underwent tensile testing. However, for PP material a new set of samples is printed as shown below.

D. Bending Testing Procedure:

There are 3 bending testing set up procedures as listed below, two for PLA and one for PP materials.

- ❖ PLA Bending Testing; Set up #1: A) Side printed: Wide-side clamped
  B) Upright printed: Wide-side Clamped
- ❖ PLA Bending Testing; Set up #2: A) Side printed: Short-side clamped
  B) Upright printed: Short-side Clamped
- ❖ PP Bending Test; Set up # 3

Material	Nozzle size (mm)	Layer Height (mm)	Shell Thickness (mm)	Fill Density (%)	Print Speed (mm/s)	Temperature (C)
PLA	0.4	0.2	0.8	100	50	210

1) PLA Bending Testing

The configurations of samples that are tested for bending testing are similar to the samples that underwent tensile testing.

PLA Bending Testing Set up #1: Wide-side clamped

There are two setups conducted. First, is Wide-side clamped which is shown in Figure 24. This set up is used for side printed samples and upright printed samples as well. The ring hook shown is used to attach the string to ensure that the center of gravity is in the middle.

Figure 24: PLA Wide-side clamped

The string holds the bucket and the sand, which serves as the load is poured slowly into the bucket. The sand is loaded slowly into the bucket until the samples break and the corresponding weight or the result is recorded for six samples.

Figure 25: PLA, Wide side Clamped set up

The string is holding the bucket suspended/hanging in the air as the vessel of the sand, which function as the force/load required to break the samples.

Figure 26: Pouring of sand into the bucket as load

The sand or load is slowly poured as possible into the bucket until the samples break.

Figure 27: Specimen after loading

The samples at breaking point as shown in Figure 27. Breaking loads of different samples are tabulated in the tables below.

E. PLA Bending Test Results: Set up # 1

Table 15: PLA; Set up # 1 A_ Side printed: Wide-side Clamped

Side printed : Wide-side Clamped		
Sample #	Diameter (mm)	Breaking Load (Kg)
0.4_S-1-W	6.25	6.20
0.4_S-2-W	6.24	5.30
0.4_S-3-W	6.15	7.50
0.4_S-4-W	6.19	5.30
0.4_S-5-W	6.24	4.10
0.4_S-6-W	6.24	6.90

Figure 28: Side printed; Wide-side clamped samples after bending testing

Table 16: PLA; PLA; Set up # 1 _B) Upright printed: Wide-side Clamped

Upright printed : Wide-side Clamped		
Sample #	Diameter (mm)	Breaking Load (Kg)
0.4_U-1-W	6.26	5.10
0.4_U-2-W	5.79	2.70
0.4_U-3-W	6.44	5.90
0.4_U-4-W	6.20	4.10
0.4_U-5-W	6.16	4.60
0.4_U-6-W	6.19	4.10

Figure 29: Upright Printed; Wide-side clamped

PLA Bending Testing Set up #2: Short-side clamped

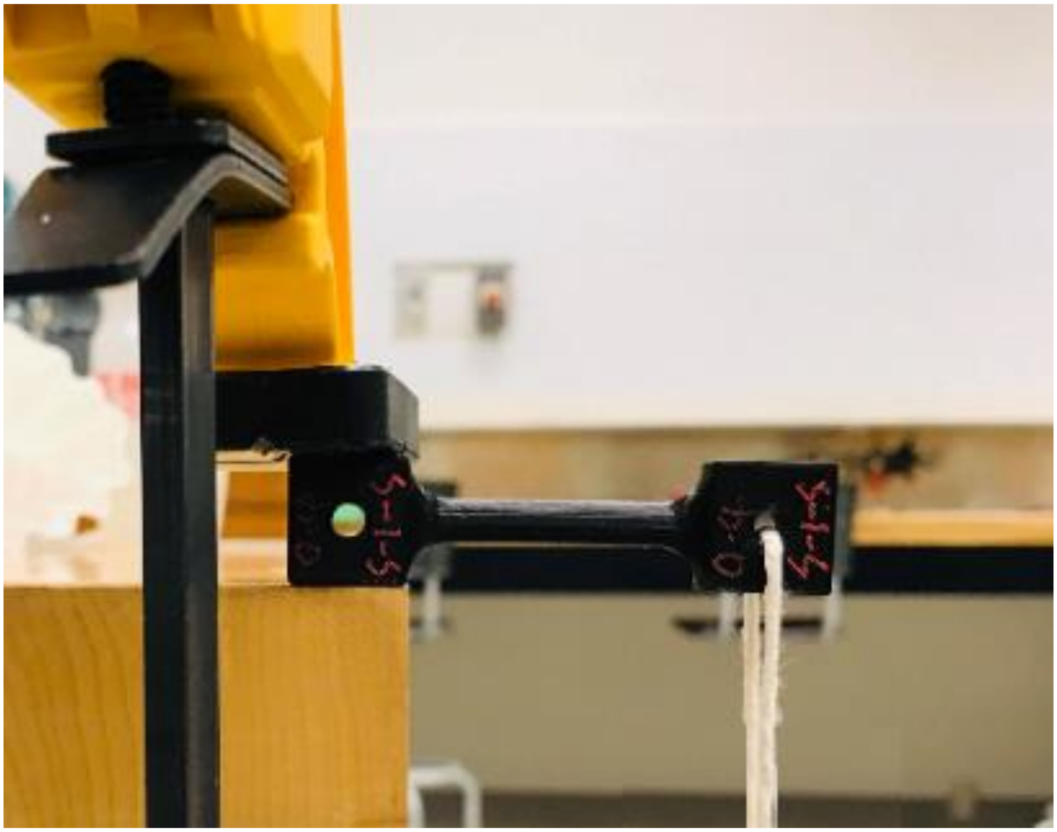


Figure 30: PLA Short side Clamped

Figure 30 shows how the sample set up for the short side is clamped. To ensure that the center of gravity is in the center, a string, hook, and bucket are used similar to the procedure conducted as the bending testing mentioned above where the sand or load is poured slowly until the samples break.

Figure 31: PLA, Short side clamped loading

Figure 31 illustrates the full set up of PLA bending testing with Short side clamped.

Figure 32: Specimen after loading

Figure 32 depicts the broken sample after bending testing. The diameters of the samples and the breaking loads are listed in the tables below.

F. PLA Bending Test Results: Set up # 2

Table 17: PLA; Set up # 2 _A) Side printed: Short-side Clamped

Side printed : Short-side Clamped		
Sample #	Diameter (mm)	Breaking Load (Kg)
0.4_S-1-S	6.21	4.30
0.4_S-2-S	6.20	4.60
0.4_S-3-S	6.24	4.90
0.4_S-4-S	6.24	4.40
0.4_S-5-S	6.22	4.40
0.4_S-6-S	6.23	4.60

Figure 33: Side printed; Short-clamped samples after bending test

Table 18: PLA; Set up # 2 _A) Upright printed: Short-side Clamped

Upright printed : Short-side Clamped		
Sample #	Diameter (mm)	Breaking Load (Kg)
0.4_U-1-S	5.86	2.90
0.4_U-2-S	6.39	4.40
0.4_U-3-S	6.38	5.00
0.4_U-4-S	6.23	3.20
0.4_U-5-S	6.45	4.30
0.4_U-6-S	6.49	4.70

Figure 34: Upright Printed; short-side clamped samples after bending testing

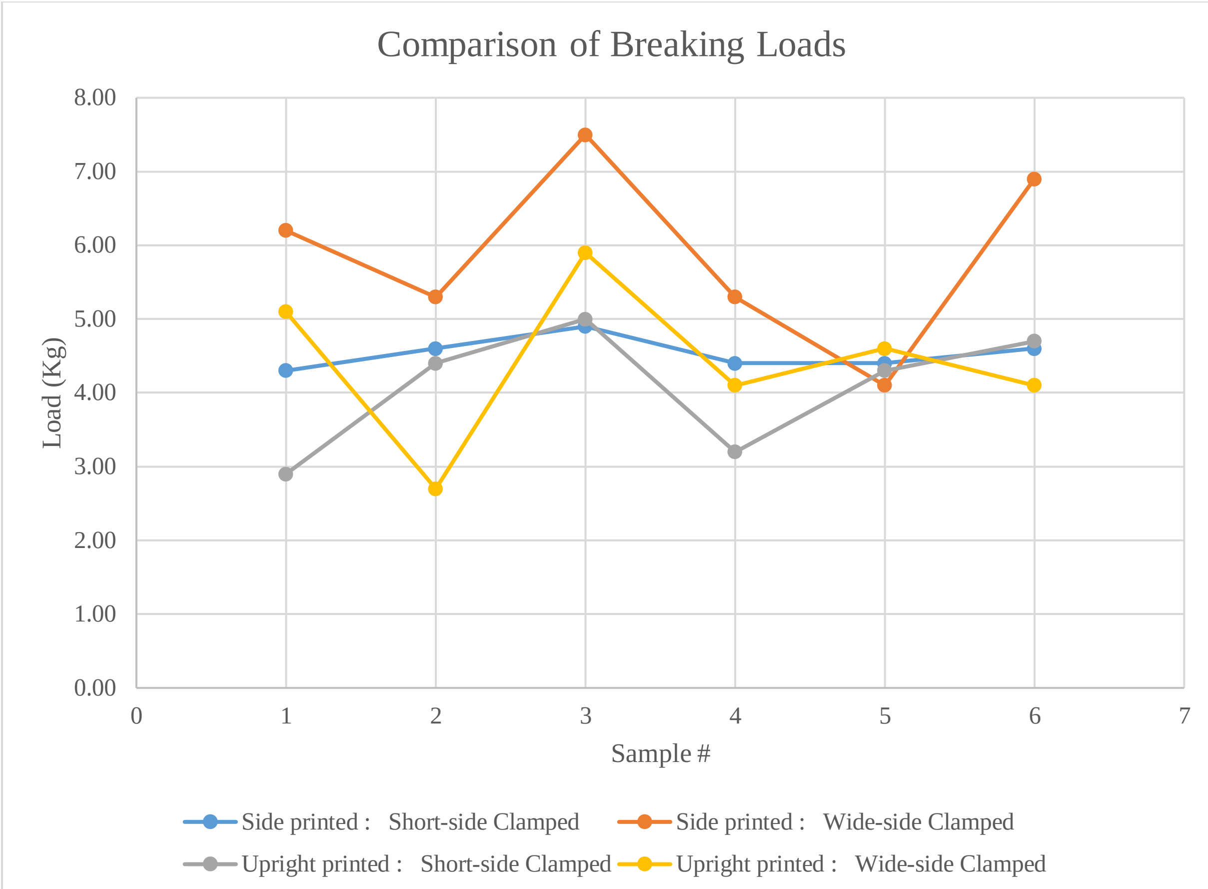


Figure 35: Comparison of breaking loads of four PLA Bending Set-up

Figure 35 depicts the breaking loads of samples at different print orientations and bending set up. Side printed Wide-side Clamped shows the highest loads in most of the samples, while the majority of the Upright printed Short Clamped's values show the lowest loads. Side printed Short-side Clamped shows almost consistent values that range between 4.00 Kg and 5.00 Kg. On the other hand, Upright printed Wide-side Clamped shows unpredictable breaking loads.

1) Polypropylene Bending Testing

The bending testing of PP is illustrated below. A PP 3D printed sample depicted in Figure 36 underwent bending testing. The dimensions of the sample are shown in Figure 37.

There are two different filaments used for PP bending testing, the Ultimaker, and Formfutura filaments. Both brands underwent the same printing setups and bending procedures to determine the difference in bending properties.

Figure 36: PP Sample for Bending Testing

The PP samples are printed using the printer setting shown in Table 19.

Table 19: Printer Settings for PP samples for bending testing

Printer Settings for PP samples for bending testing				
Nozzle size	0.6mm		Infill Density	100%
Layer height	0.3mm		Brim	20mm
Wall Thickness	1.8mm		Buildplate Temperature	100 C
Print Speed	30mm/s		Nozzle Temperature	230 C

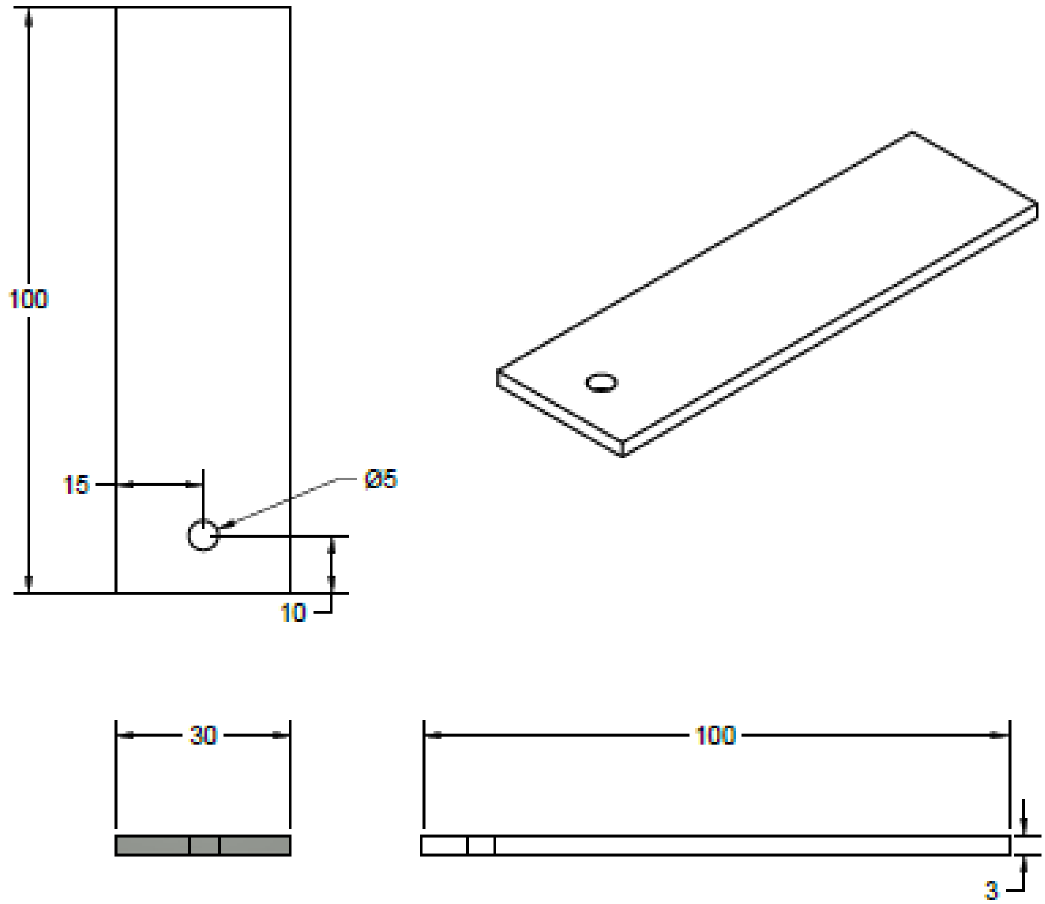


Figure 37: PP Sample Dimensions in Millimeters

PP Bending Test; Set up # 3

Figure 38: PP Samples bending set up

Figure 37 shows the level of the bottom of the sample as the starting point of the bending deflection when zero load is applied – this is load 1. At this point, the level is considered zero and the starting load (Load 1). Load 1 has zero load and is the basis of deflection for the different loads. The following loads are Load 2 =200g, Load 3=400g, Load 4= 600g, Load 5= 800g, Load 6 =1000g.

Figure 39: Position of the specimen as it is bending as the load is applied

Figure 39 illustrates the position of the specimen as it is bending as the load is applied. Eyebolt, nut, string, sand, bucket, and weights are added to obtain the specific weights to determine the measurement of deflections as per load application.

Figure 40: PP Bending Testing Full Set-up

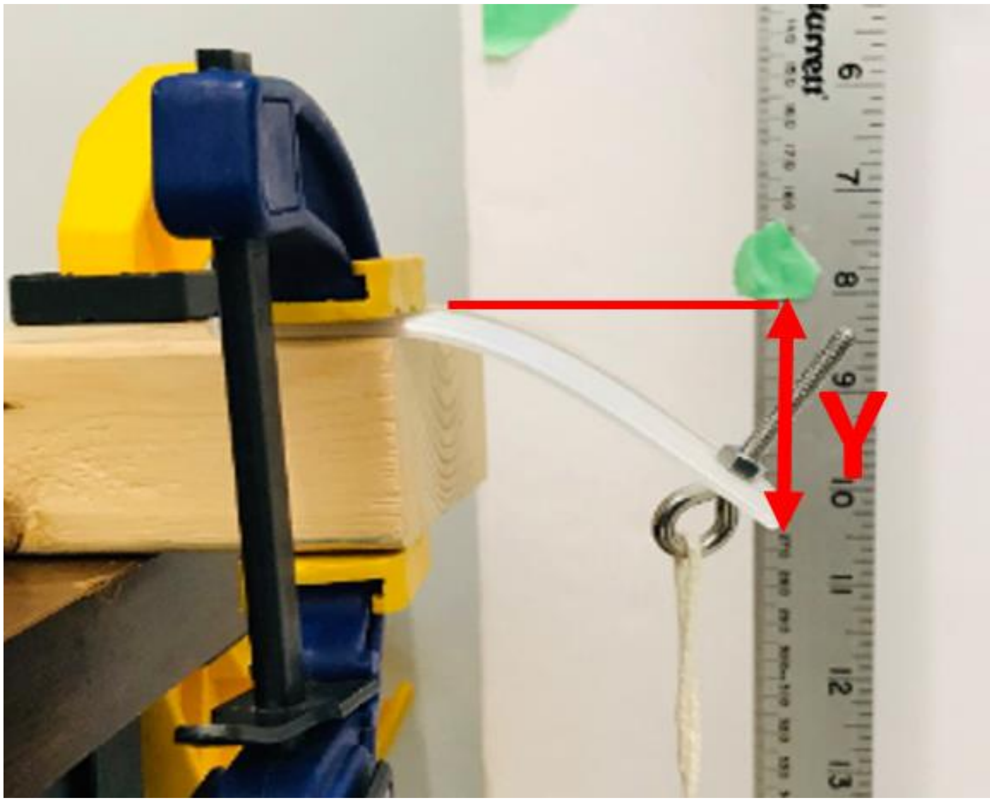


Figure 41: Desired measurement as per load application

Figure 41 shows the deflection (Variable Y) measurement in millimeters as different loads are applied.

G. PP Bending Test Results: Set up #3

PP Bending Test; Set up # 3_ Ultimaker Filament

Table 20: Ultimaker Filament Deflection Table

	Load1 (0g)	**Load2** (200g)	**Load3** (400g)	**Load4** (600g)	**Load5** (800g)	**Load6** (1000g)	
Sample 1	0	9	14	22	27	32	Deflection (mm)
Sample 2	0	6	13	21	27	33	Deflection (mm)
Sample 3	0	8	15	22	29	33	Deflection (mm)
Sample 4	0	5	13	19	28	32	Deflection (mm)
Sample 5	0	6	14	22	27	32	Deflection (mm)
Sample 6	0	7	15	23	28	33	Deflection (mm)

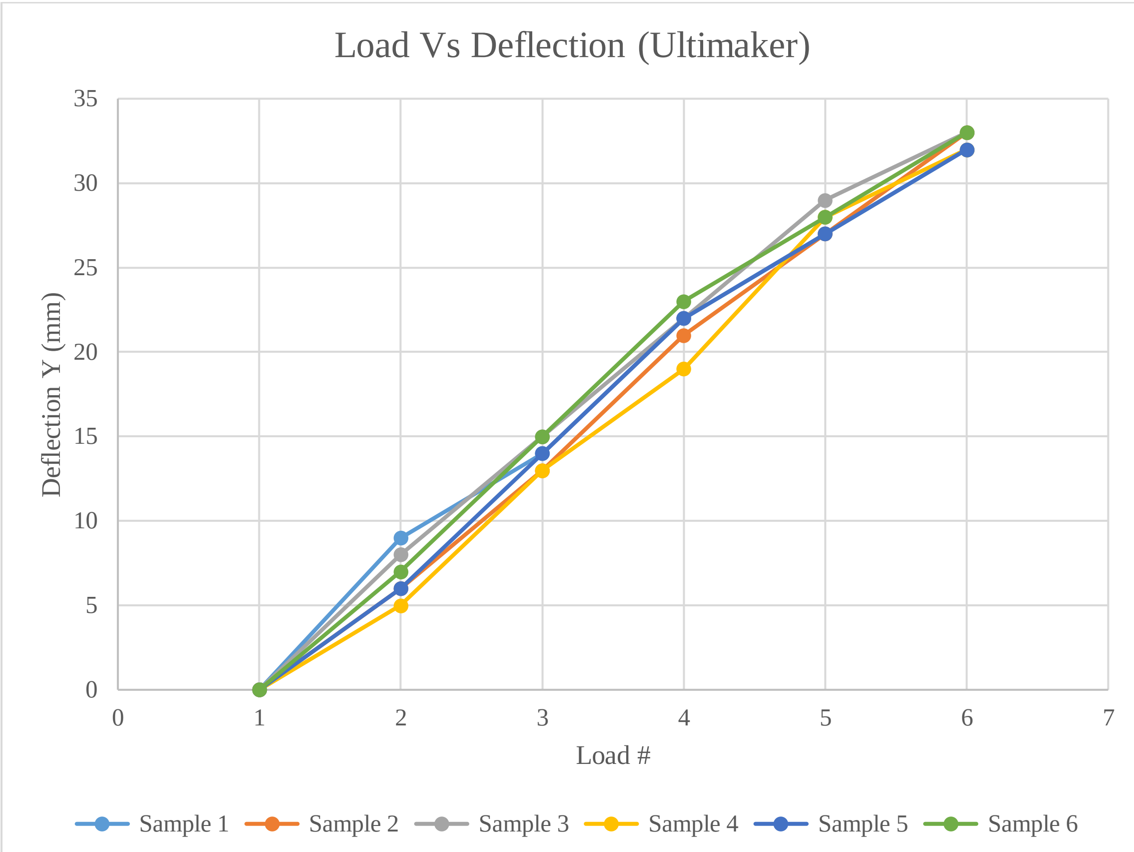


Figure 42: Load Vs Deflection Y (Ultimaker)

Figure 42 depicts the variations of deflections of Ultimaker filament 3D printed PP. The figure shows that in load 2 almost all six samples have different values. With Load 3 and Load 4, the values are closer together, while almost all the values at load 6 are the same with only 1mm difference.

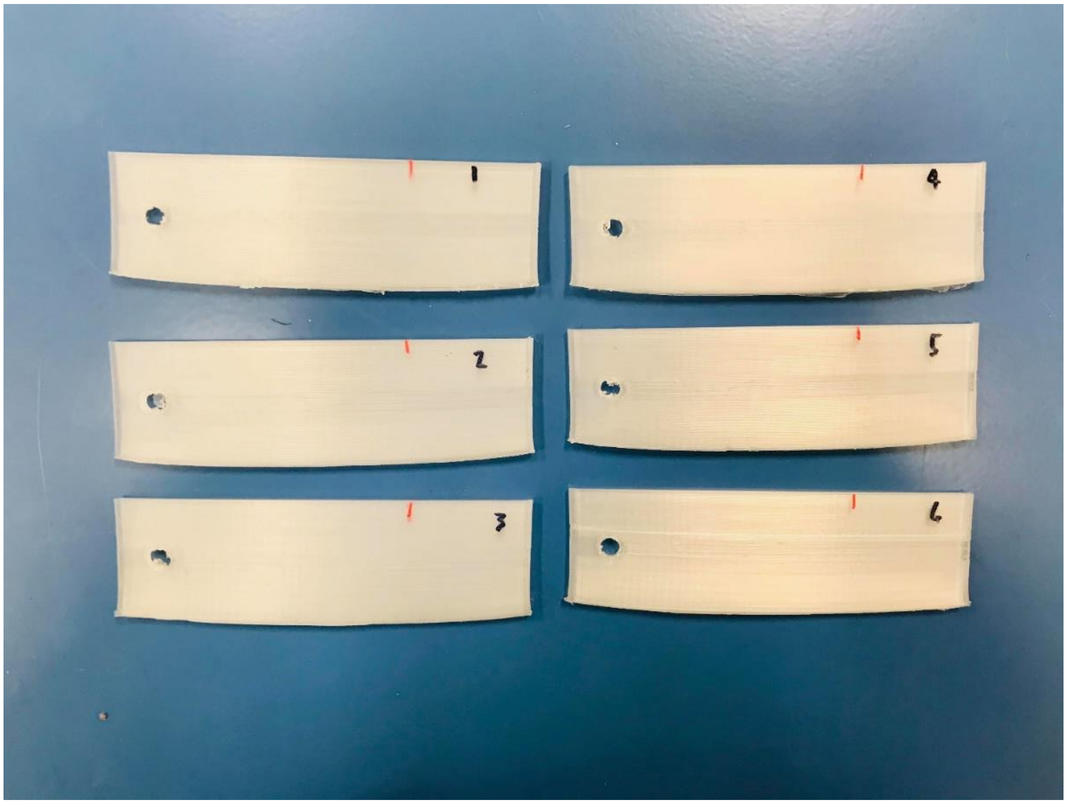


Figure 43: Ultimaker PP 3D Printed Samples

PP Bending Test; Set up # 3_ Formfutura Filament

Table 21: Formfutura Filament Deflection Table

	Load1 (0g)	**Load2** (200g)	**Load3** (400g)	**Load4** (600g)	**Load5** (800g)	**Load6** (1000g)	
Sample 1	0	6	14	21	27	32	Deflection (mm)
Sample 2	0	6	15	22	28	34	Deflection (mm)
Sample 3	0	5	13	19	25	29	Deflection (mm)
Sample 4	0	6	13	20	26	32	Deflection (mm)
Sample 5	0	7	14	23	28	33	Deflection (mm)
Sample 6	0	7	13	21	27	33	Deflection (mm)

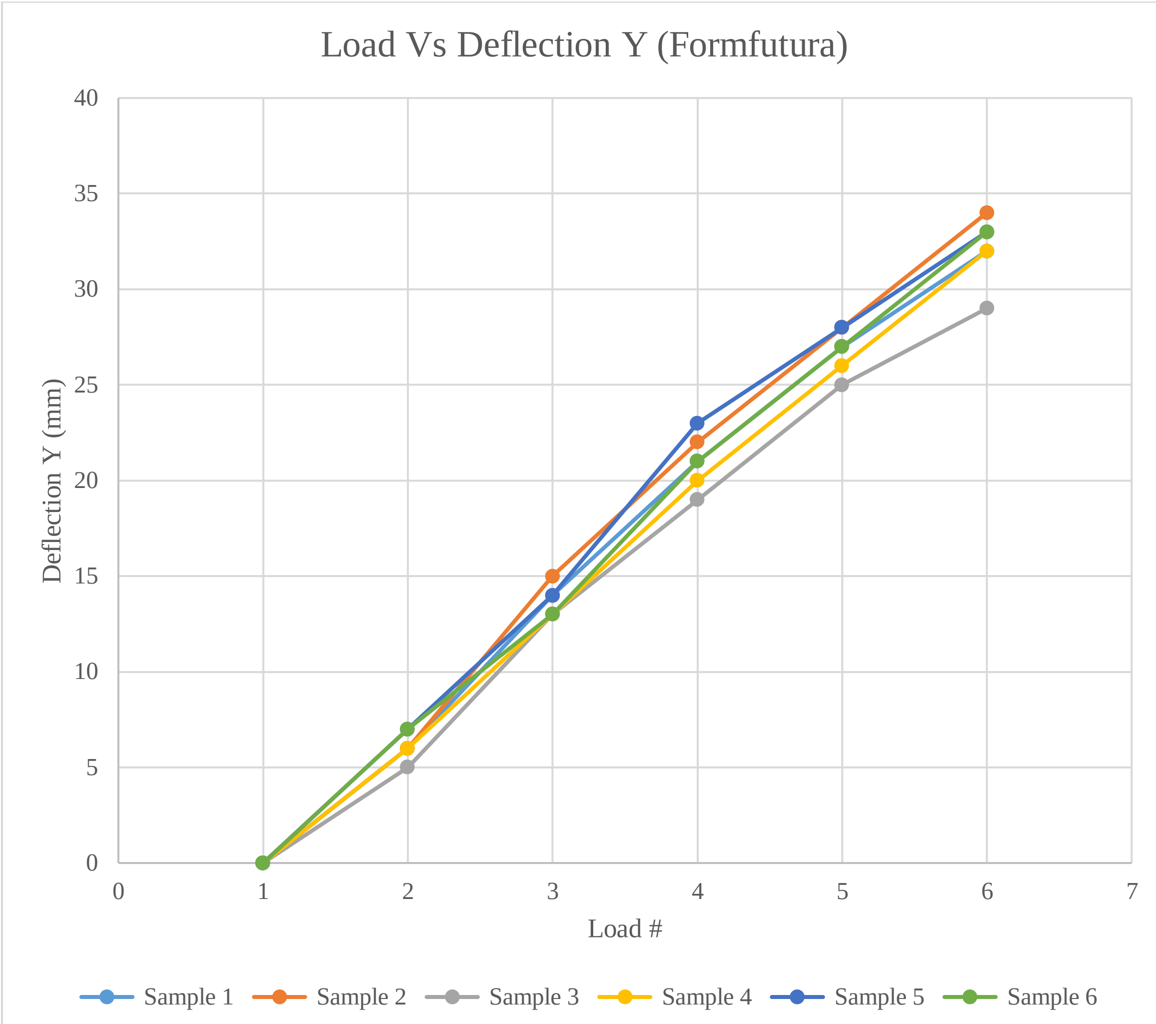
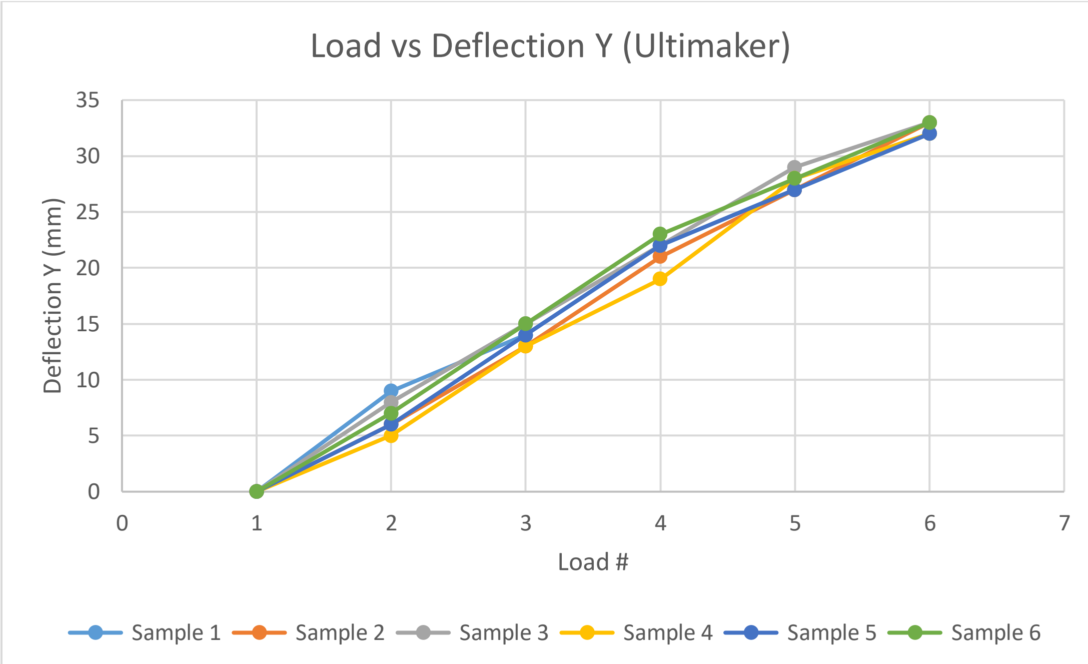


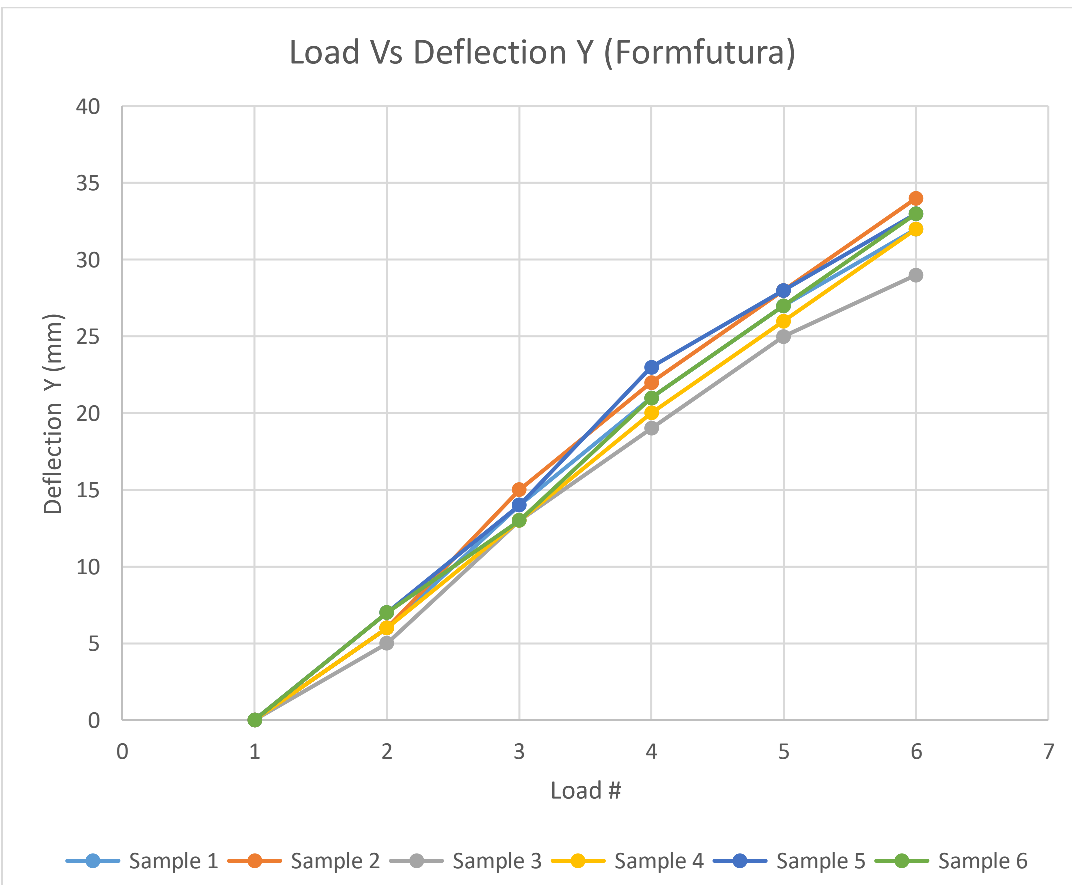
Figure 44: Load vs Deflection Y (Formfutura)

Figure 44 illustrates the behavior of the 3D printed PP sample of Formfutura filament. Load 2 and Load *3* have consist of values that are closer together, however, starting from Load 4 to Load 6 consists of almost all different values. On the other hand, Sample 3 shows to be bending the least in Load 6 compared to all samples.

Figure 45: PP 3D Printed Samples (Formfutura)

Comparison of Ultimaker and Formfutura filaments





The figures above show the variation of deflection Y for Ultimaker and Formfutura filaments. Both filaments have an extremely slight difference in deflection in the same loading. The only visible difference is Sample 3 in Futura filaments that shows significantly low deflection compared to all samples in Load 6. All of these samples are printed in the same printer settings, therefore tracing the cause of the difference in deflection based on printing settings is challenging.

VI. Experiment Summary.

Tensile Testing:

In tensile testing, for PLA materials, side orientation 3D printed samples dominated in terms of mechanical properties in tensile to upright printed ones. The size of the nozzle also plays an important factor in enhancing the strength of the printed part for the bigger the nozzle the higher the tensile strength. The bigger nozzle is preferable when printing bigger design parts as it prints faster. On the other hand, the small nozzle is more practical when printing small parts as it offers provides a better surface finish. As well, the infill density also plays a significant part as it affects the strength of the part. But, in general, for any application in which the part is not required to be strong and the production time is the priority, the smaller value of infill density is preferable.

For PP 3D materials printed from 0.6mm diameter nozzle, upright orientation shows better printing procedures to enhance the strength of the 3D printed parts.

Bending Testing:

In bending testing of PLA 3D printed samples, Side printed Wide-side clamped show highest loads in most of the samples, while Upright printed Short Clamped show mostly the lowest values of all. Side printed Short-side Clamped show almost consistent values that range between 4.00 Kg and 5.00 Kg. On the other hand, Upright printed Wide-side Clamped show unpredictable breaking loads.

For PP 3D printed samples, Ultimaker and Formfutura show predictable bending deflection as an interval of loads applied. The difference in mechanical behavior is extremely small to determine the exact reasons or factors that might account for the difference of deflection. Both filament materials projected similar bending deflections.

Problems Encountered during experimentations:

As an Extensometer is required for small displacement samples in bending testing, the instrumentation should be set to extensometer to let the MTI machine use the data from the extensometer for the calculation to get accurate results. In the MTI manual, some items have no definitions, contacting MTI is important to make sure that one is using the correct values.

VII. Conclusion

Based on the results presented above, the materials, print orientations, nozzle sizes, and infill density in 3D printing technology play a vital role when determining the strength of the 3D printed design parts. The experiment results presented in this project thesis can be utilized as a possible starting point to determine the strength of a specific 3D printed part in 3D printing technology.

PLA material shows high ultimate tensile stress and Young's Modulus, however, at maximum load they snapped and broke. On the other hand, PP material samples show better flexibility and elasticity, which can add comfort to the patients and a safer option as they do not break easily.

Therefore, PP may be suitable for the utilization of scoliosis braces, but further testing is required as 3D printing produces a non-homogeneous design part, so the properties of strength and young's modulus are different in different print orientations.

VIII. Recommendation for Future Work

In this project, tensile testing and bending testing are conducted for PLA and PP. For future work, compressive testing and impact testing can be explored as well. Another 3D printing parameter that warrants further exploration is the different effects of infill density. One can manipulate this parameter as this has a directly proportional relationship with the material strength. Specifically, as the percentage of infill density decreases, the strength also decreases. But, it is also important to consider that decreasing the infill percentage also decreases printing time and cost. Another recommendation is to explore the effects of the numerous infill patterns available in Cura as it is believed that as the pattern changes the strength also changes accordingly.

As the material being tested is for scoliosis braces, the comfort of the patient as it relates to the flexibility of the material and the overall design is also worth exploring because it plays a significant role in whether or not a patient chooses scoliosis braces or other remedies. Some remedies for scoliosis have been explored by different inventors. The pain that is supposedly caused by wearing scoliosis braces has been used by an advertisement as a drawback and instead encourage the consumers to try the products they are advertising. One advertisement states, "Full-time bracing often causes more problems for the person wearing it, such as pain that didn't exist before, breathing problems, and weakened muscles. It hasn't been consistently proven to prevent scoliosis surgery, either."[8]. The braces are aimed to help manage and prevent the progression of patient's scoliosis, therefore the materials utilized for the production of braces play a significant role in ensuring patient comfort and the possible prescription of braces. Another recommendation pertains to the production of 3D printed scoliosis braces with composite materials and exploring the characteristics of the design, including comfort, safety, flexibility, durability, performance, cost, and more.

End of the Report

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Appendix

H. PLA 0.4mm diameter nozzle, 100% Infill, Side printed

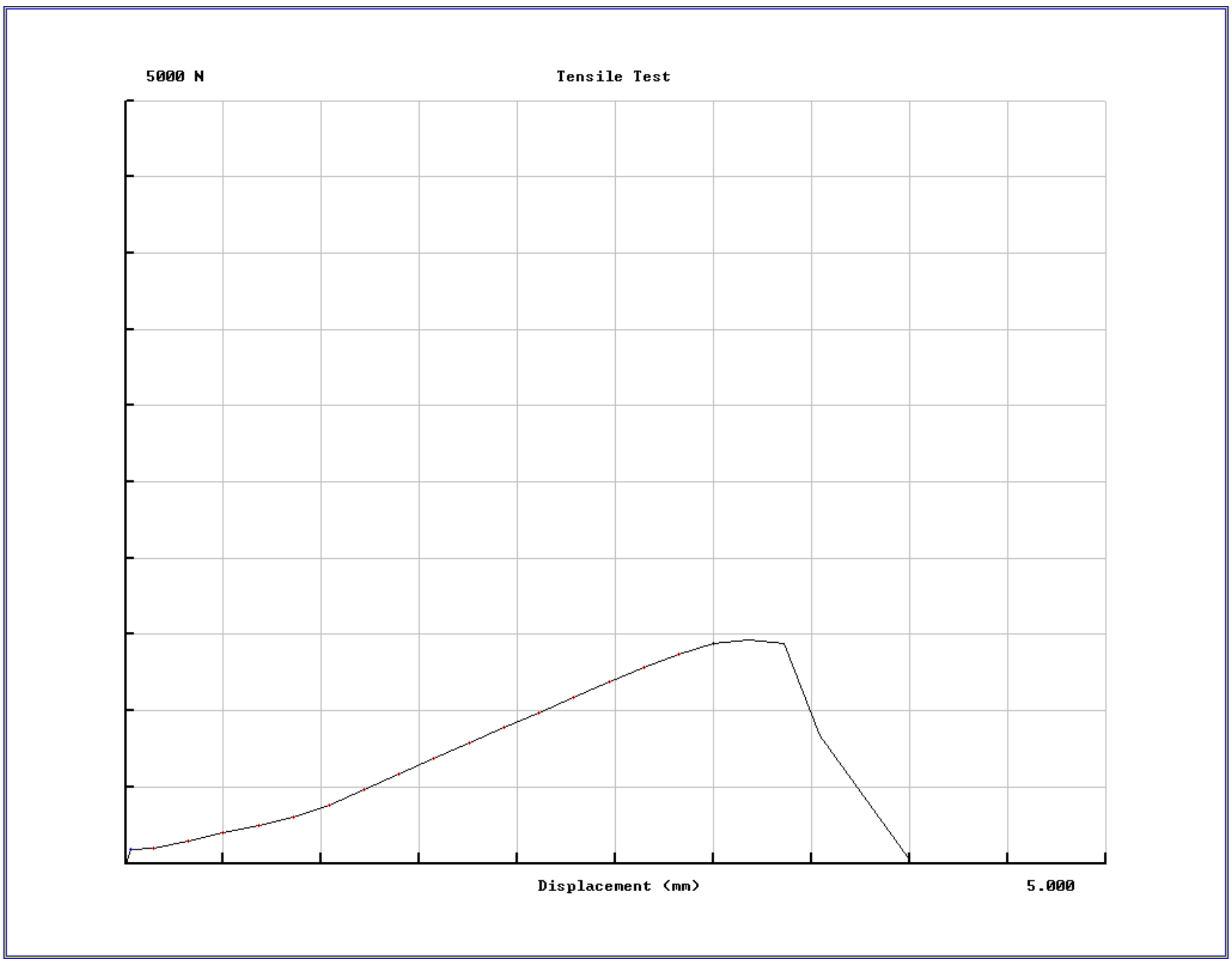


Figure 46: 0.4_S-100-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Diameter (mm)
PLA	2547.04	1462.08	46.61	0.4	4.01	Side	6.32

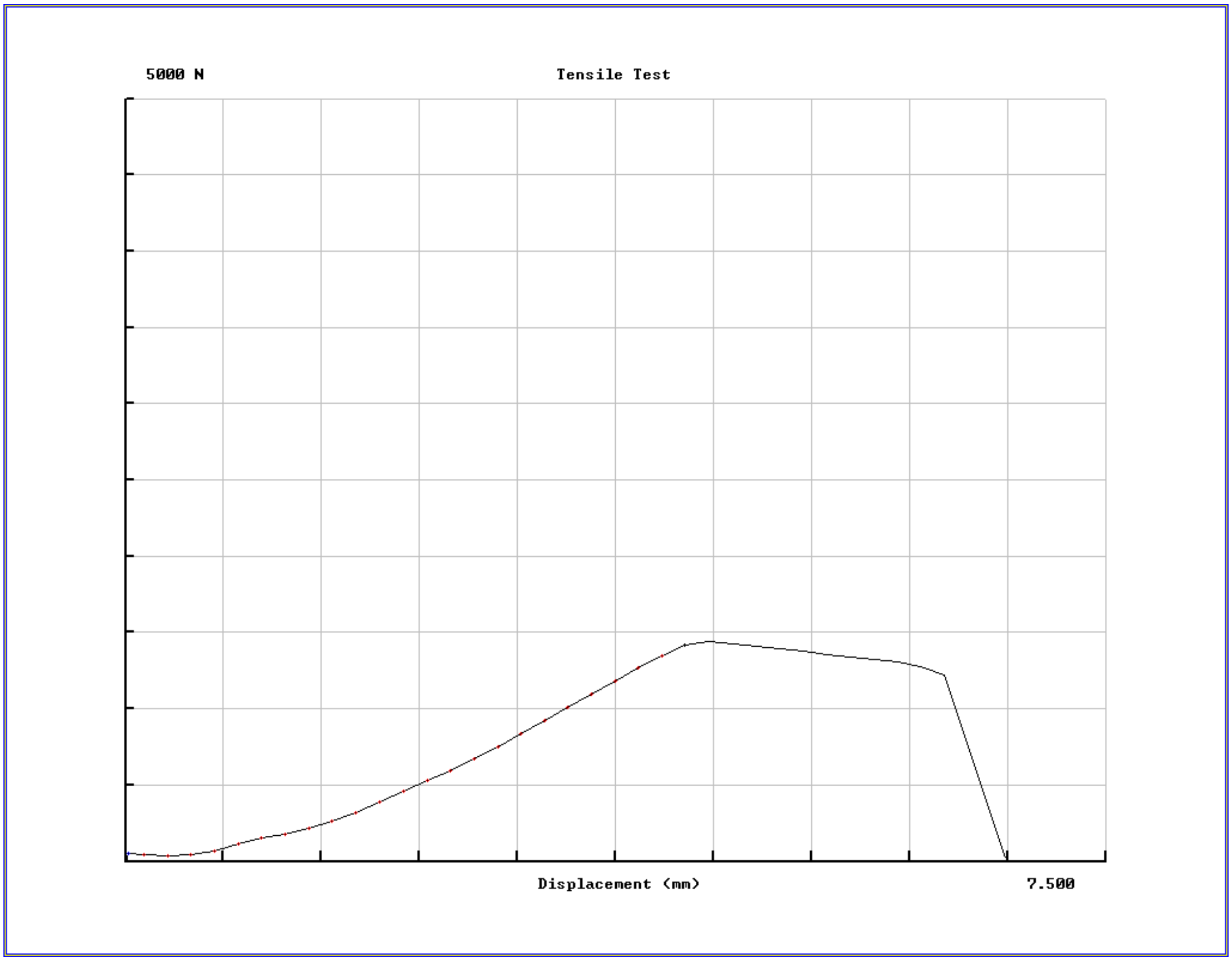
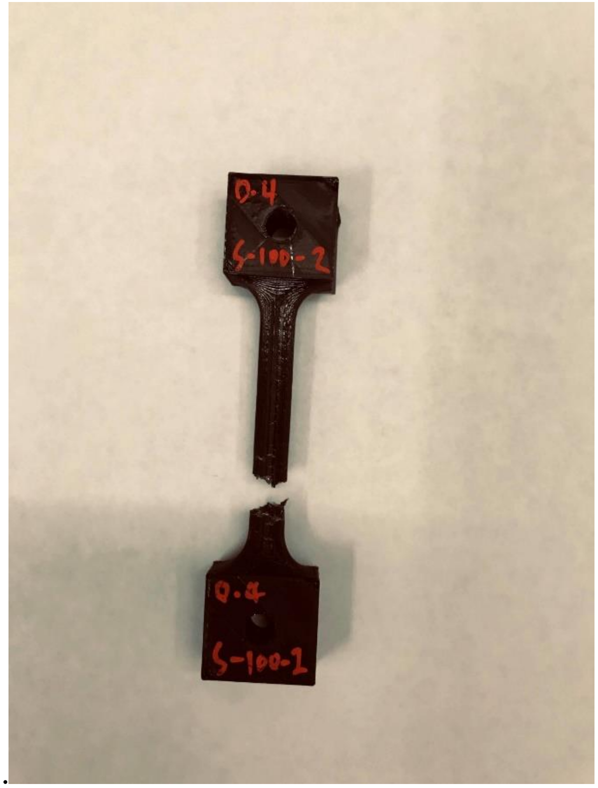


Figure 47: 0.4_S-100-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2537.69	1437.92	46.13	0.4	6.74	Side	6.3


0.4
S-100-2
0.4
S-100-2
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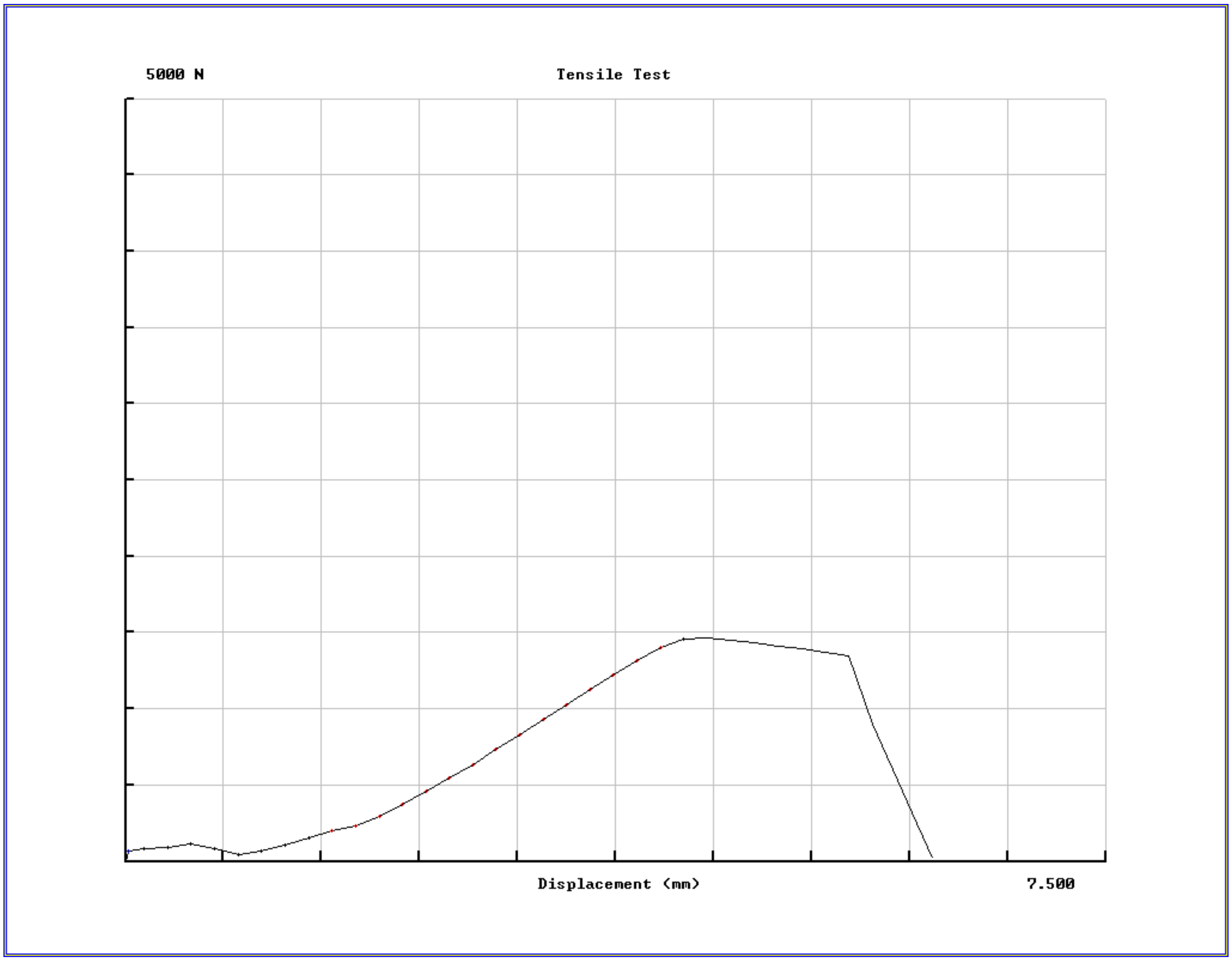


Figure 48: 0.4_S-100-3

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2508.23	1467.38	46.33	0.4	6.18	Side	6.35


0.4
S-100-3
0.4
S-100-3

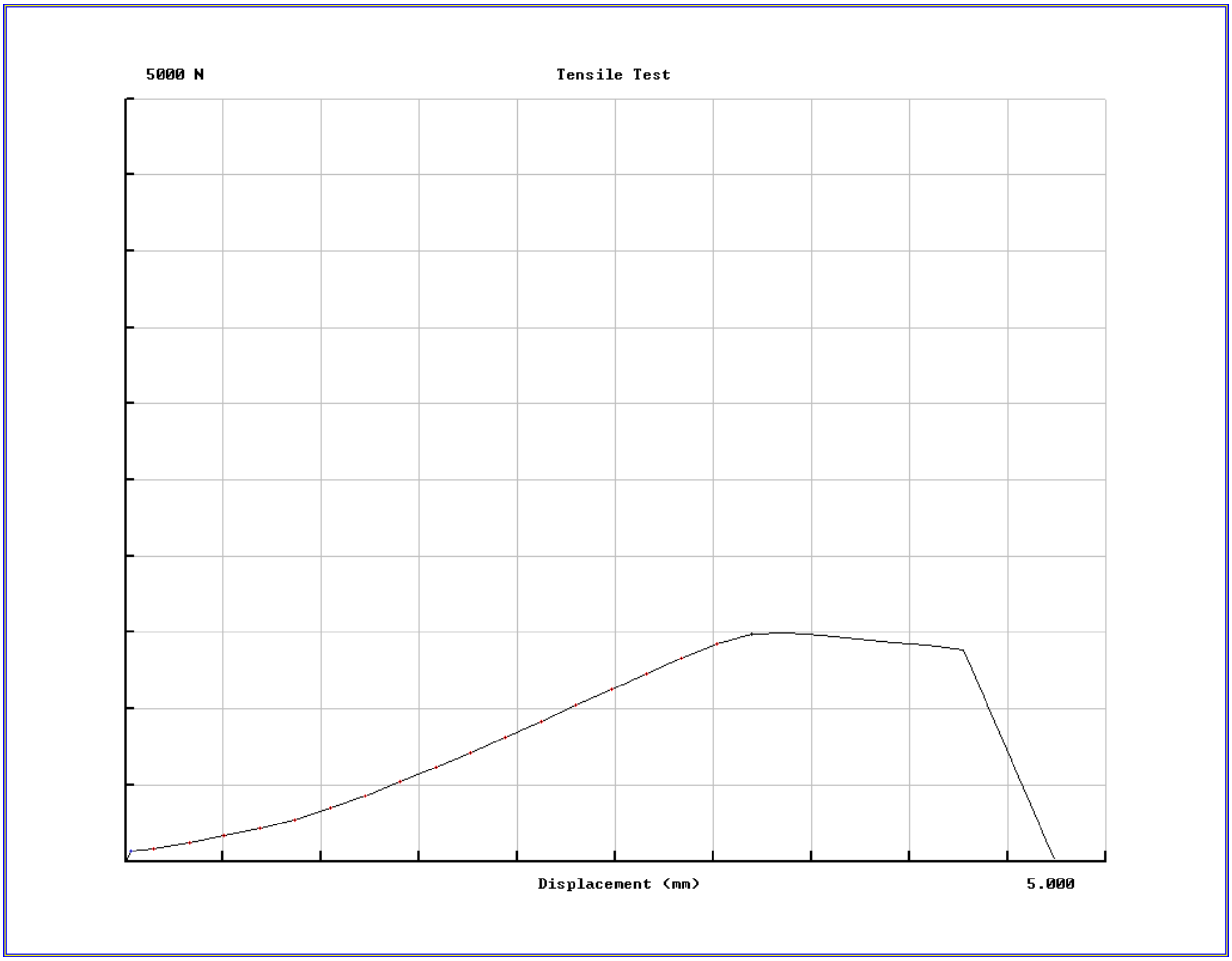
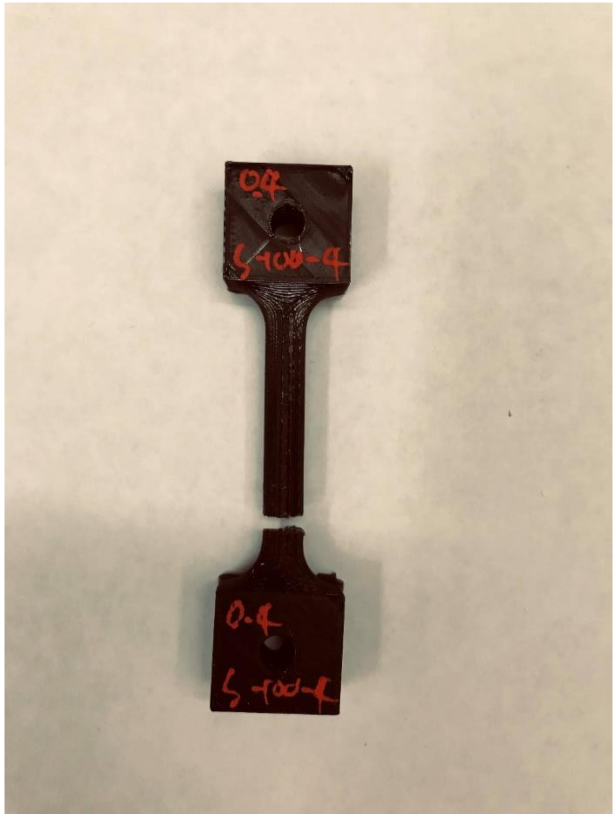


Figure 49: 0.4_S-100-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2532.41	1496.57	48.01	0.4	4.74	Side	6.3



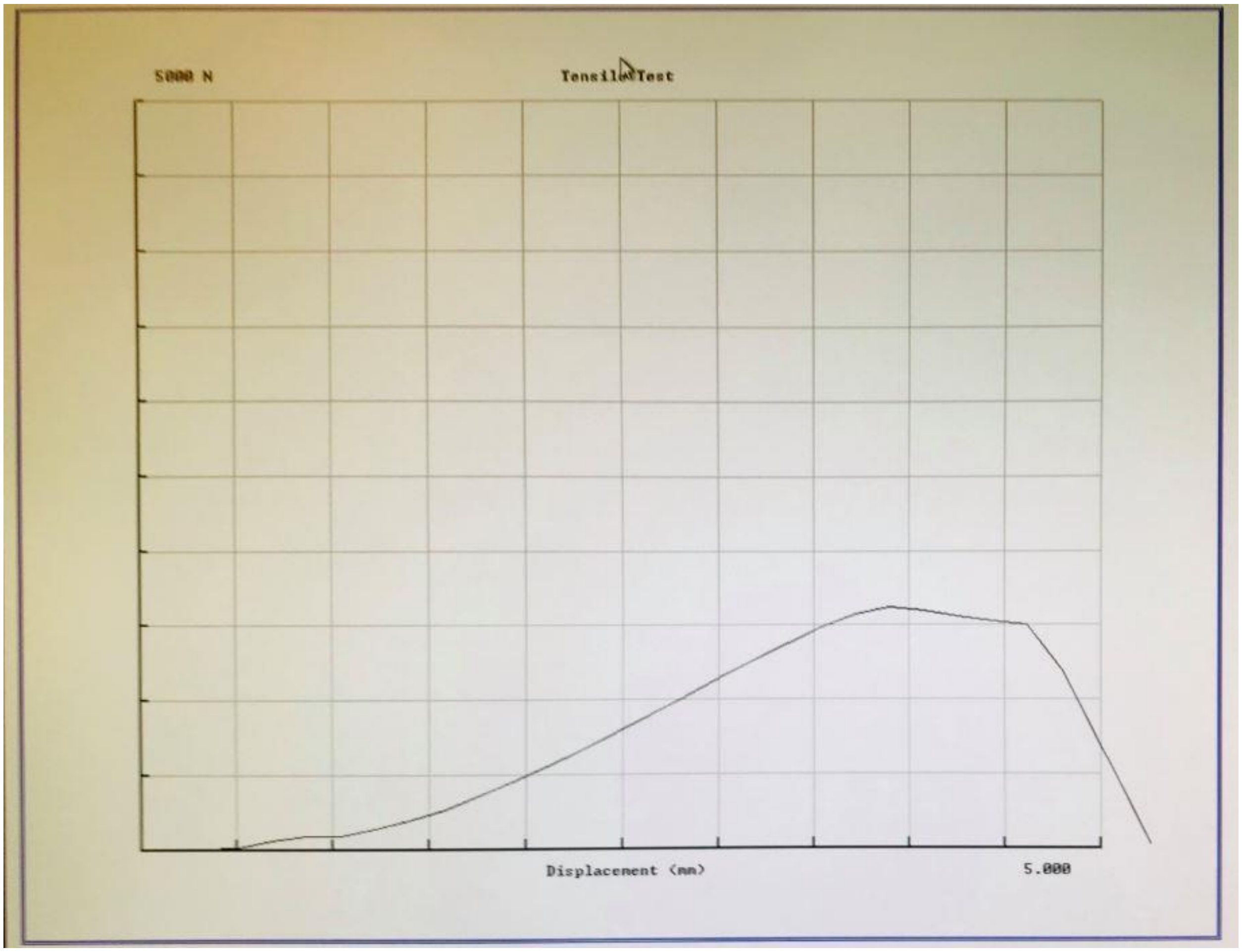


Figure 50: 0.4_S-100-5

Material	**Young's Modulus (N/mm^2)**	**Rupture Force (N)**	**Ultimate Stress (N/mm^2)**	**Nozzle Size (mm)**	**Displacement (mm)**	**Print Orientation**	**Sample Diameter (mm)**
PLA	3181.84	1617.63	51.08	0.4	5.27	Side	6.35


0.4
S-100-5
0.4
S-100-5

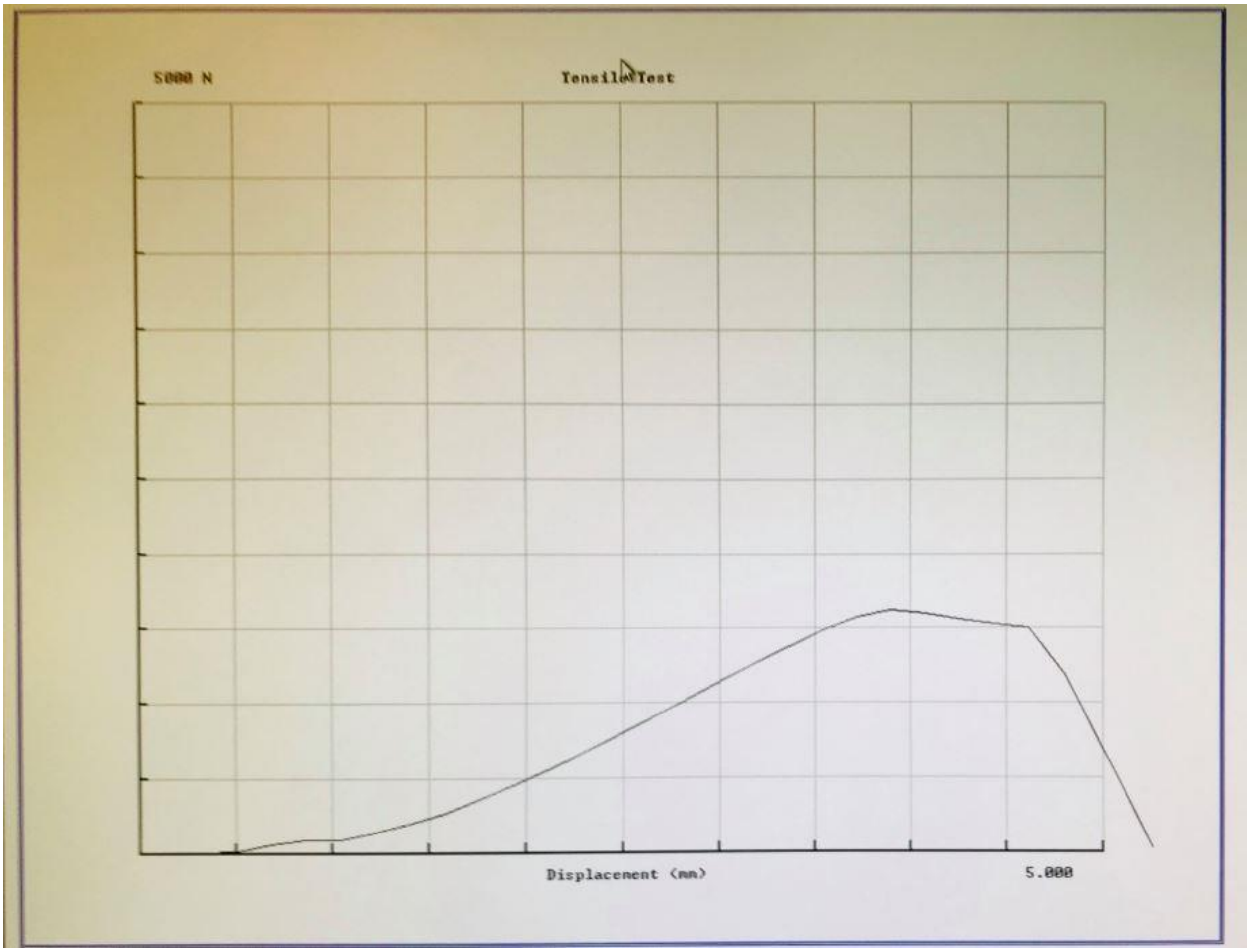


Figure 51: 0.4_S-100-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3197.69	1535.09	48.47	0.4	5.09	Side	6.35


S-100-6

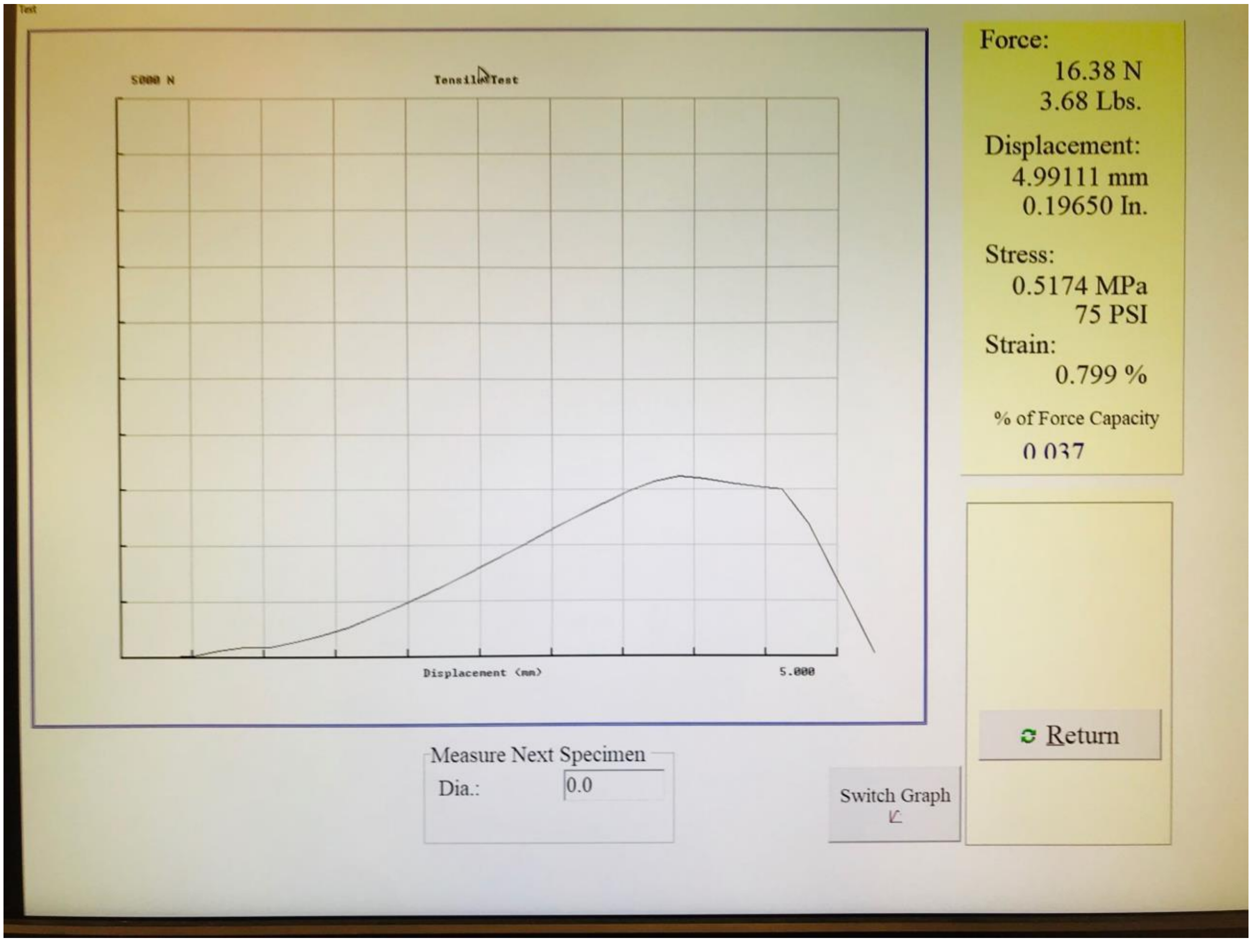
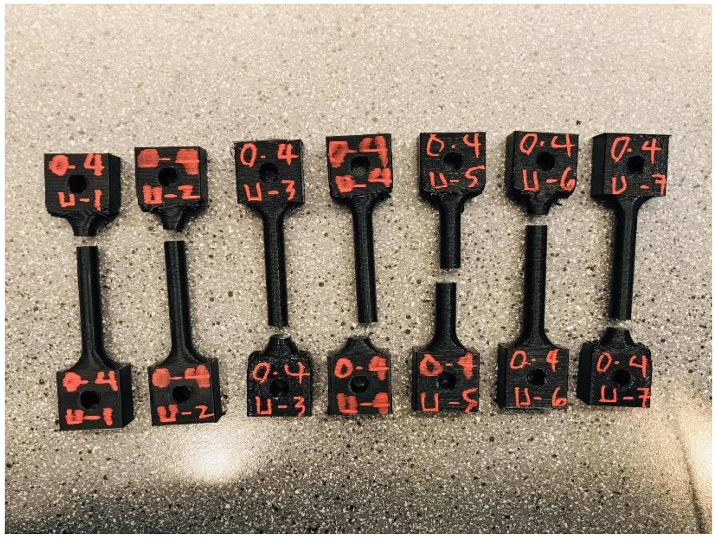


Figure 52: 0.4_S-100-7

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2976.57	1514.97	47.84	0.4	5.52	Side	6.35

I. PLA 0.4mm diameter nozzle, 100% Infill, Upright printed



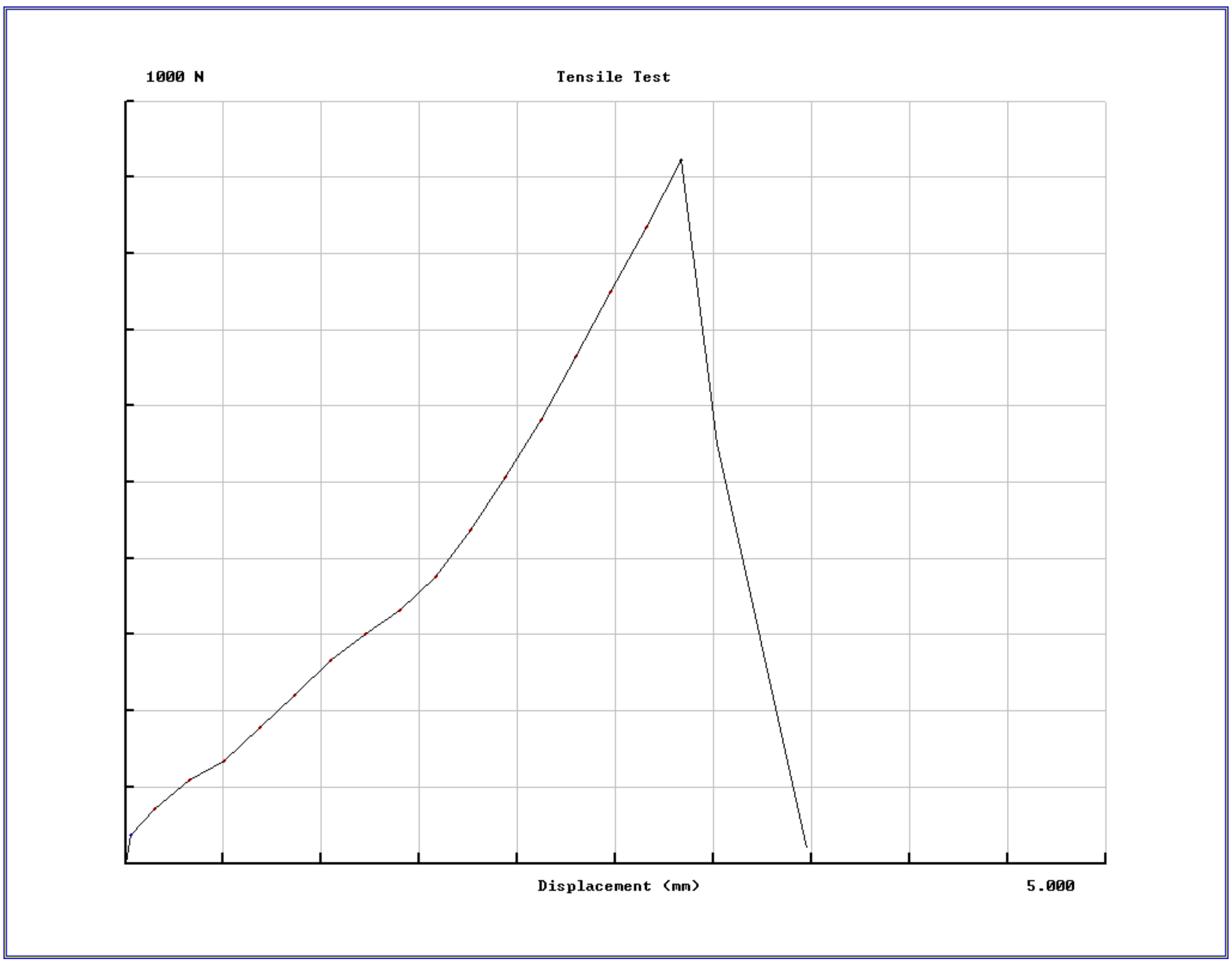
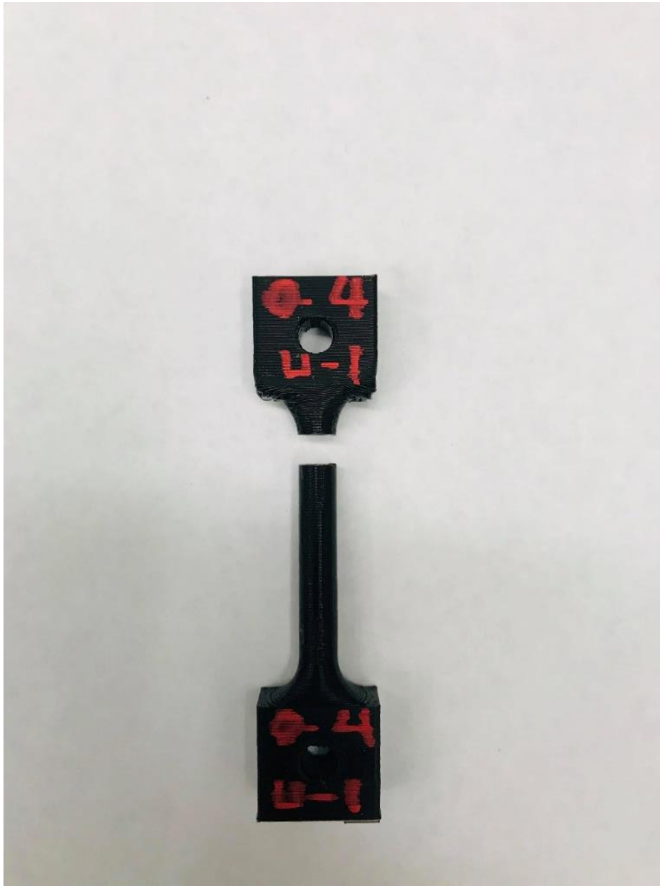


Figure 53:0.4_U-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3104.31	921.63	31.54	0.4	3.47698	Upright	6.1



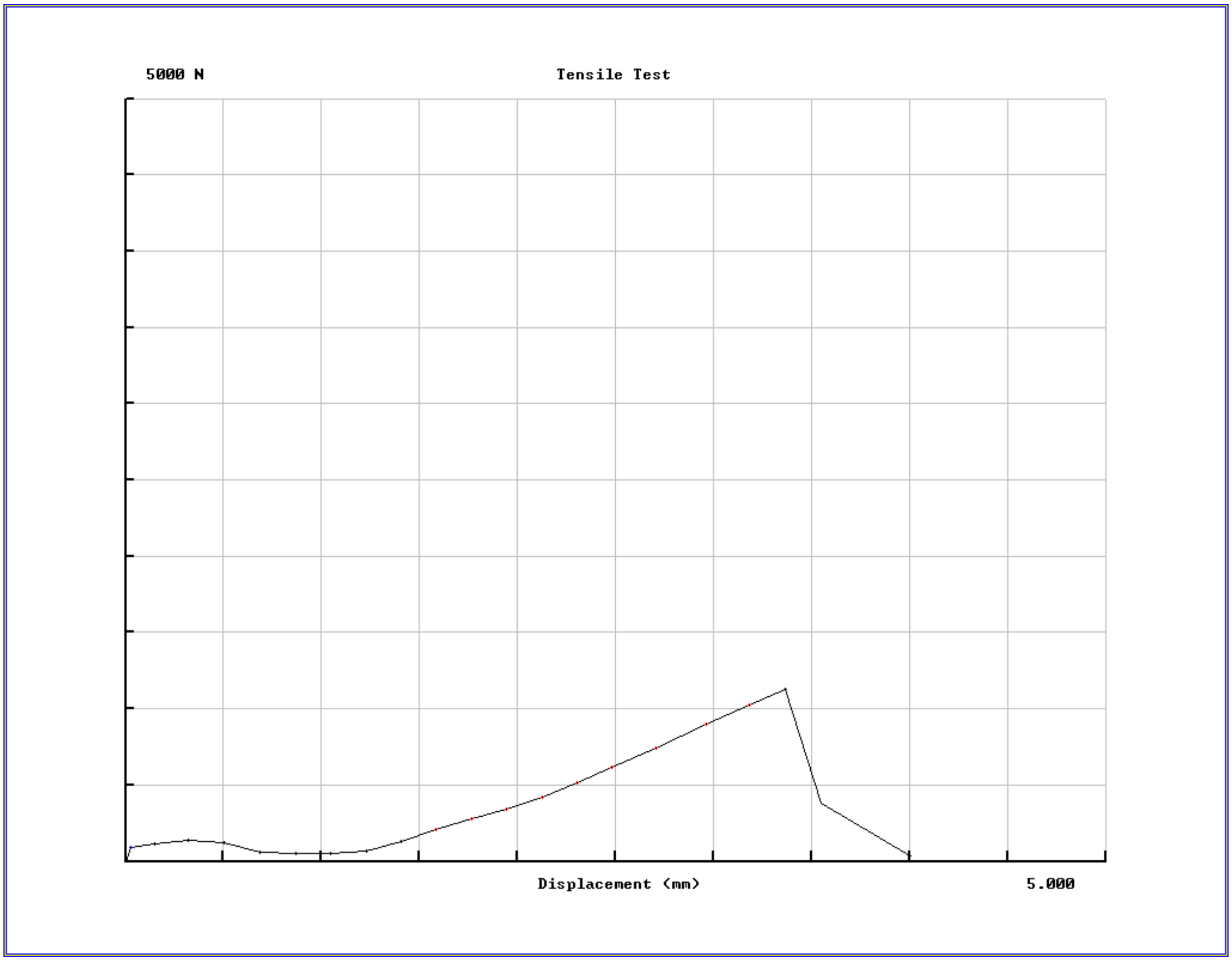


Figure 54: 0.4_U-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2847.19	1125.37	37.52	0.4	4.0123	Upright	6.18

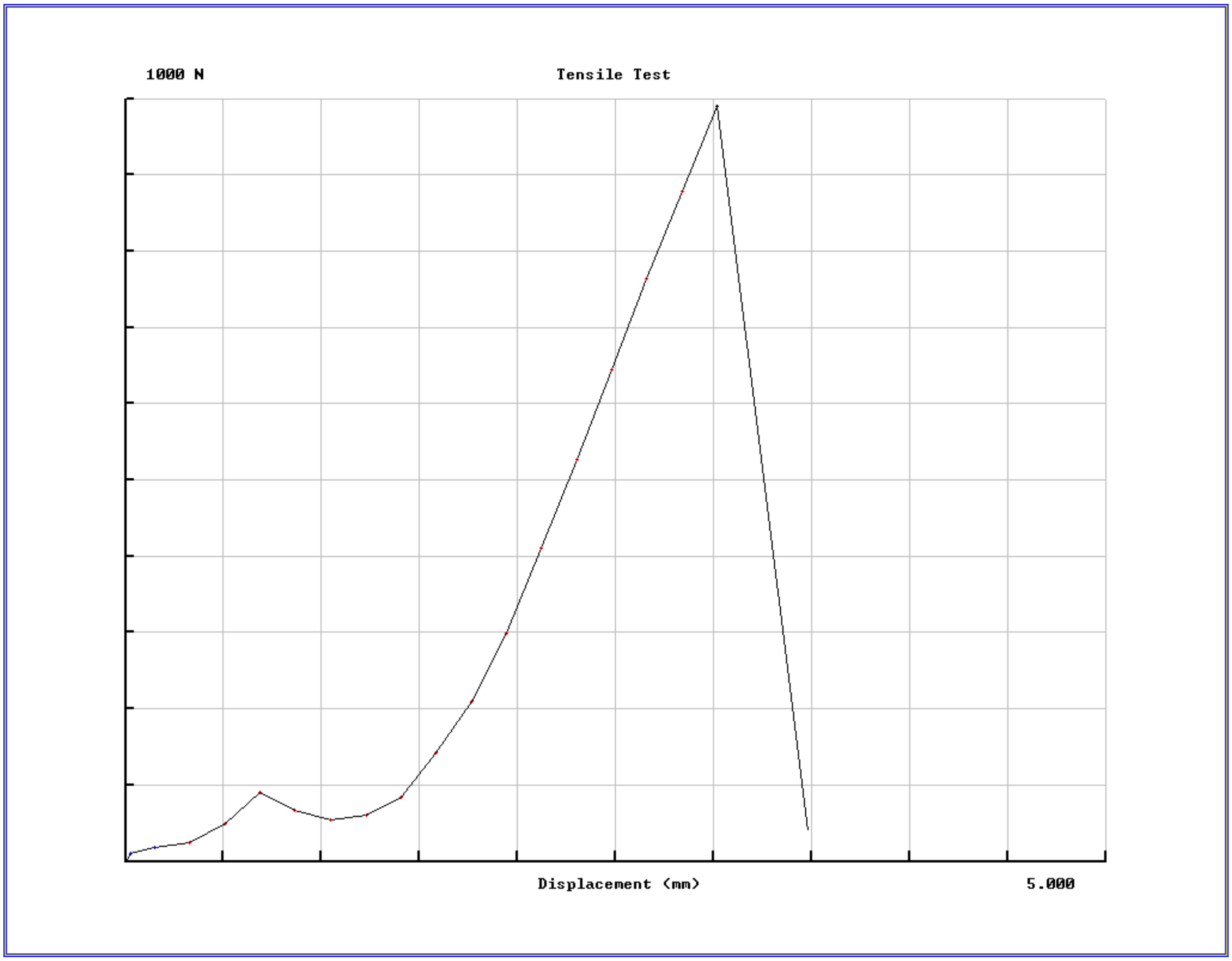
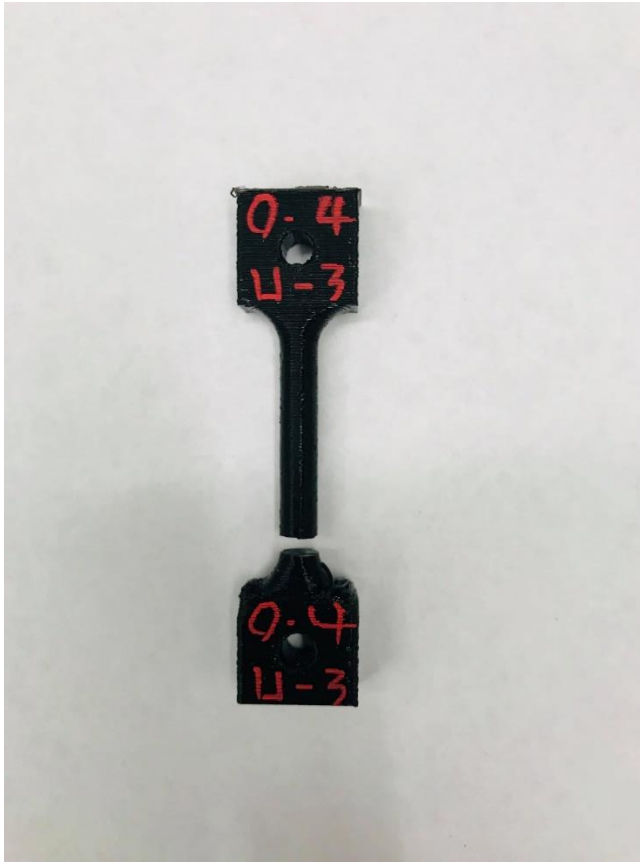


Figure 55: 0.4_U-3

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3214.71	989.99	31.36	0.4	3.48198	Upright	6.34


0.4
U-3
0.4
U-3

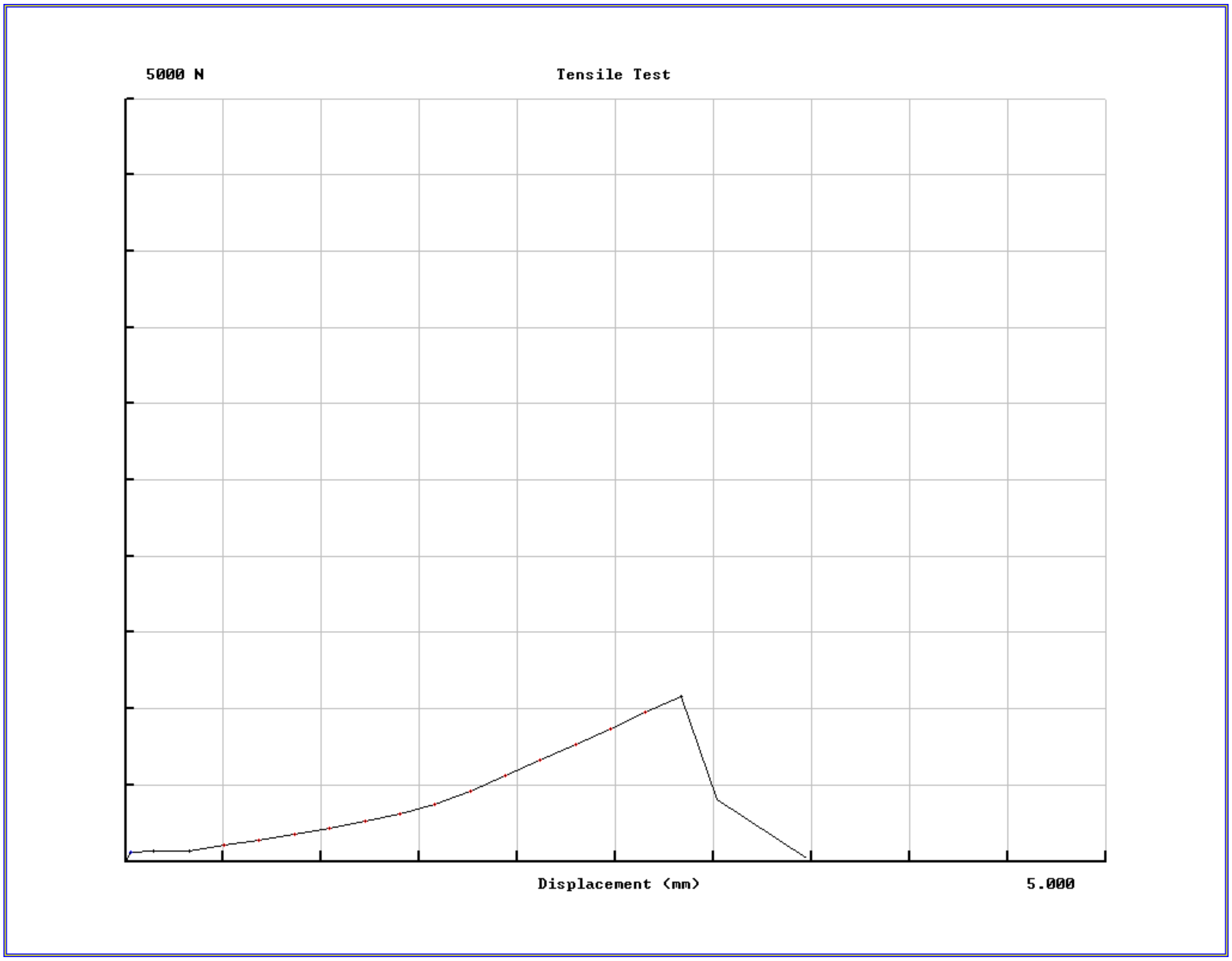


Figure 56: 0.4_U-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3469.85	1076.15	35.64	0.4	3.48	Upright	6.2


0-4

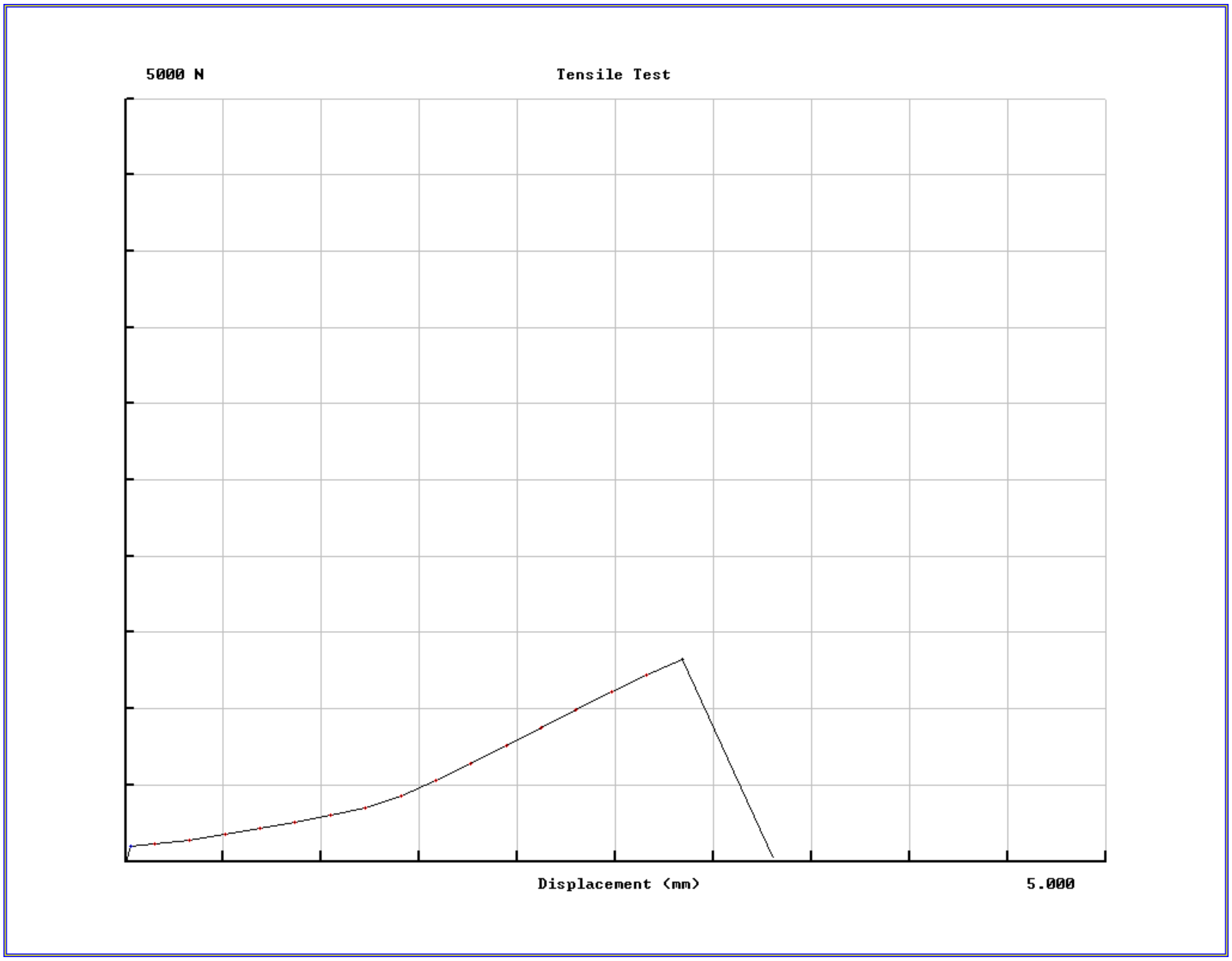


Figure 57: 0.4_U-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2633.3	1321.74	41.34	0.4	3.30362	Upright	6.38


0-4
U-5
0-4
U-5

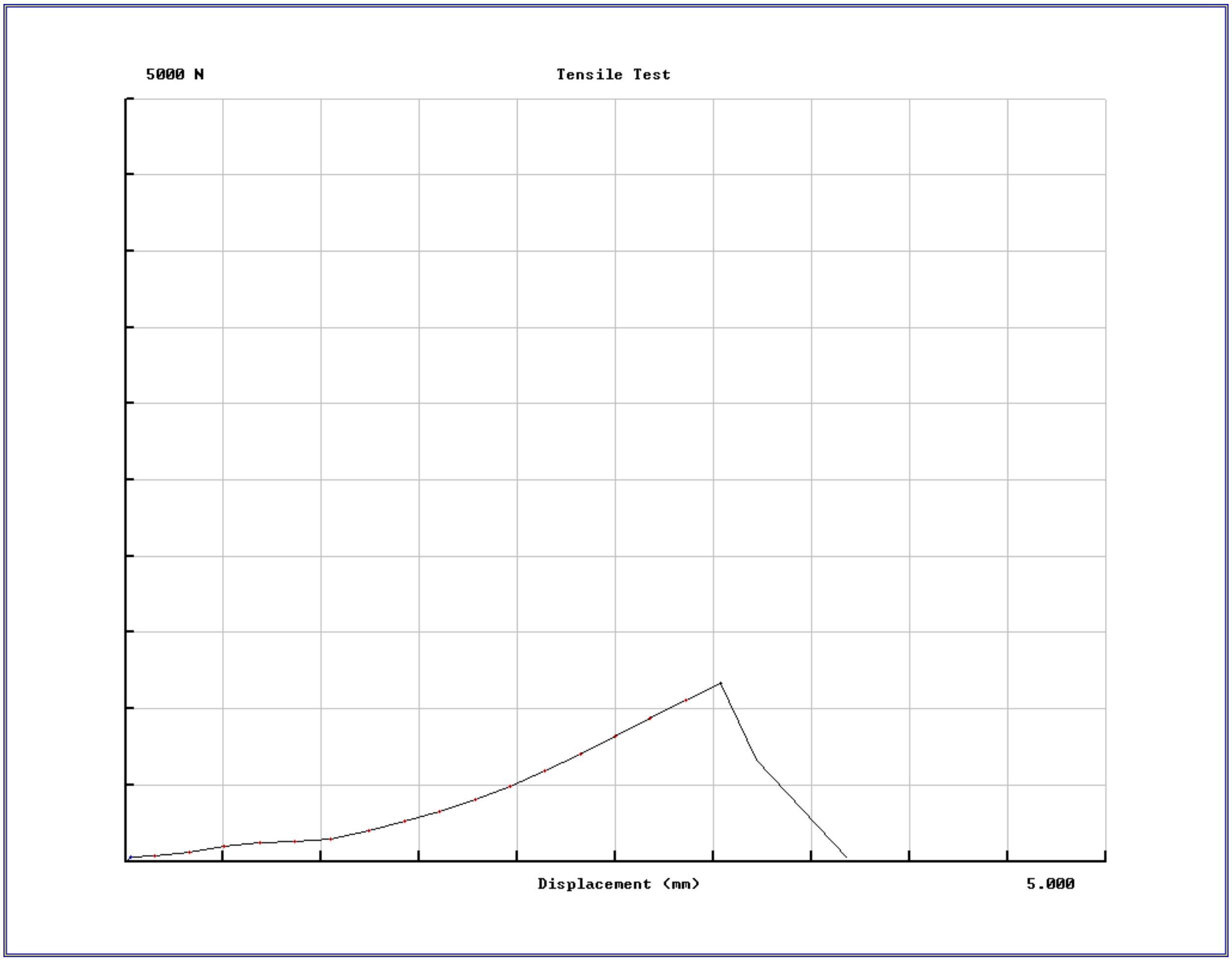
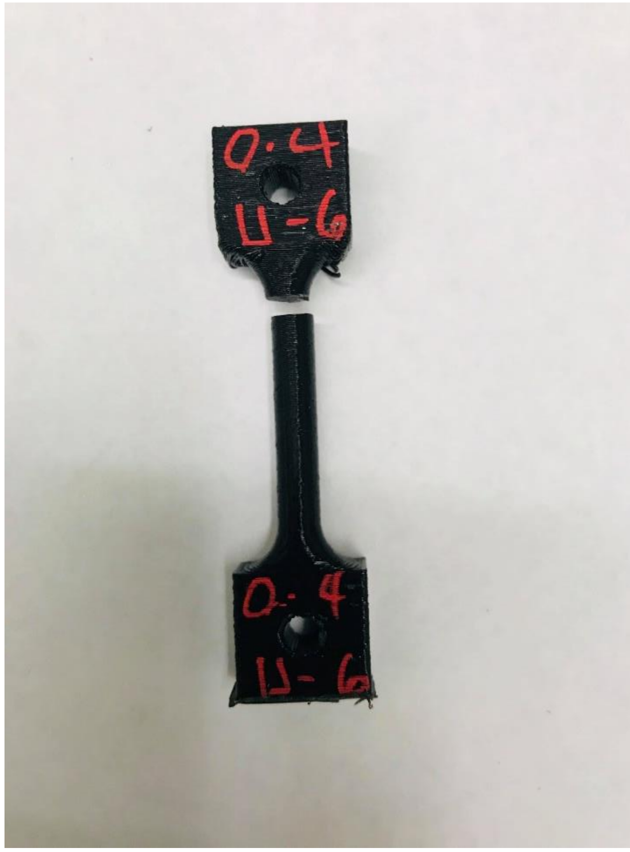


Figure 58: 0.4_U-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2785.26	1164.92	36.1	0.4	3.68177	Upright	6.41


0.4
0.4

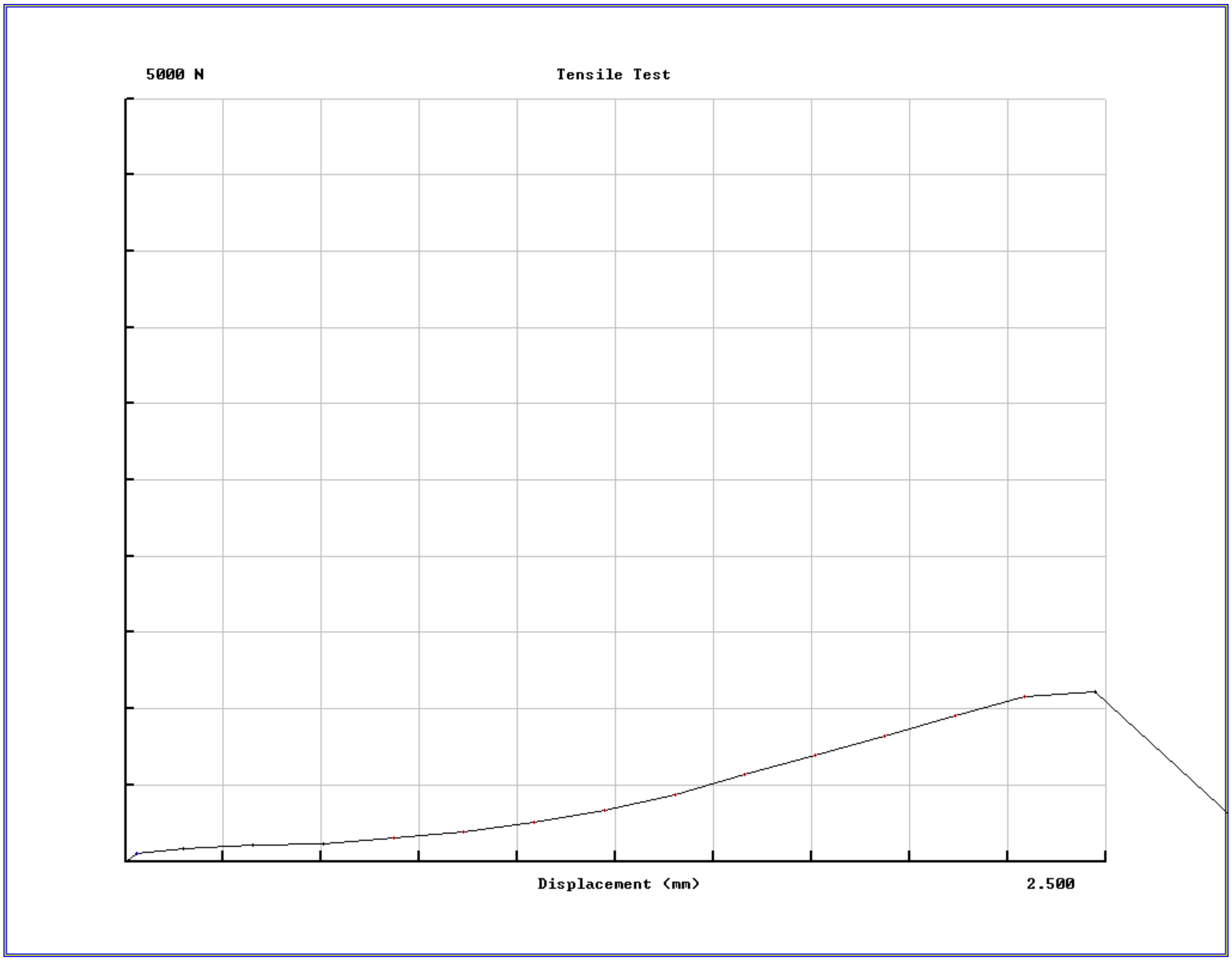


Figure 59: 0.4_U-7

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2643.33	1112.11	34.04	0.4	2.93531	Upright	6.45


0.4
U-7
0-4
U-7

J. PLA, 0.6mm diameter nozzle, 100% Infill, Side printed

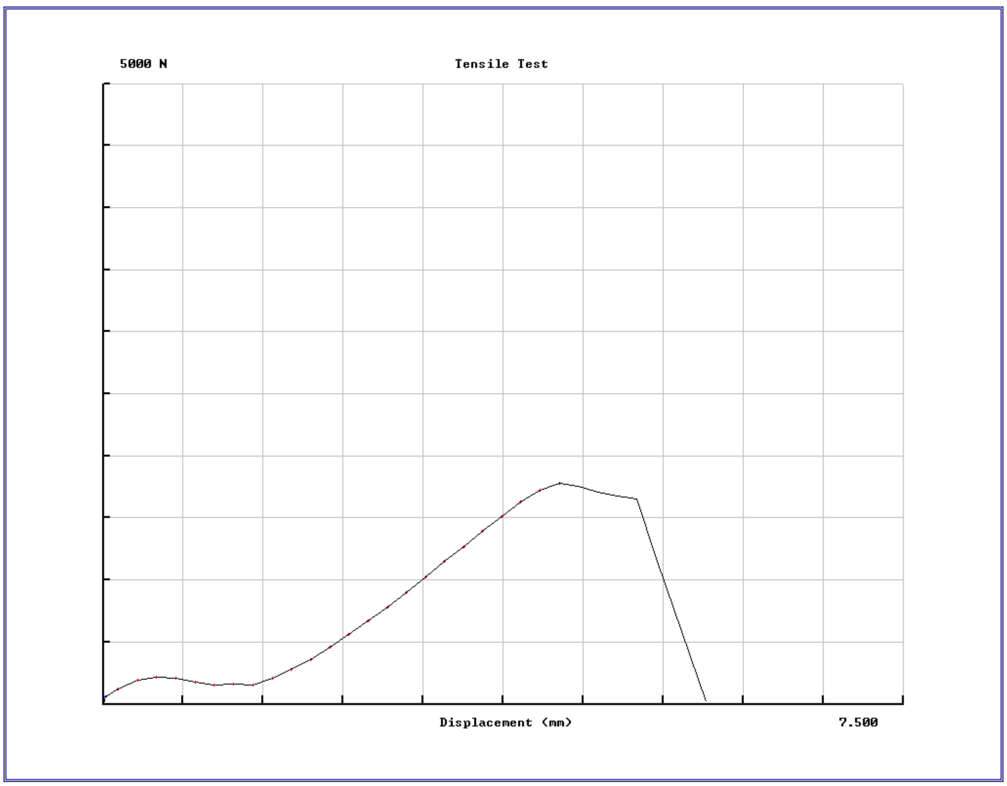


Figure 60: 0.6_S-100-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3129.96	1777.32	56.12	0.6	5.65	Side	6.35

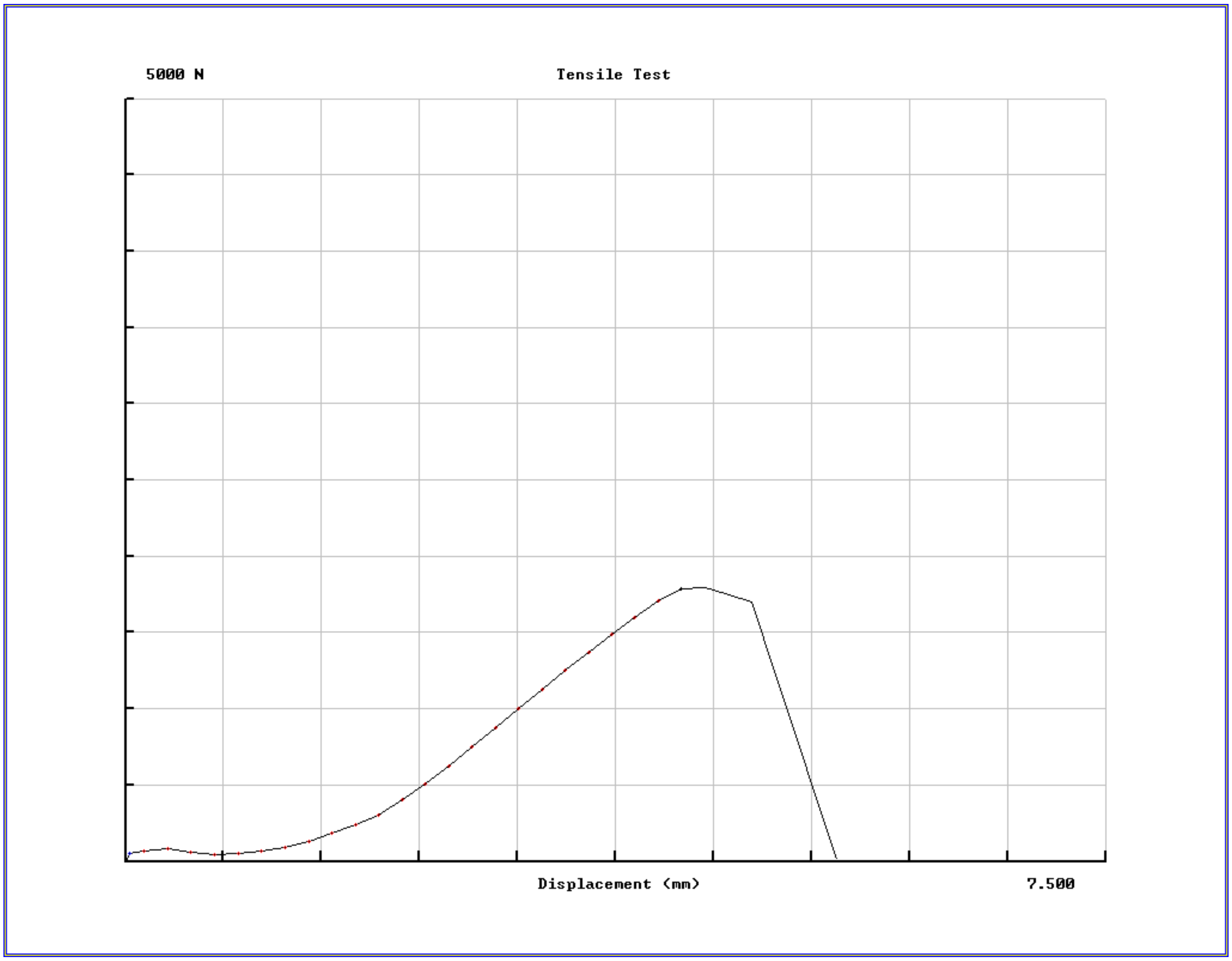


Figure 61: 0.6_S-100-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3100.30	1795.13	55.80	0.6	5.45	Side	6.4

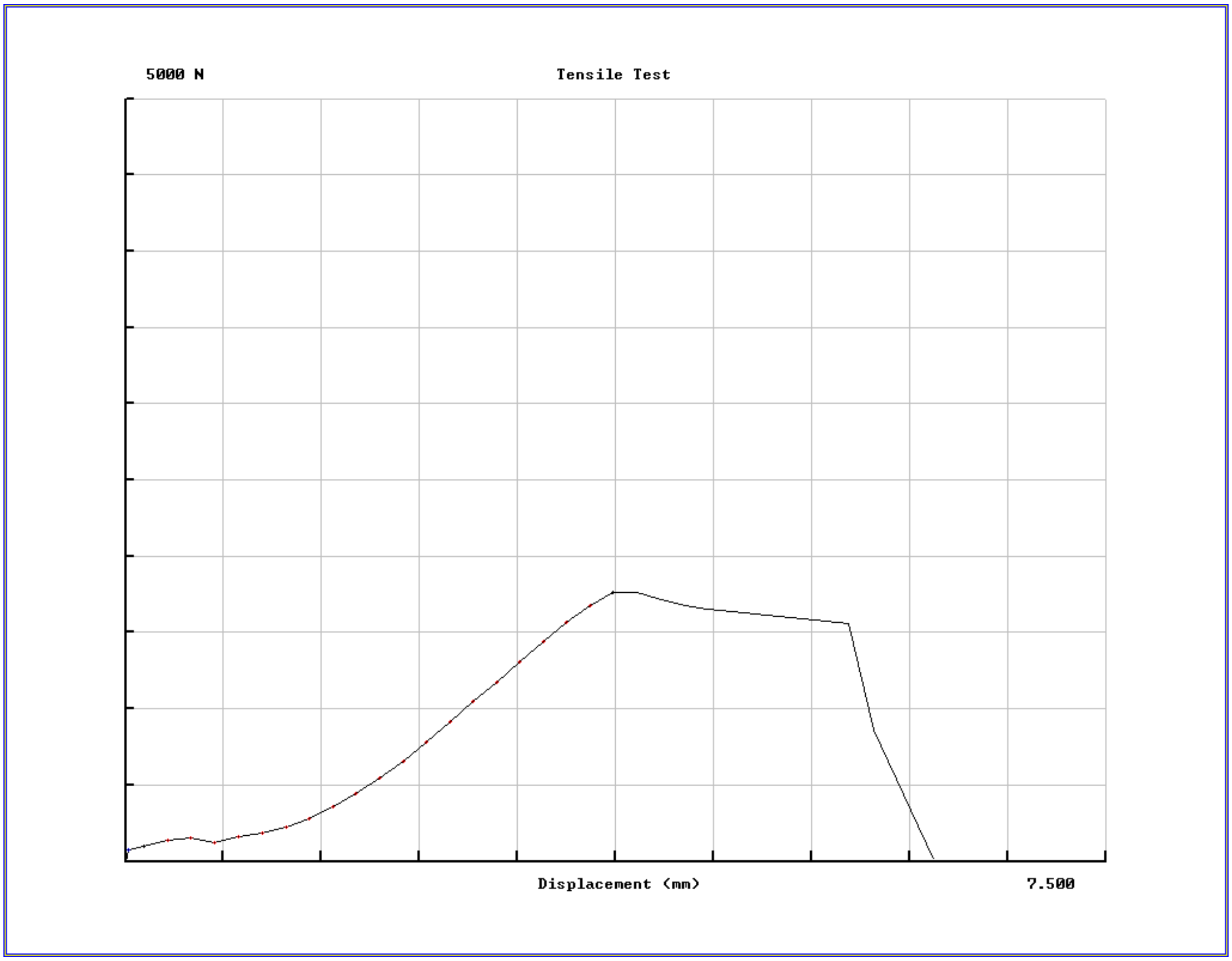


Figure 62: 0.6_S-100-3

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	3071.09	1761.90	55.63	0.6	6.19	Side	6.35

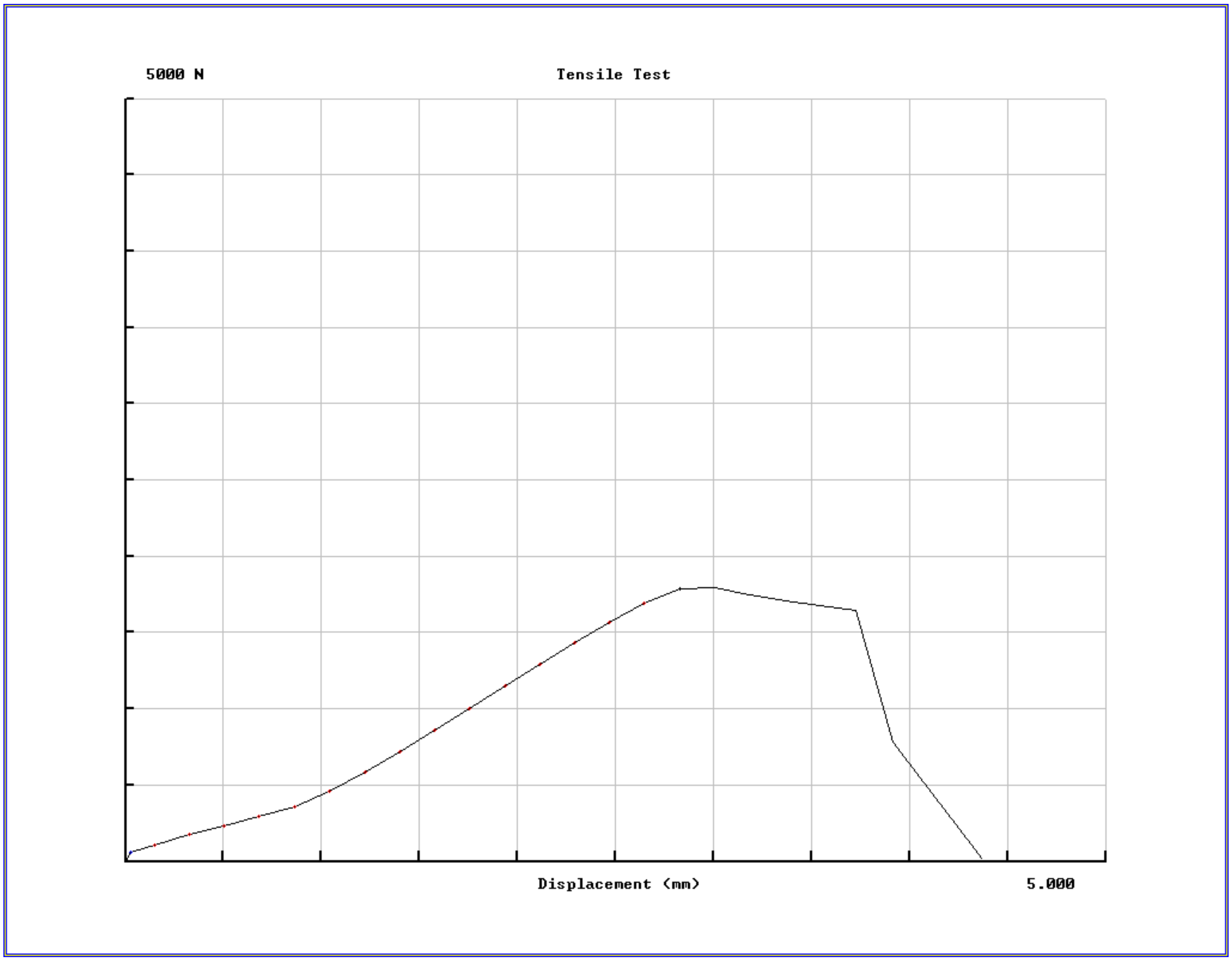


Figure 63: 0.6_S-100-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2817.96	1796.25	54.63	0.6	4.38	Side	6.47


0.6
S-100-4
0.6
S-100-4

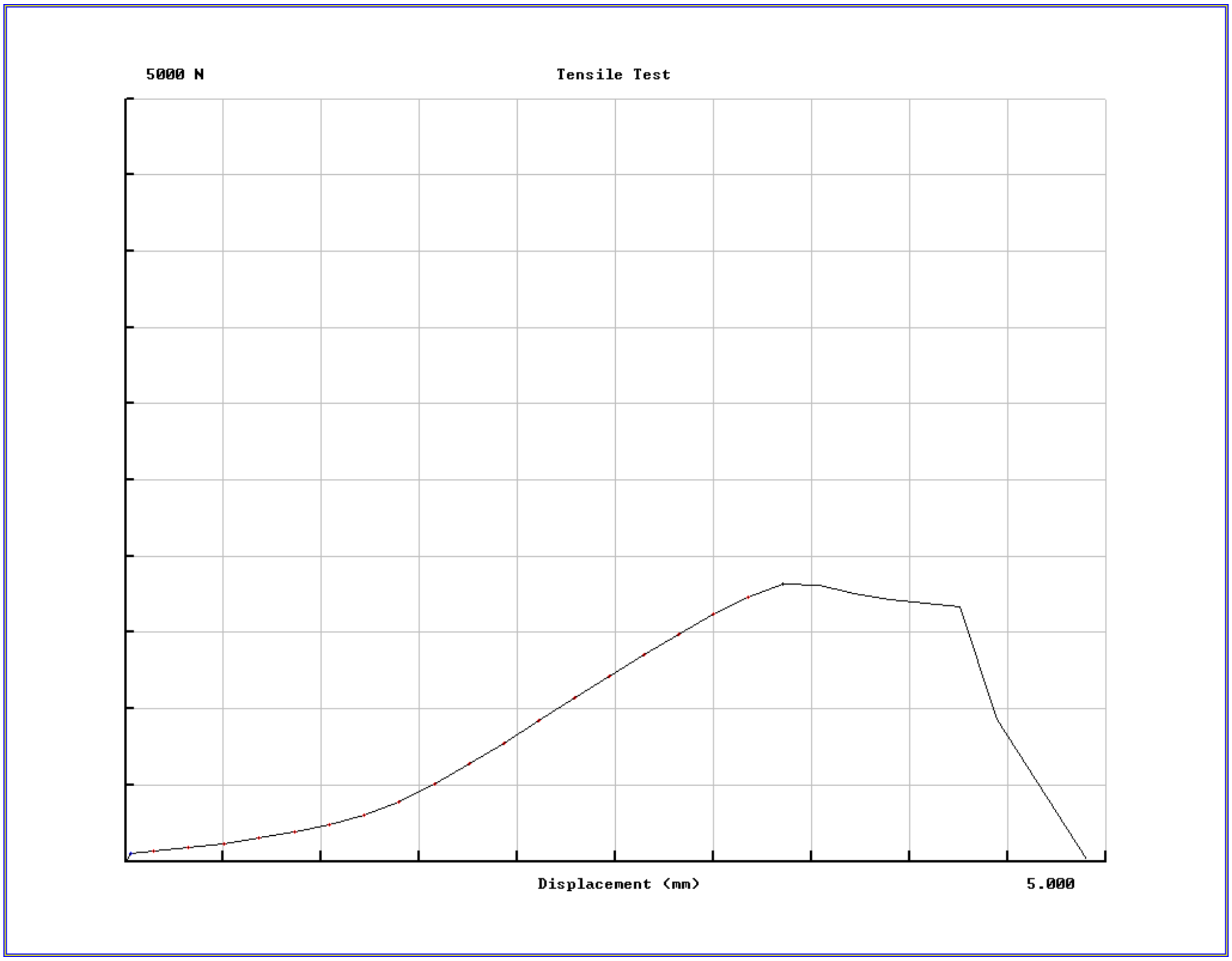


Figure 64: 0.6-S-100-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2865.90	1816.08	54.56	0.6	4.91	Side	6.51


0.6
S-100-5
0.6
S-100-5

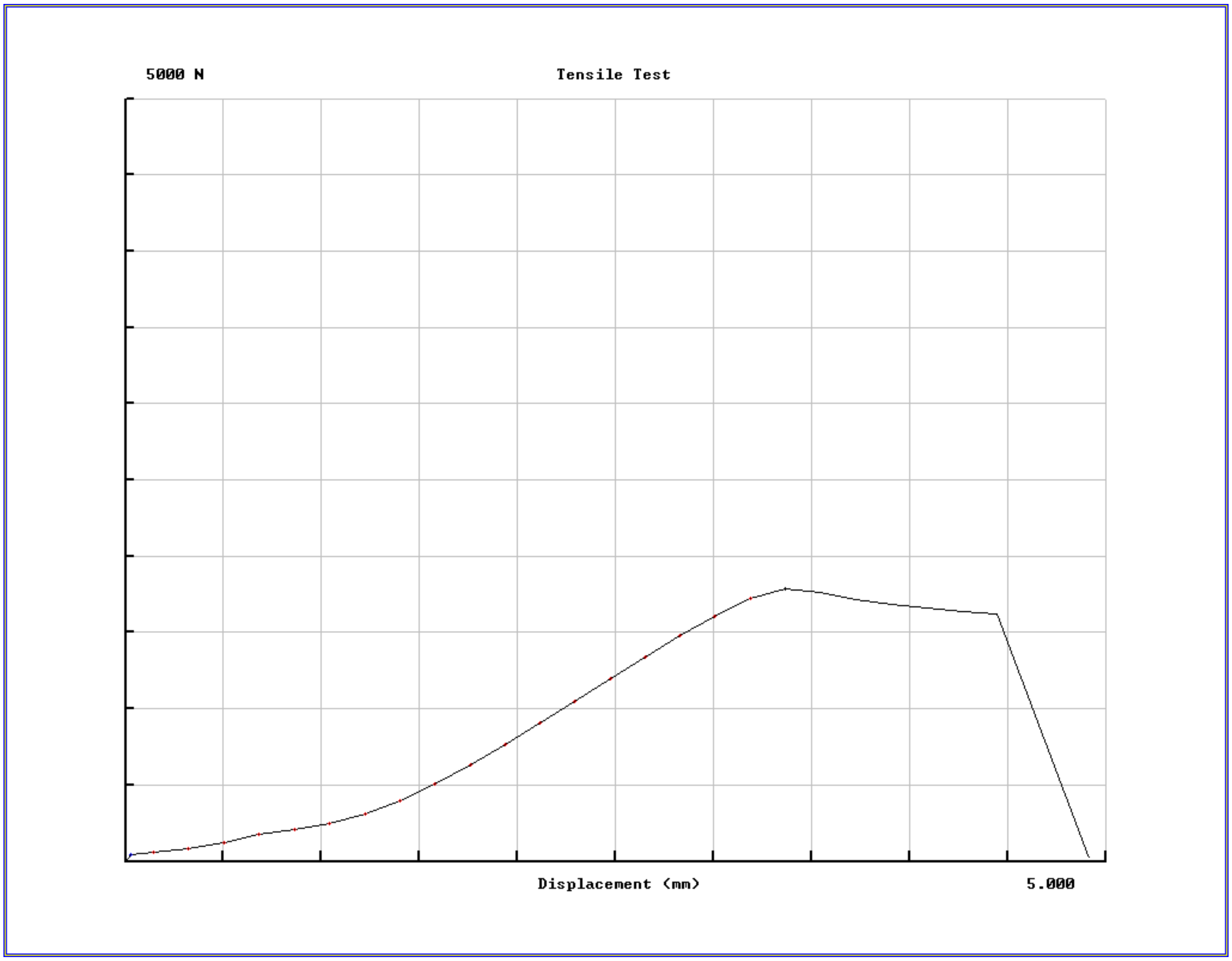


Figure 65:0.6_S-100-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2844.27	1785.84	55.34	0.6	4.92	Side	6.41


0.6
S-100-6
S-100-6

K. PLA, 0.6mm diameter nozzle, 100% Infill, Upright printed

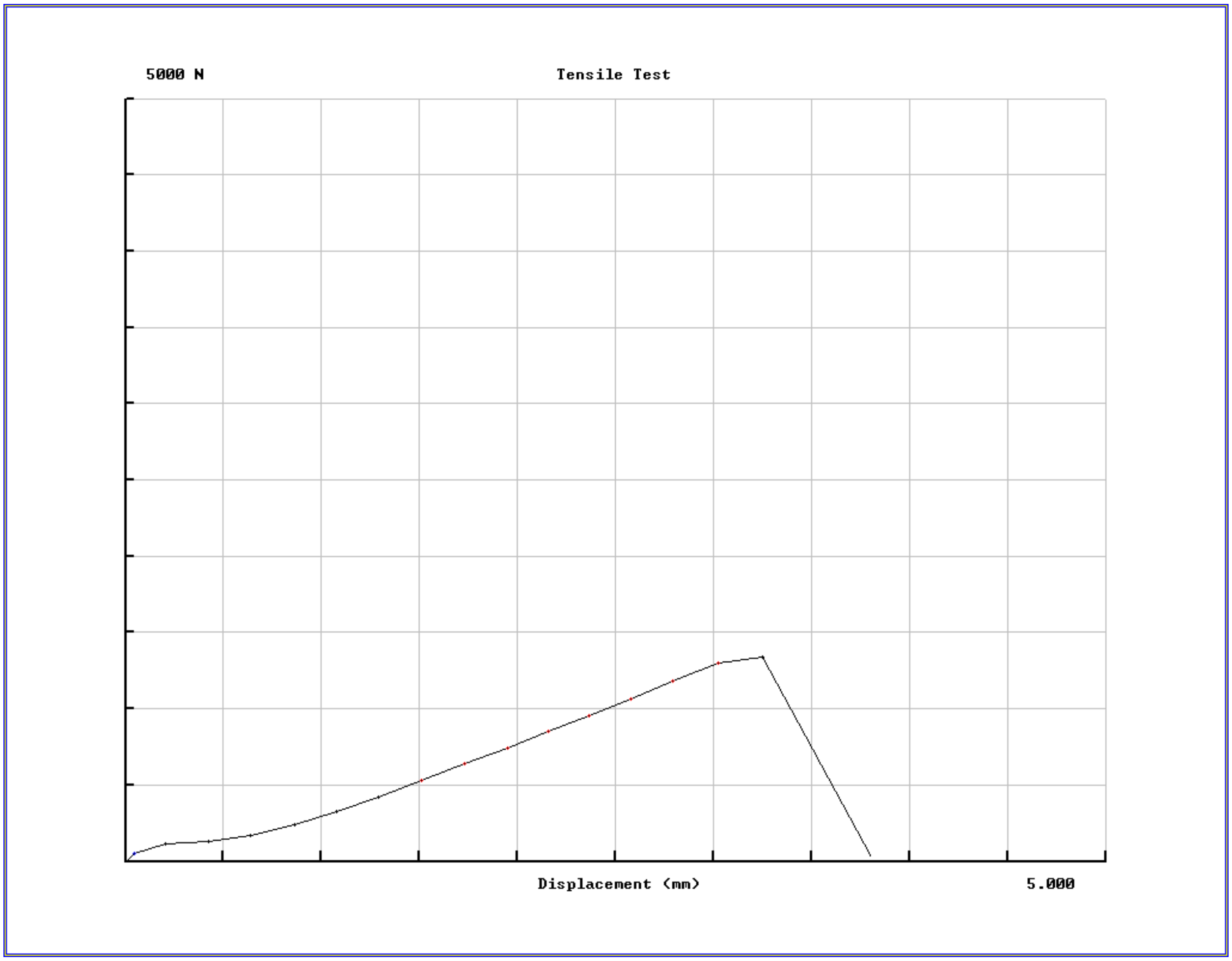


Figure 66: 0.6_U-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2751.03	1338.85	41.49	0.6	3.81	Upright	6.41

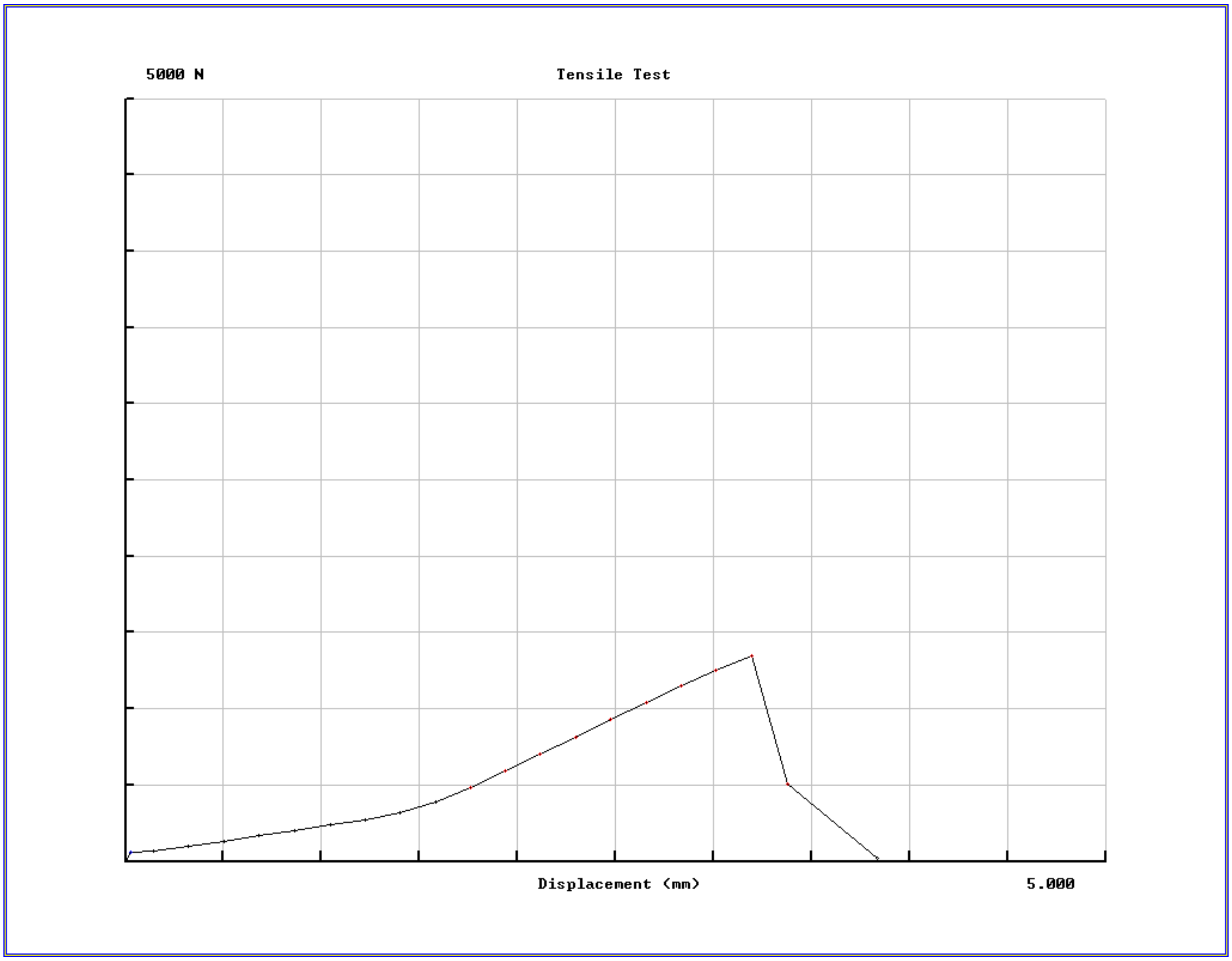
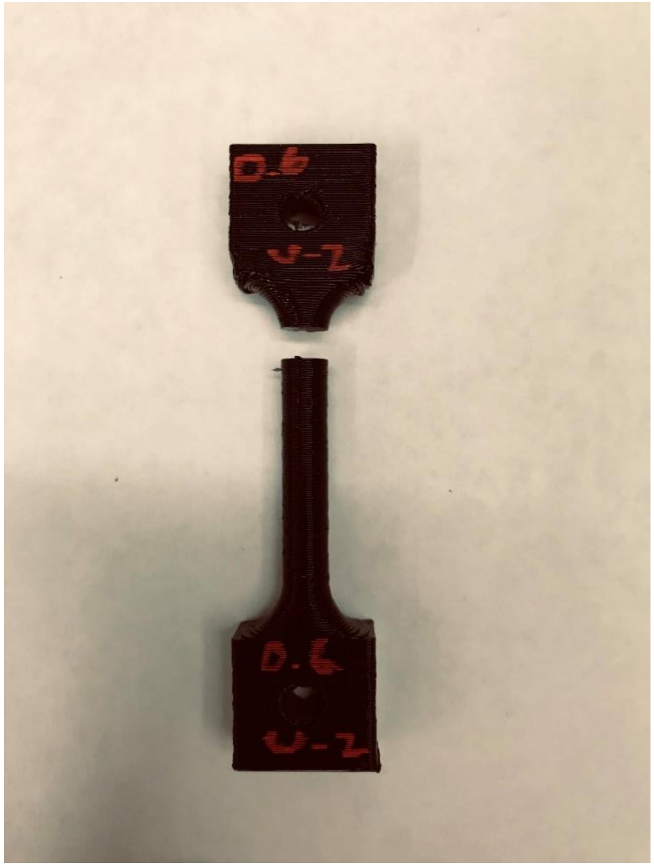


Figure 67: 0.6_U-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2415.53	1342.68	41.74	0.6	3.84	Upright	6.4



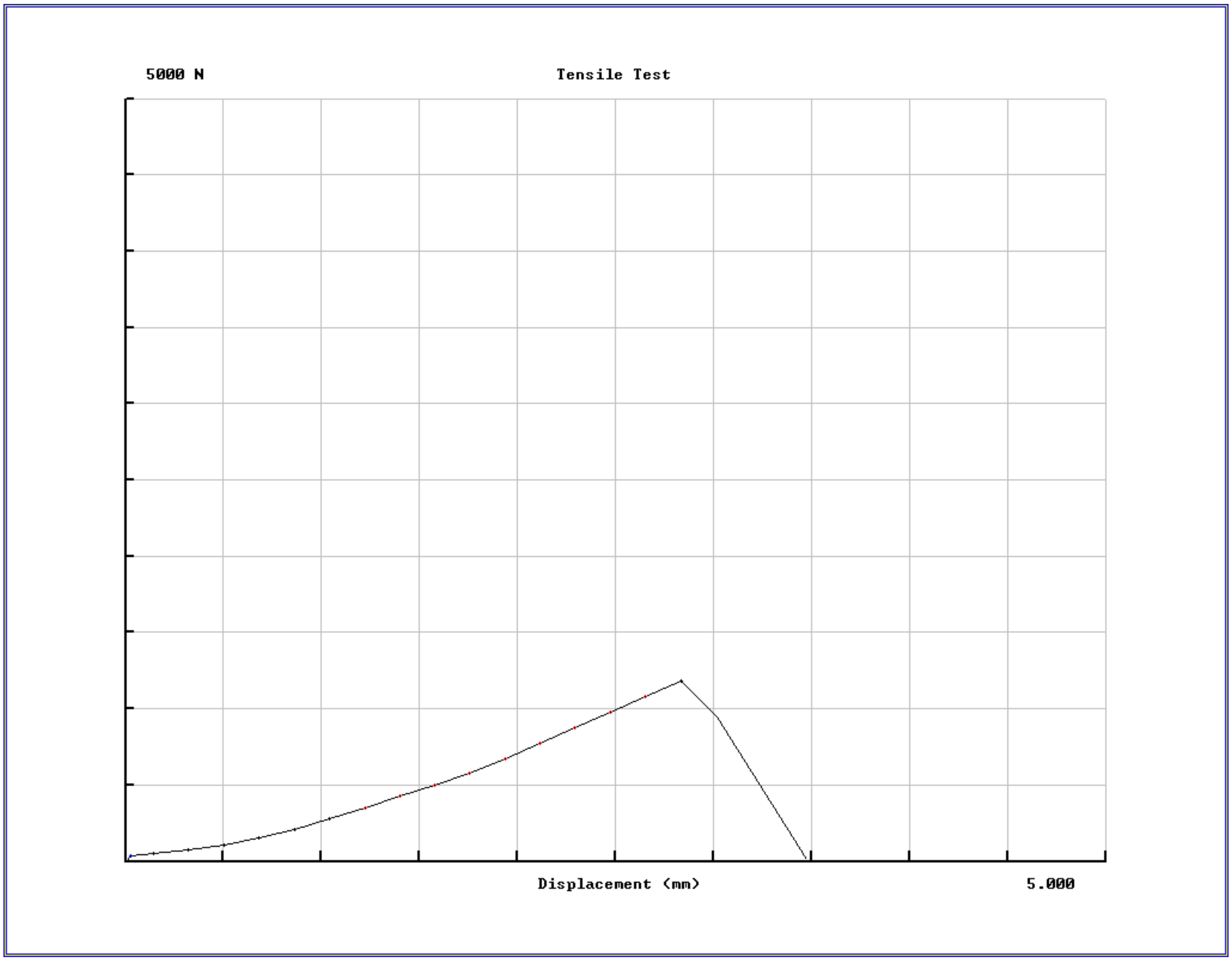
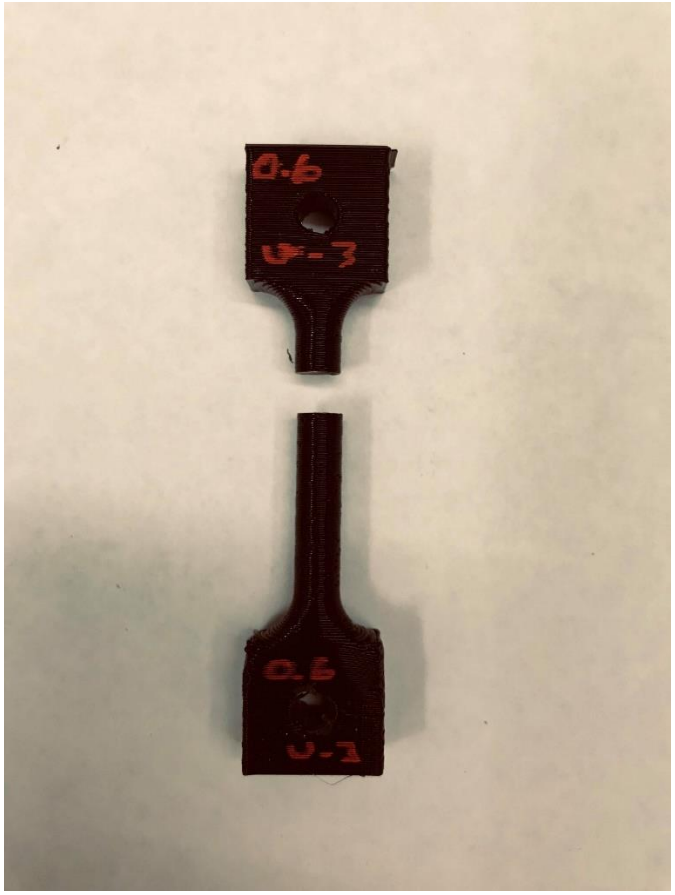


Figure 68: 0.6_U-3

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2515.82	1182.84	36.54	0.6	3.48	Upright	6.42


0.6
U-3
0.6
U-3

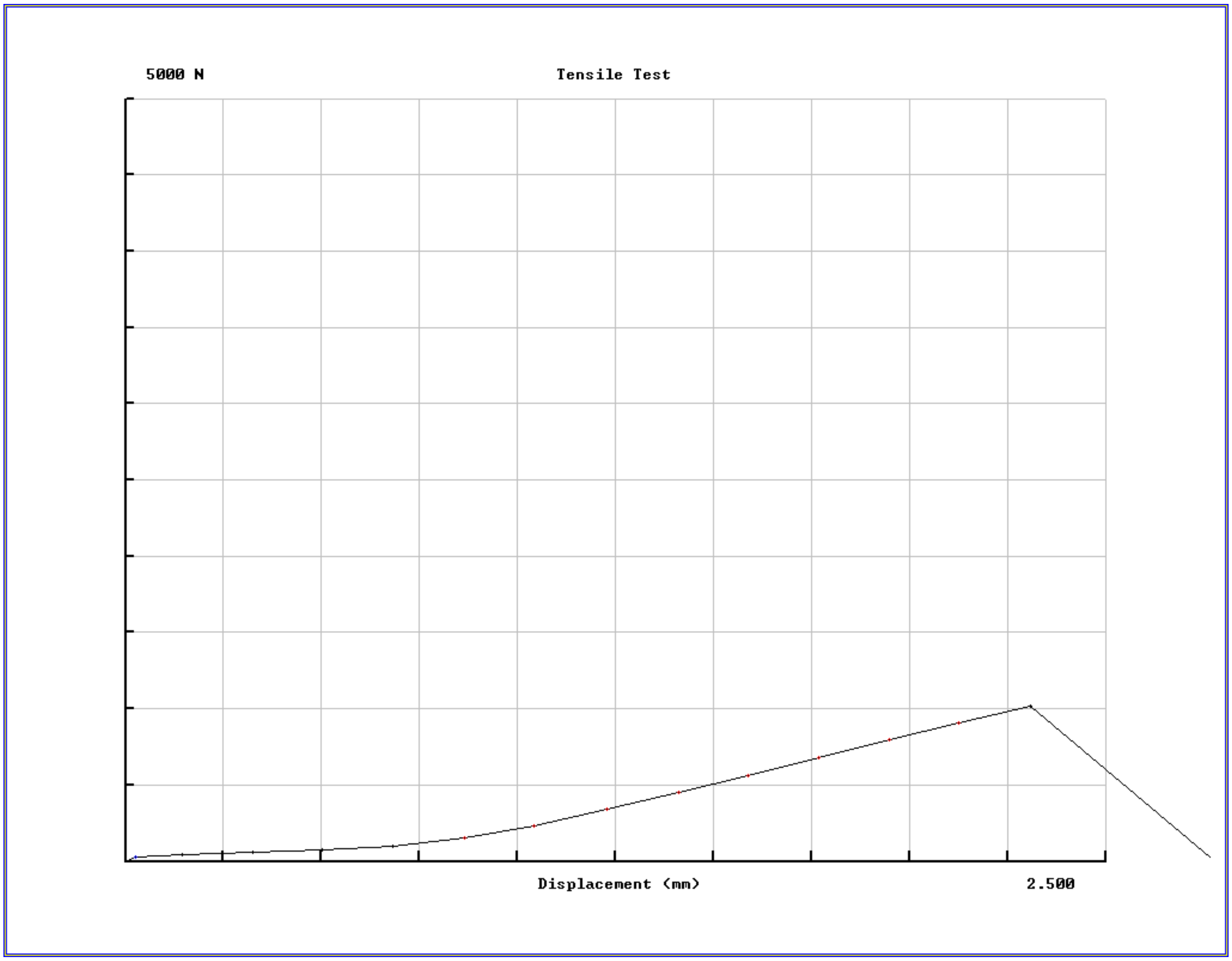
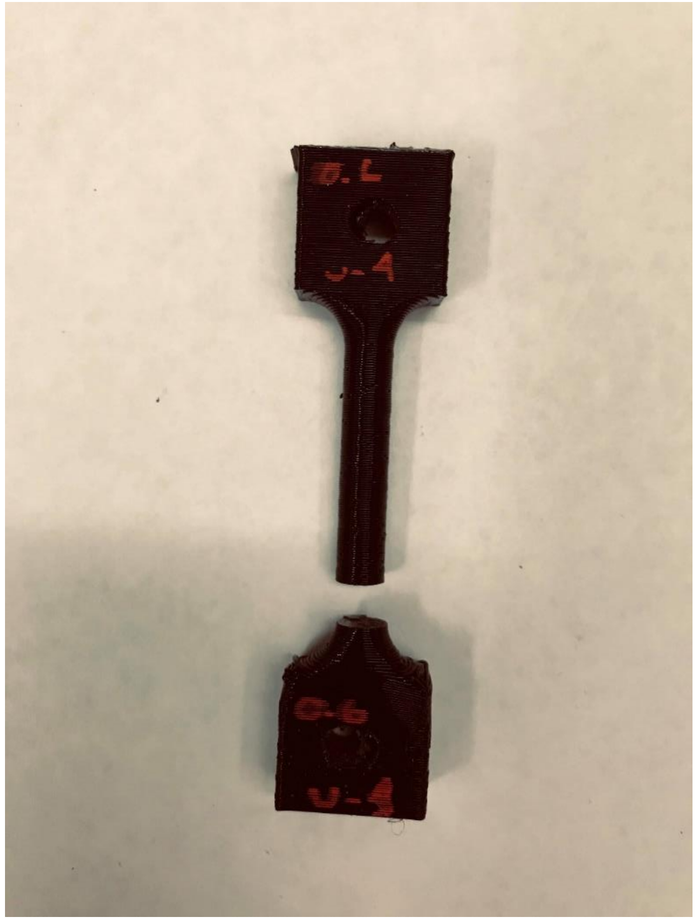


Figure 69: 0.6_U-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2382.91	1013.00	30.53	0.6	2.77	Upright	6.5



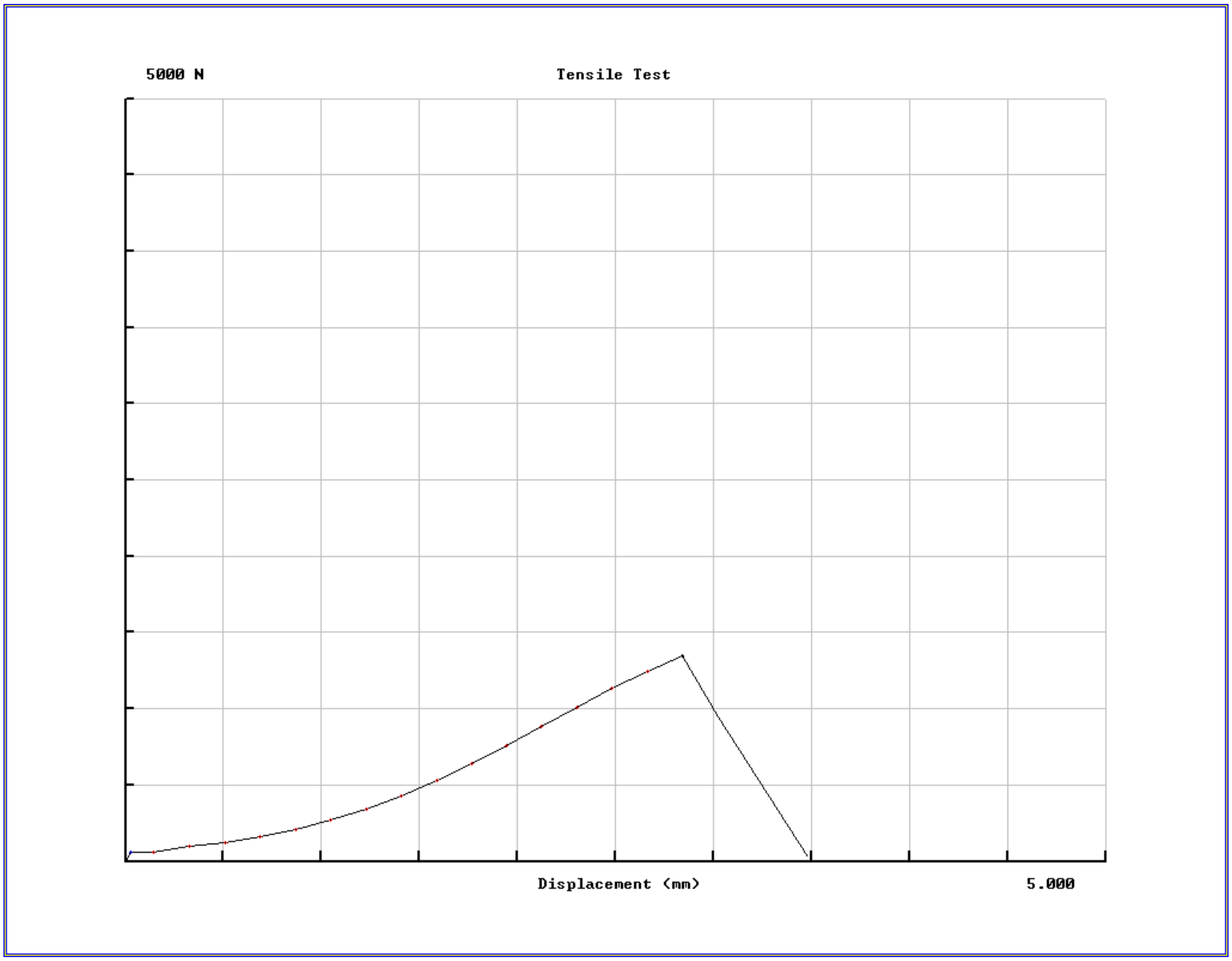
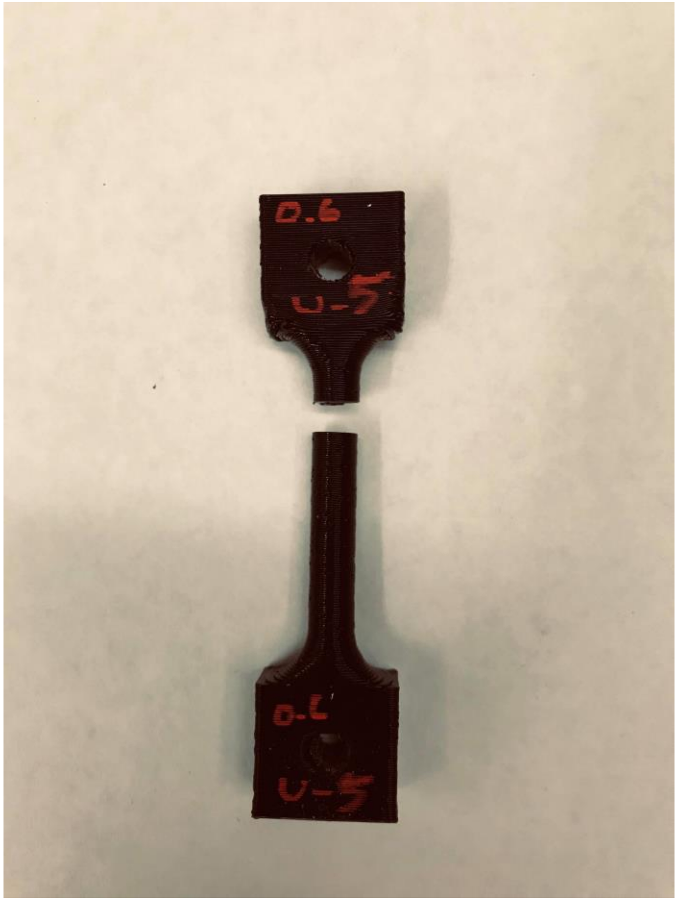


Figure 70: 0.6_U-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2653.37	1348.06	41.77	0.6	3.49	Upright	6.41


0.6
U-5
0.6
U-5

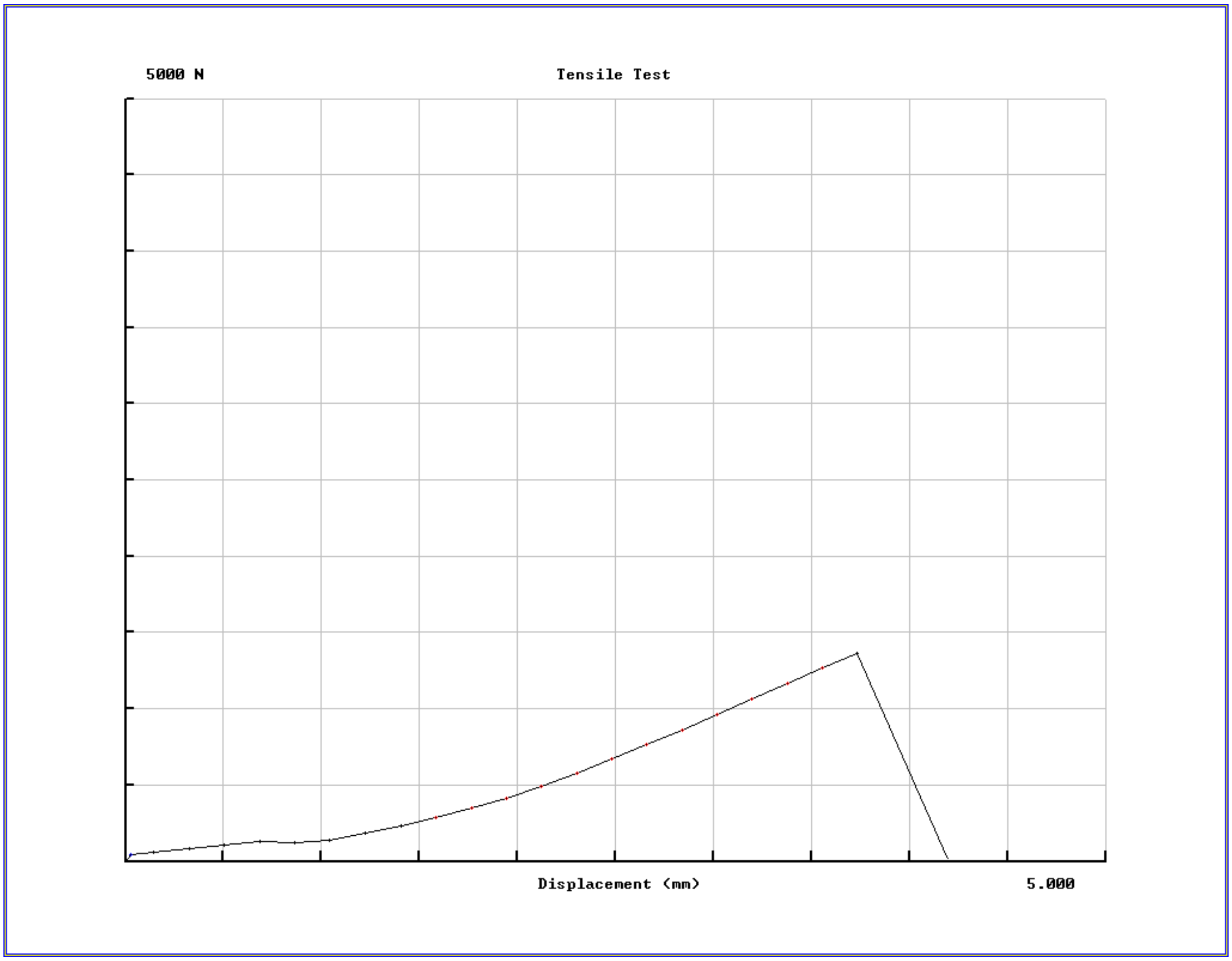


Figure 71: 0.6_U-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2484.86	1363.80	42.39	0.6	4.20	Upright	6.4

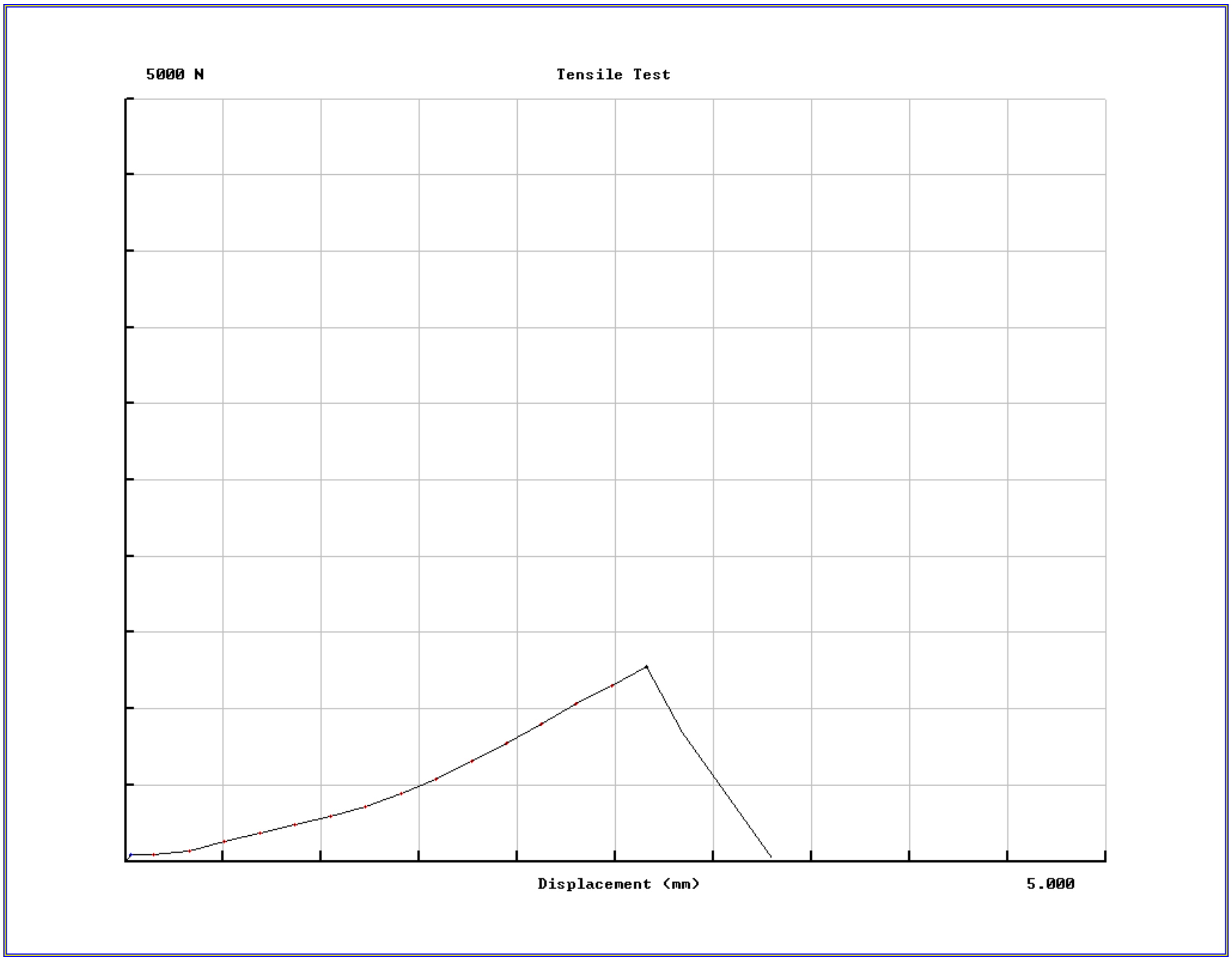
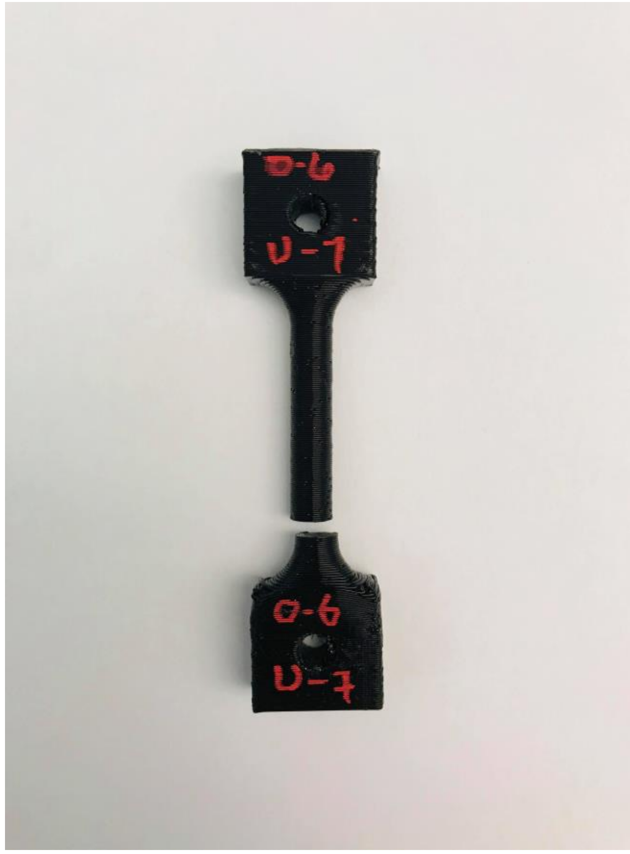


Figure 72: 0.6_U-7

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	2520.70	1272.01	39.42	0.6	3.30	Upright	6.41


O-6
U-7
O-6
U-7

L. PLA, 0.4mm diameter nozzle, 50% Infill, Side printed

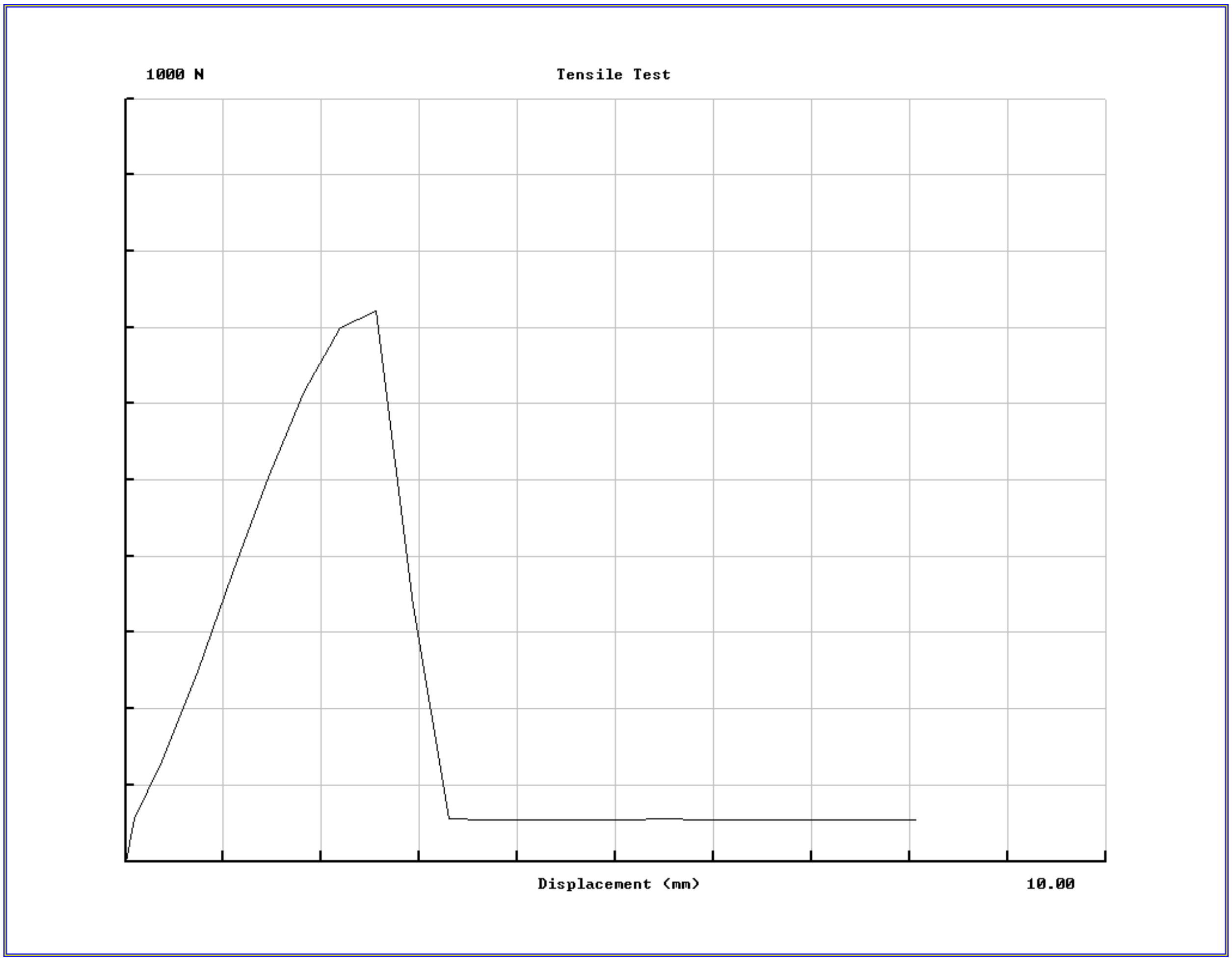
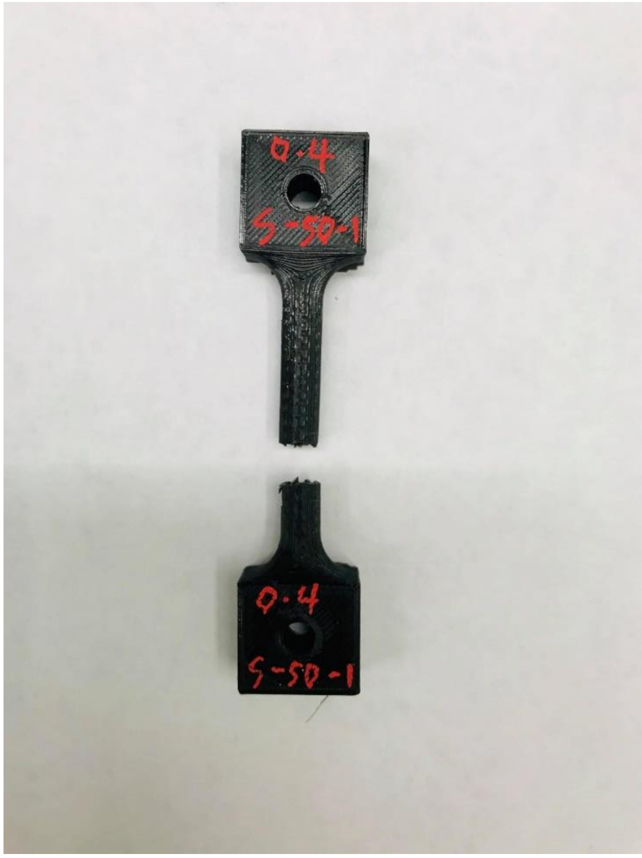


Figure 73: 0.4-S-50-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1105.33	720.74	22.76	0.4	8.08	Side	6.35



`

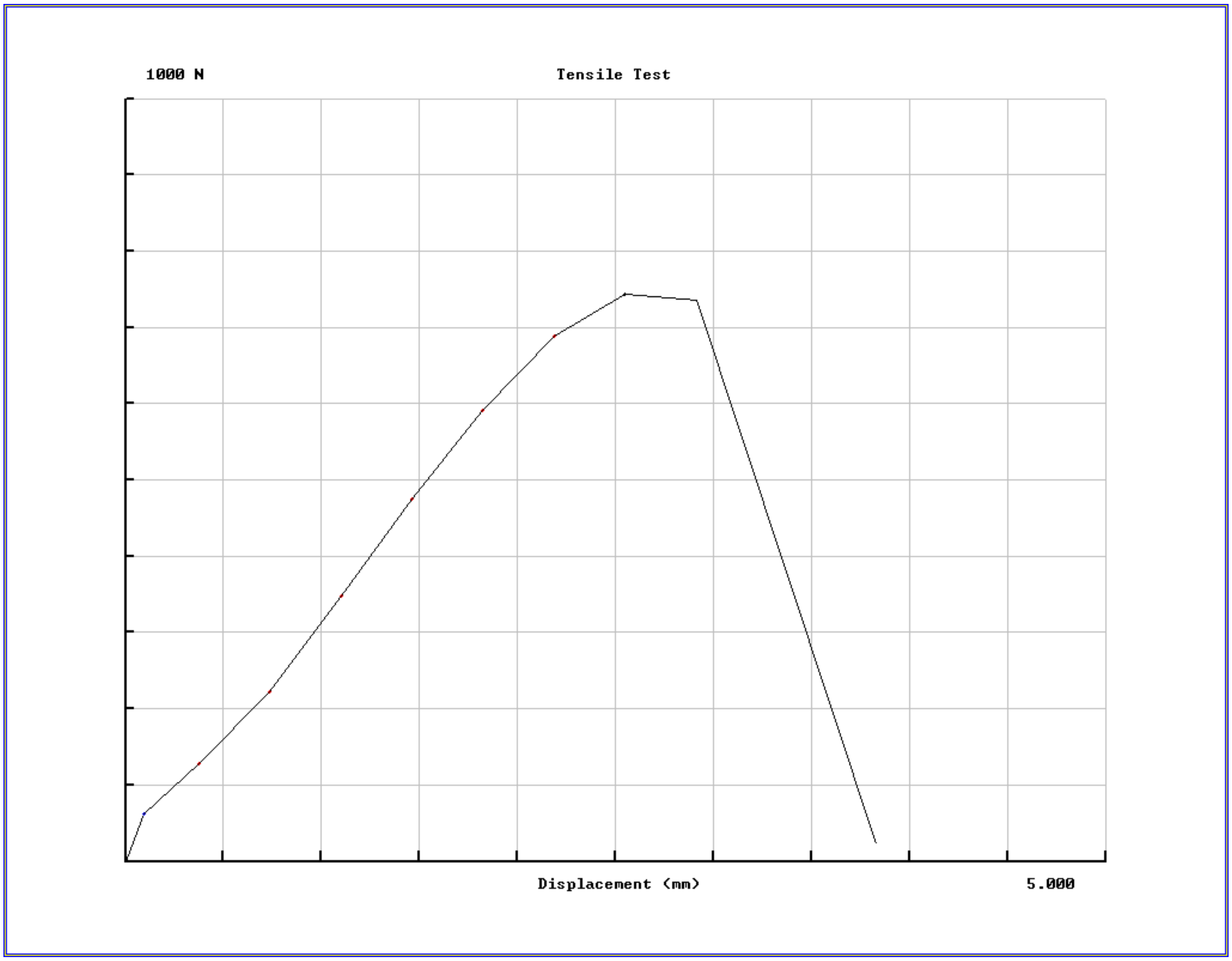
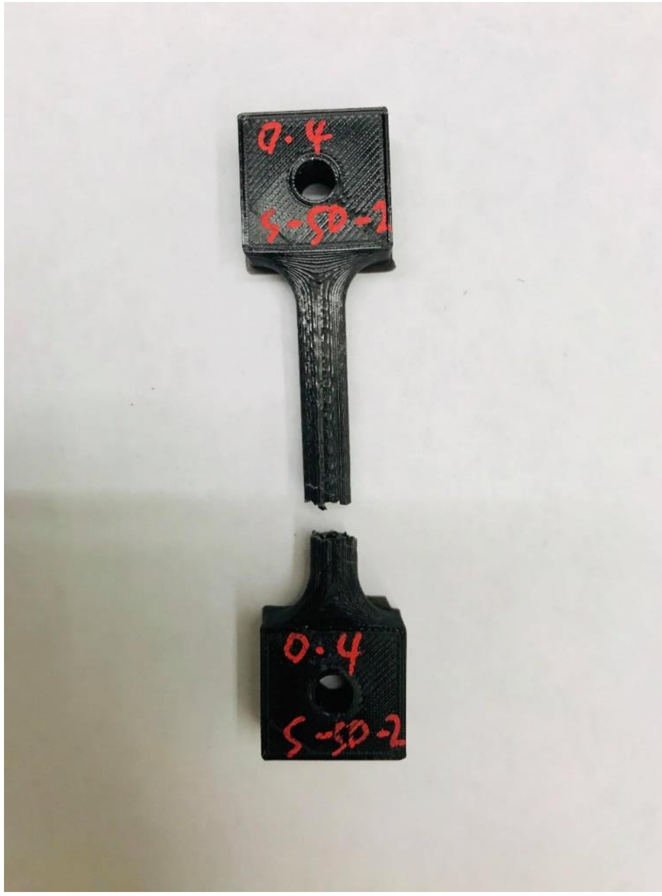


Figure 74: 0.4-S-50-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1207.52	742.98	23.46	0.4	3.83	Side	6.35


0.4
0.4

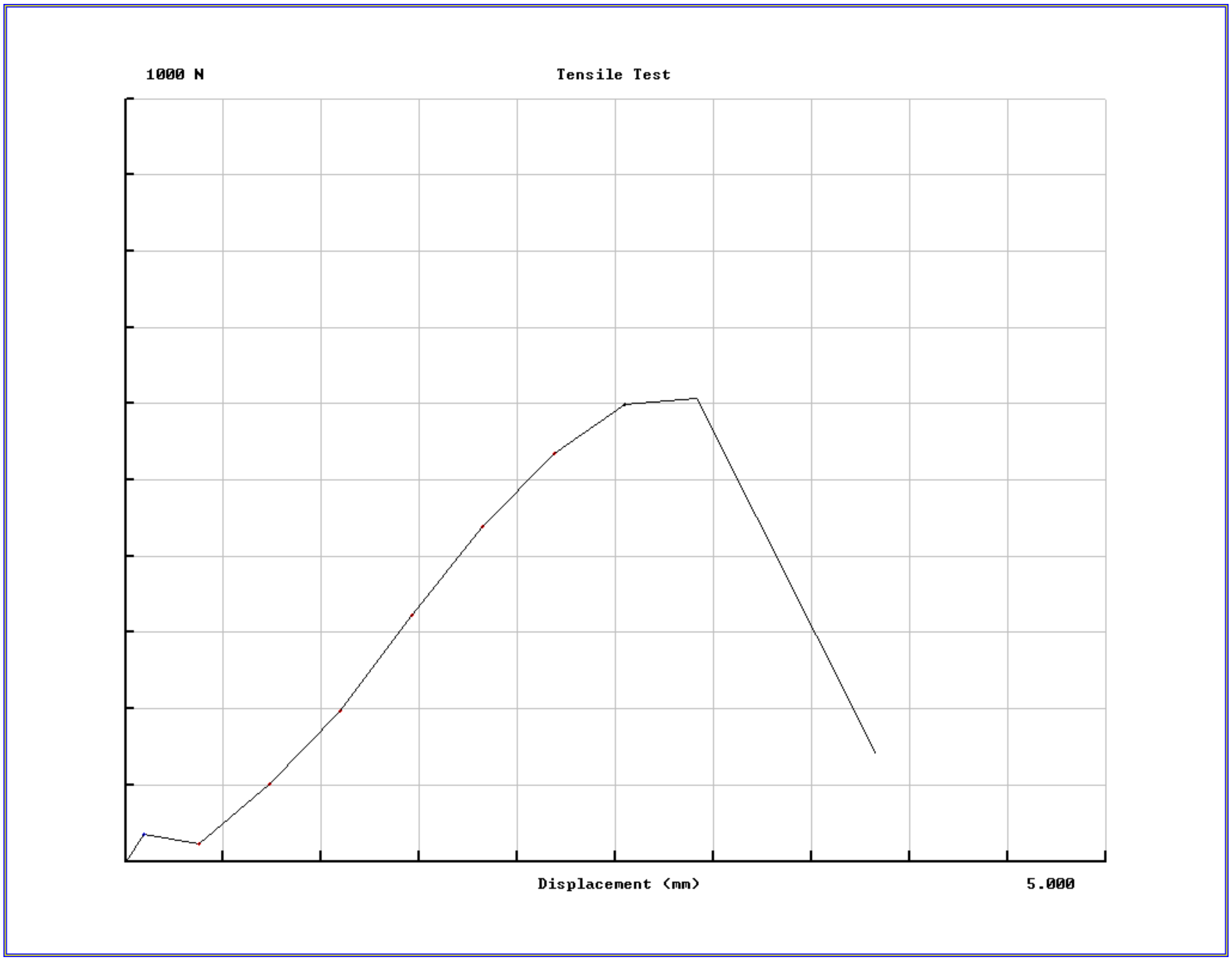


Figure 75: 0.4-S-50-3

Material	**Young's Modulus (N/mm^2)**	**Rupture Force (N)**	**Ultimate Stress (N/mm^2)**	**Nozzle Size (mm)**	**Displacement (mm)**	**Print Orientation**	**Sample Diameter (mm)**
PLA	1163.82	606.22	19.14	0.4	3.83	Side	6.35


0.4
S-50-3
0.4
S-50-3

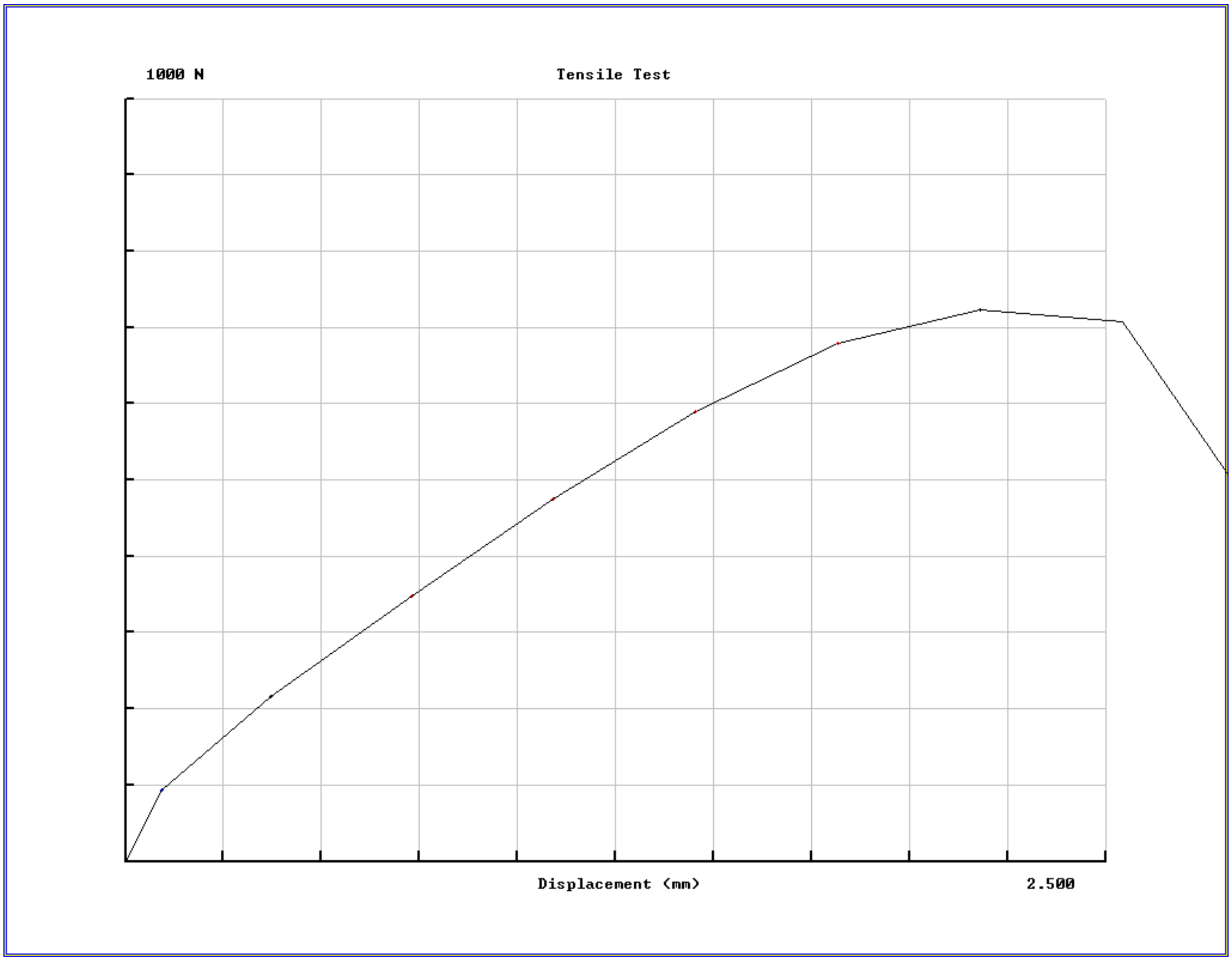
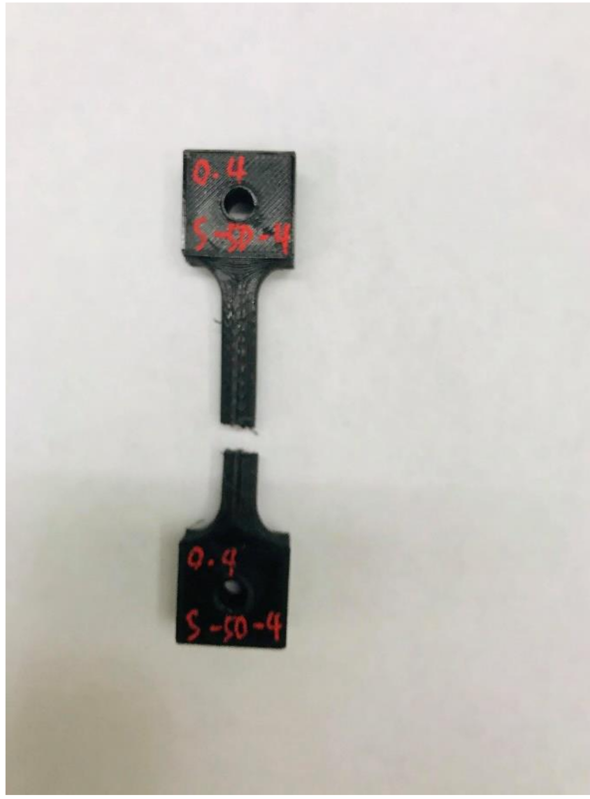


Figure 76: 0.4-S-50-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	947.57	723.08	22.76	0.4	3.46	Side	6.36


0.4
S-50-4
0.4
S-50-4

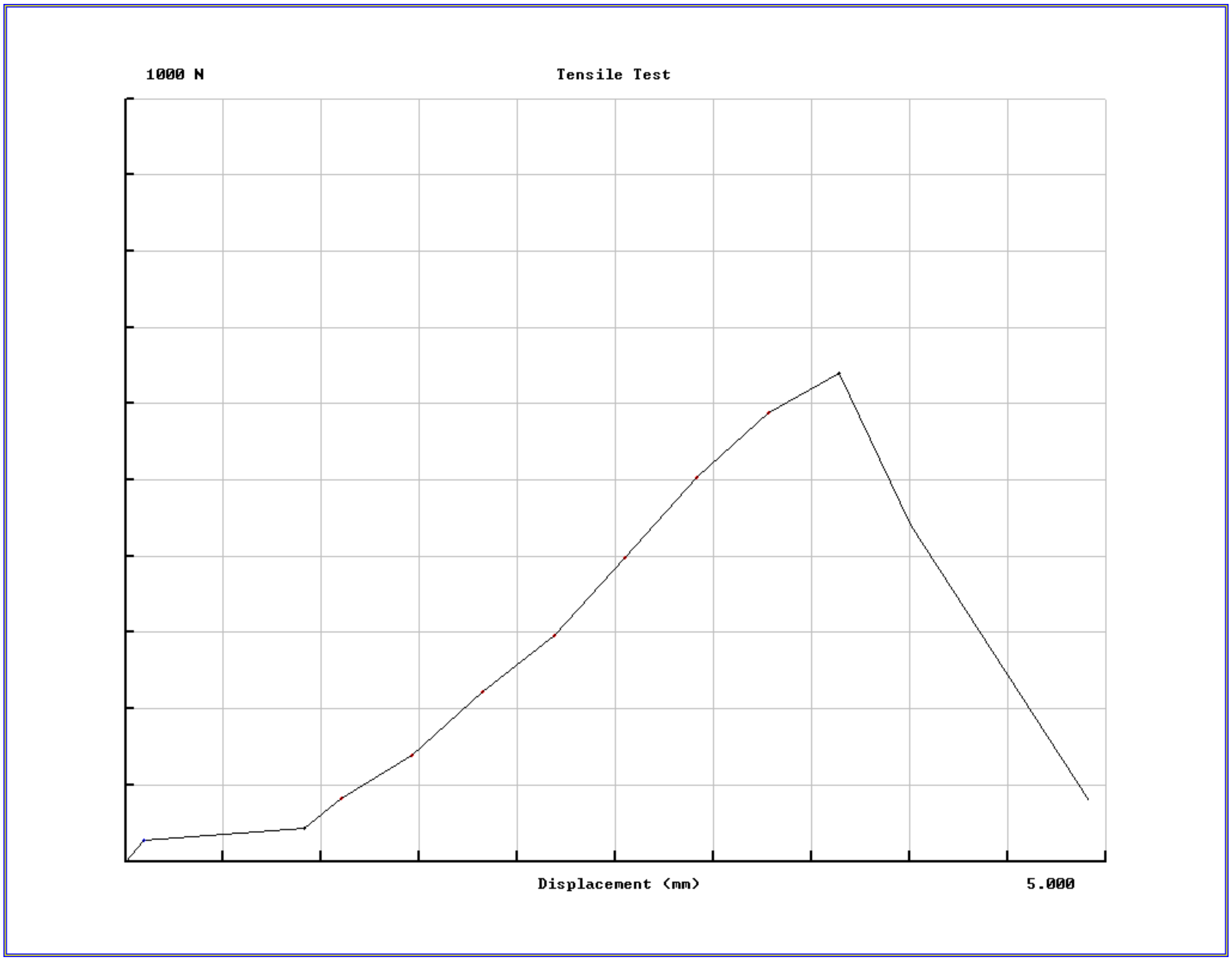


Figure 77: 0.4-S-50-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1180.06	640.23	20.28	0.4	4.92	Side	6.34


0.4
S-50-5
0.4
S-50-5

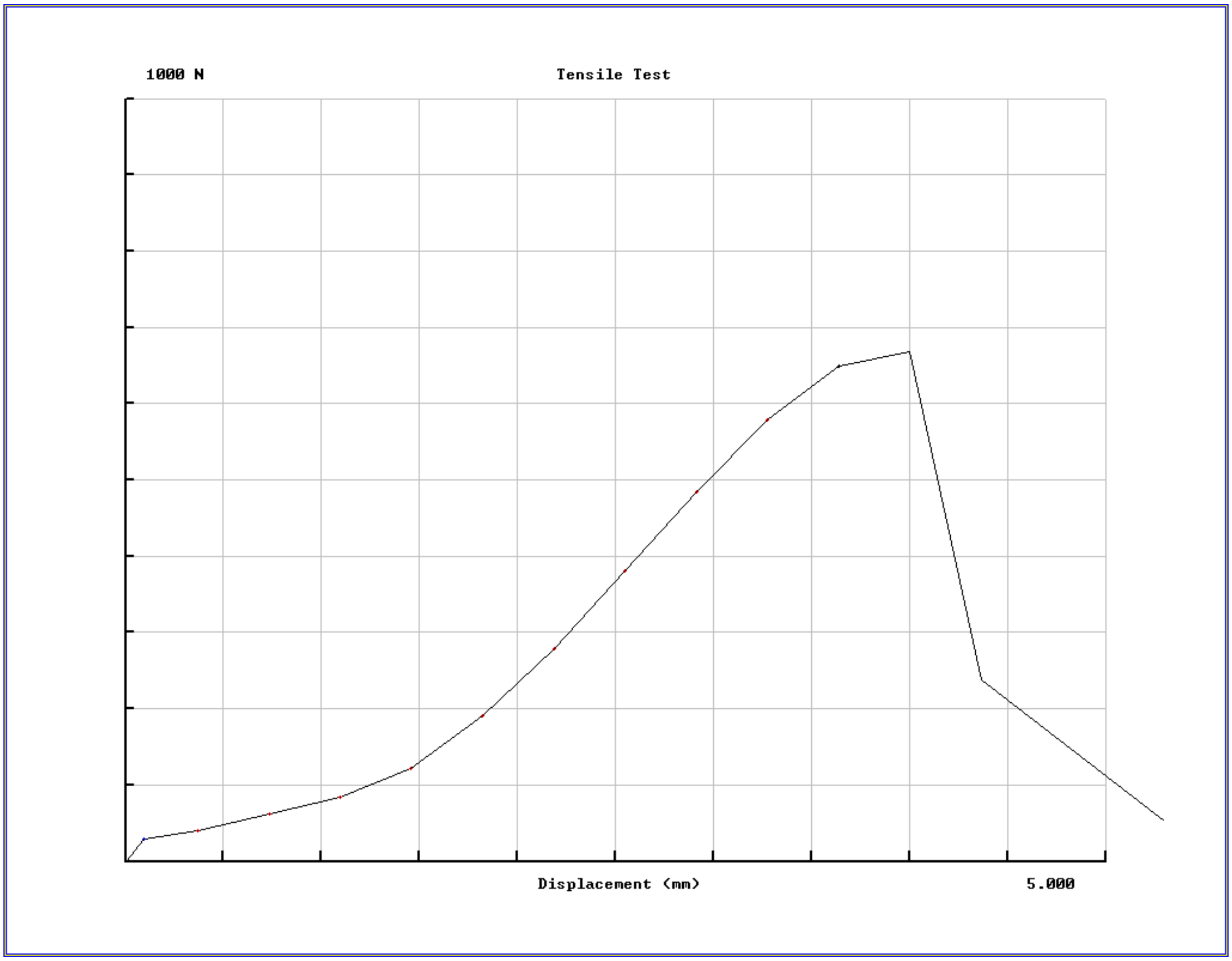
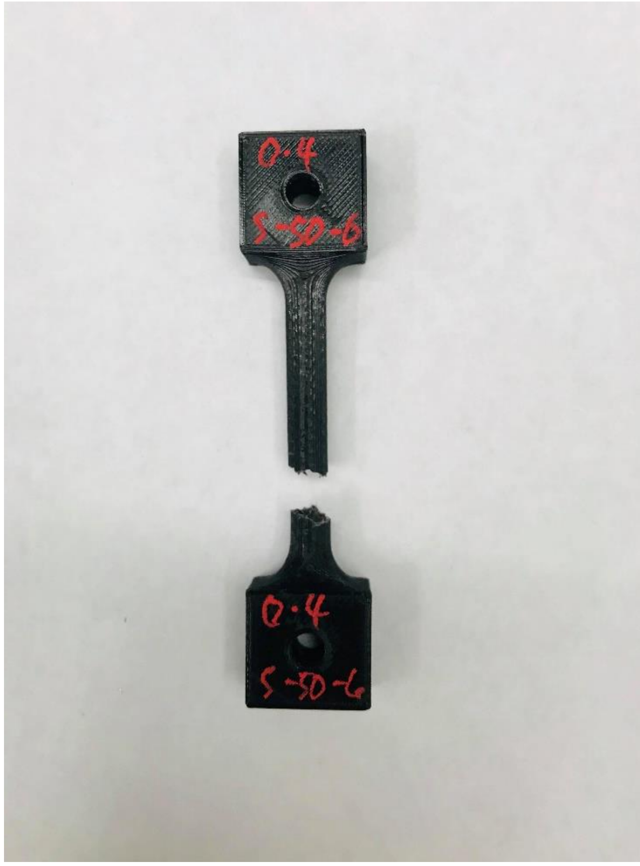


Figure 78:0.4-S-50-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1247.25	667.58	21.62	0.4	5.30	Side	6.27


0.4
S-50-6
0.4
S-50-6

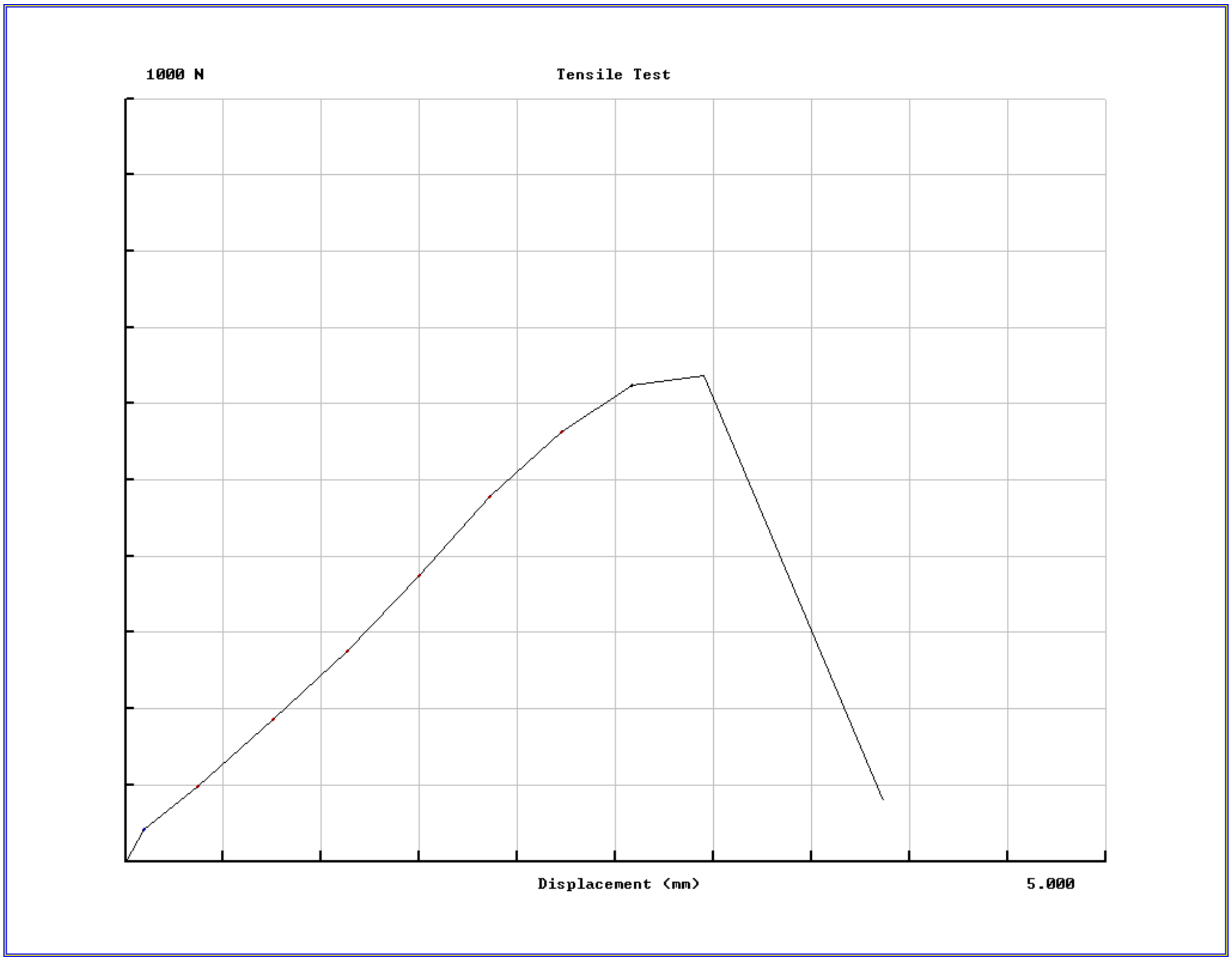


Figure 79: 0.4-S-50-7

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1113.49	637.12	19.68	0.4	3.87	Side	6.42

M. PLA, 0.4mm diameter nozzle, 50% Infill, Upright printed

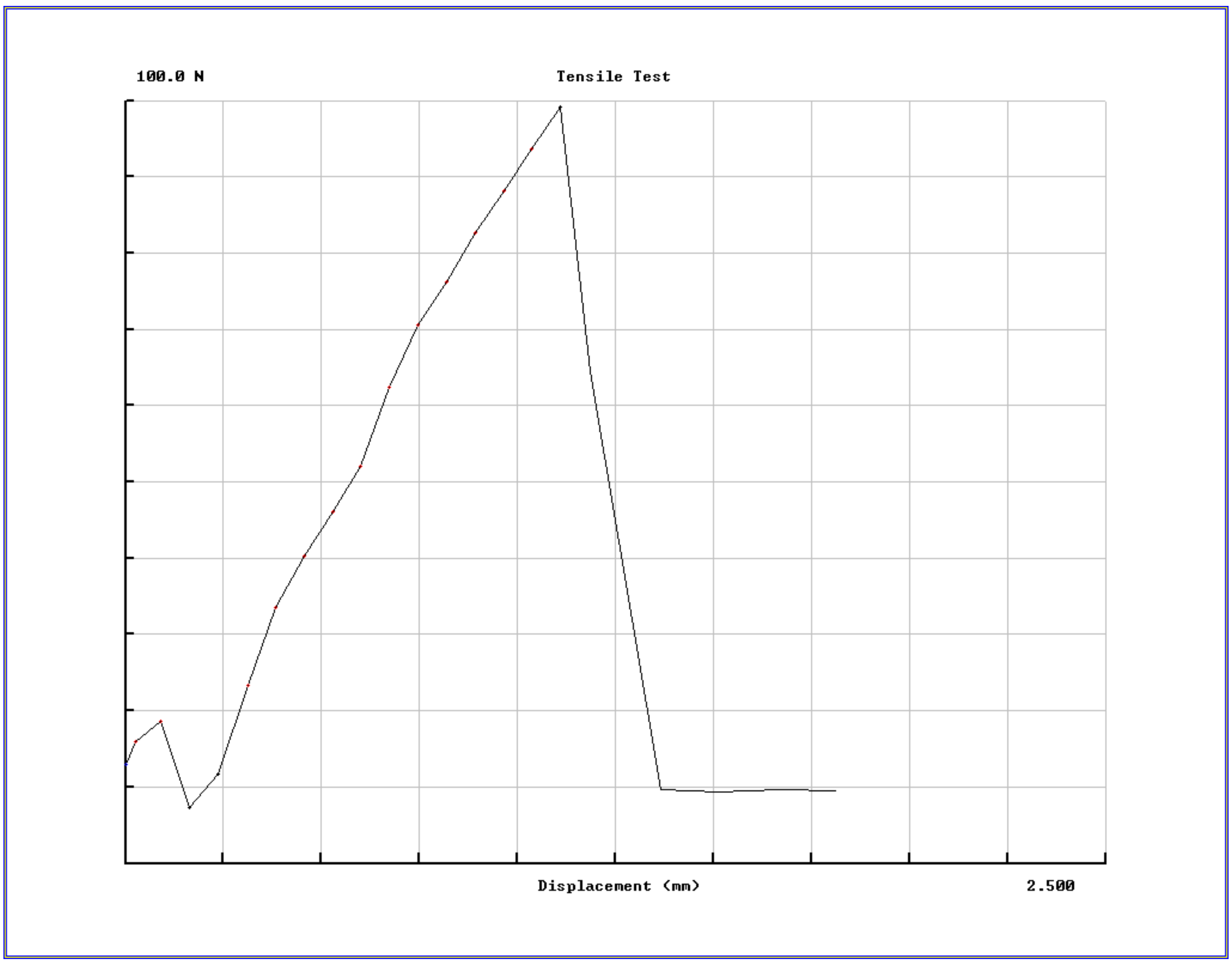
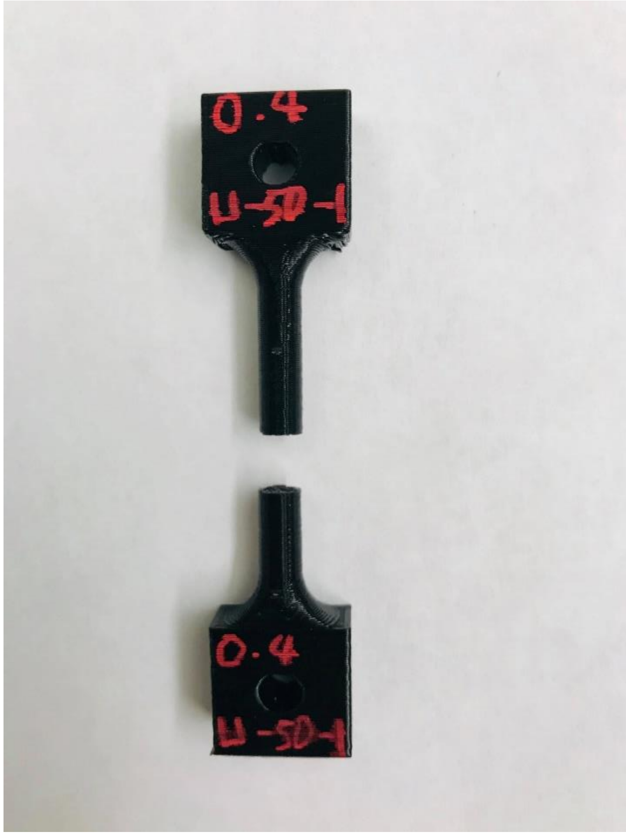


Figure 80: 0.4-U-50-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	896.31	99.18	3.59	0.4	1.82	Upright	6.41



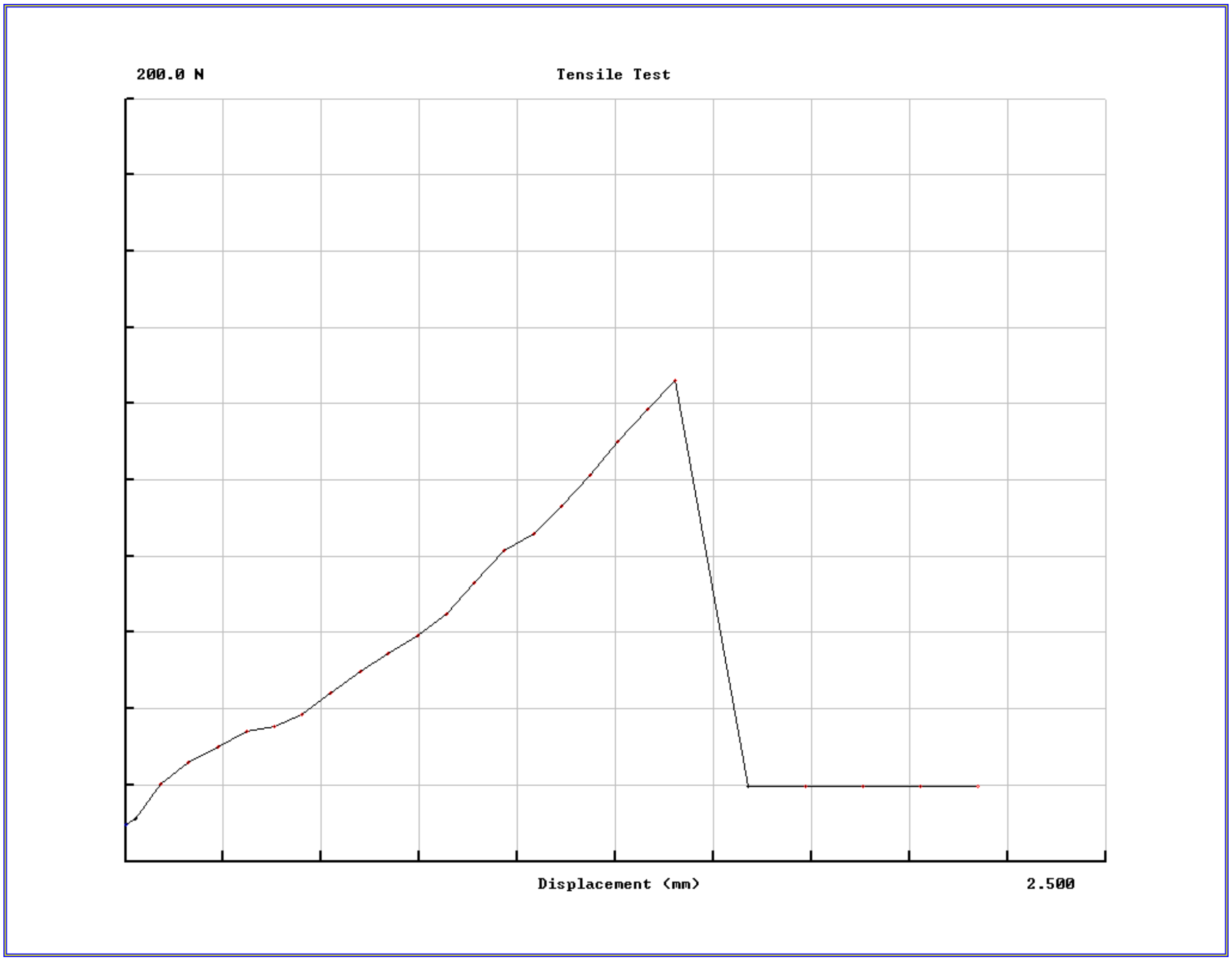


Figure 81: 0.4-U-50-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	-44.44	125.97	4.59	0.4	2.17	Upright	6.4


0.4
U-5D-2
0.4
U-5D-2

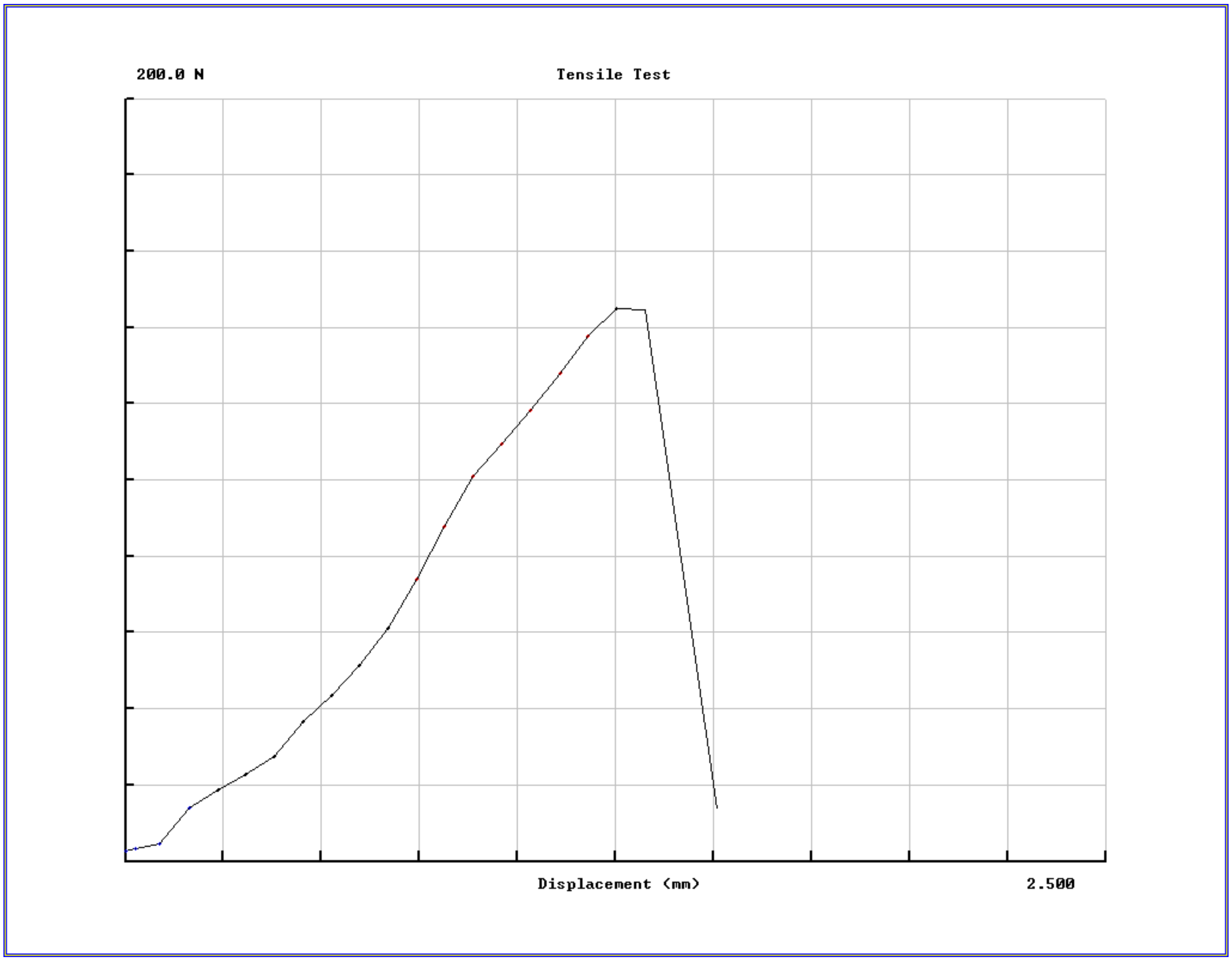
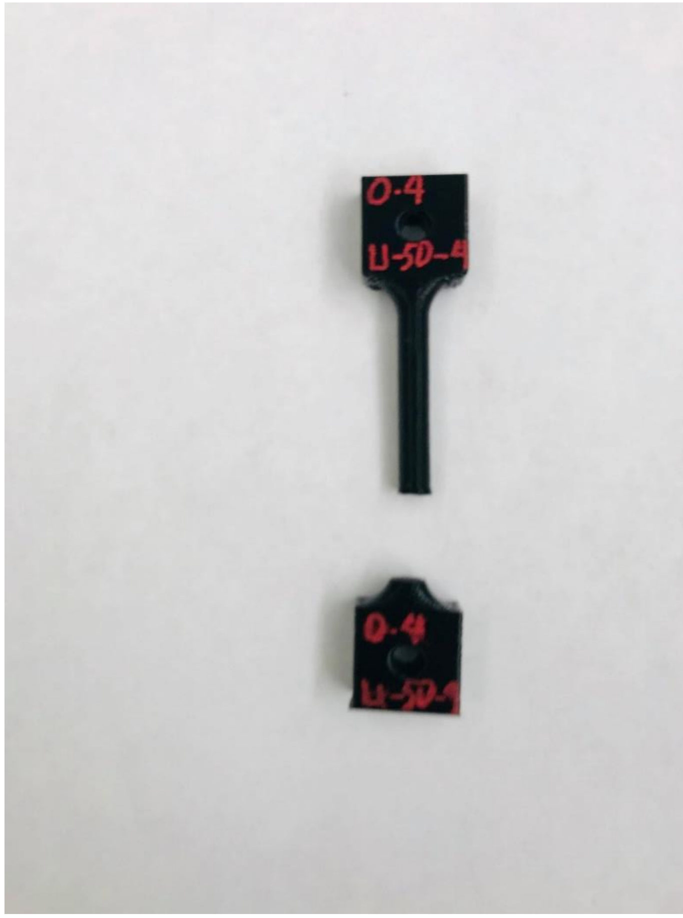


Figure 82: 0.4-U-50-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1331.08	145	5.18	0.4	1.51	Upright	6.42


O-4
U-5D-4
O-4

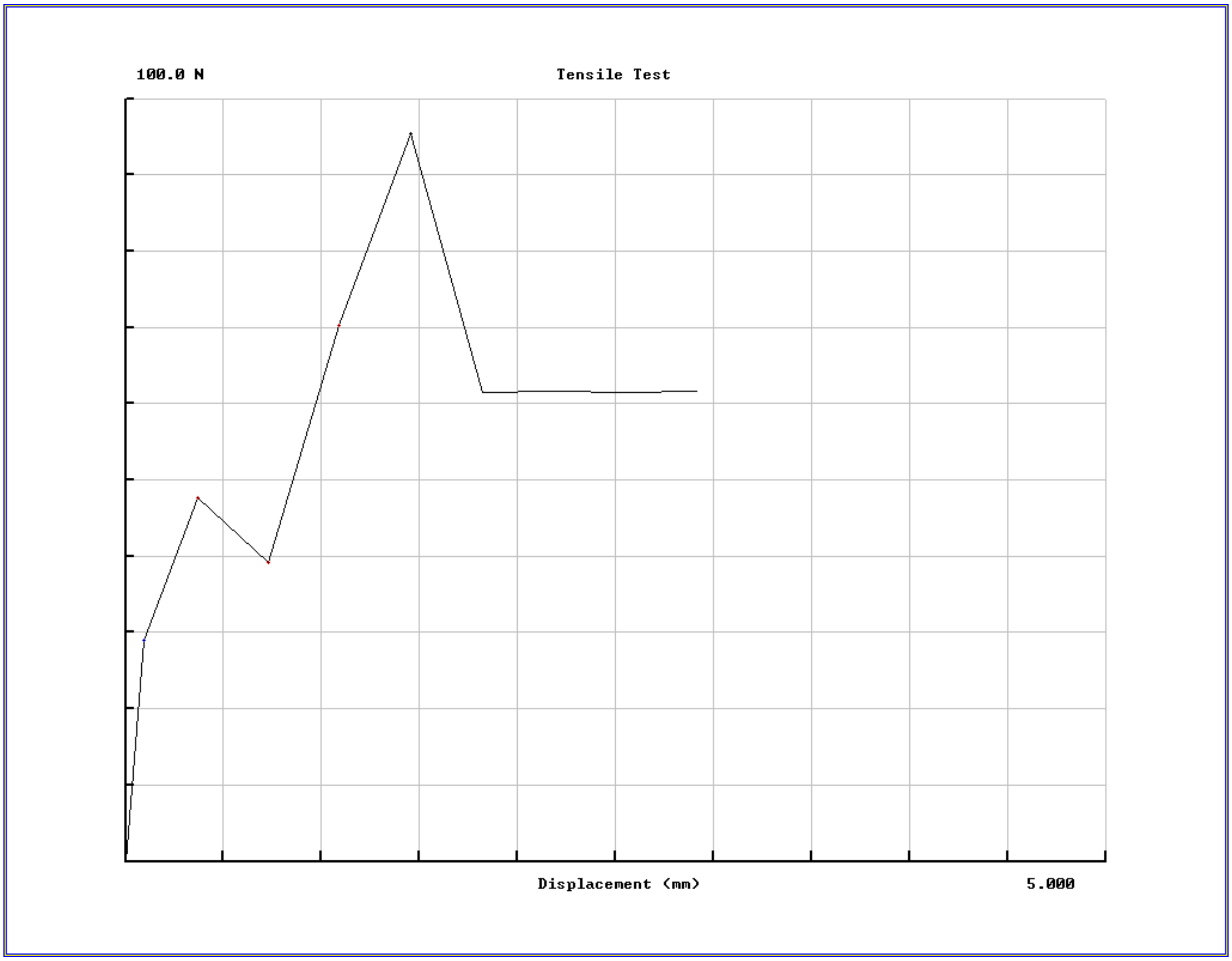
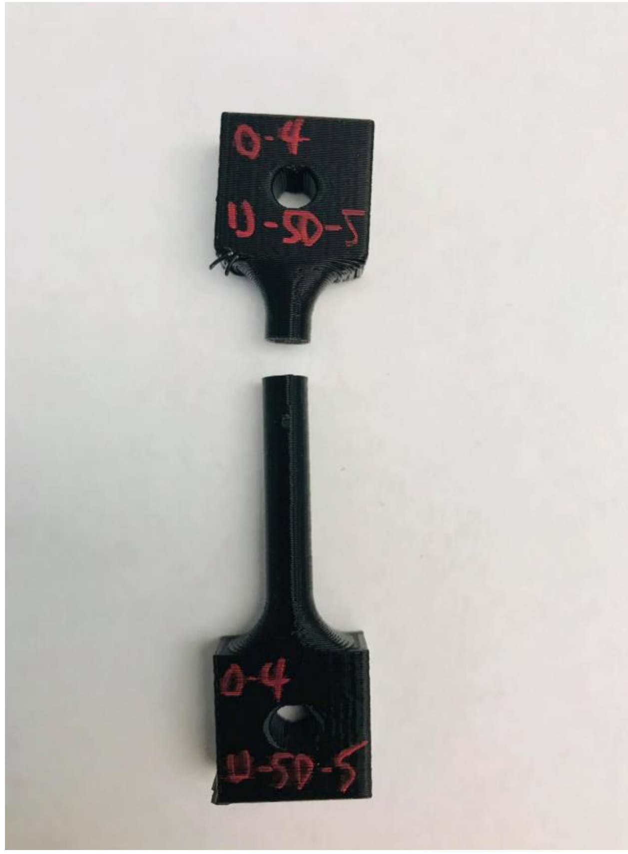


Figure 83: 0.4-U-50-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	847.49	95.37	3.43	0.4	2.92	Upright	6.5


0-4
U-SD-5
0-4
U-SD-5

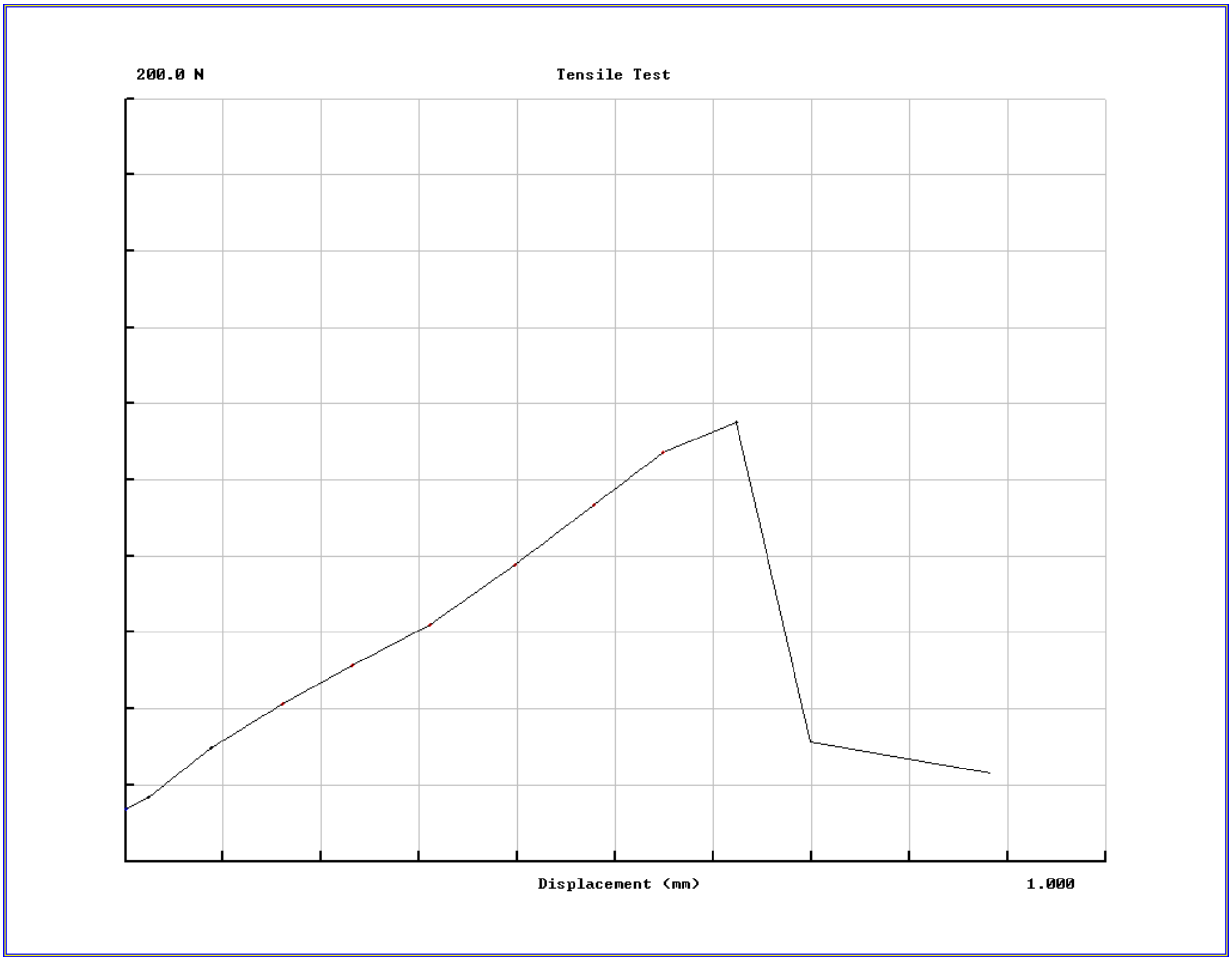


Figure 84: 0.4-U-50-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	905.77	115.06	4.19	0.4	0.88	Upright	6.41


0.4
U-50-6
0.4
U-50-6

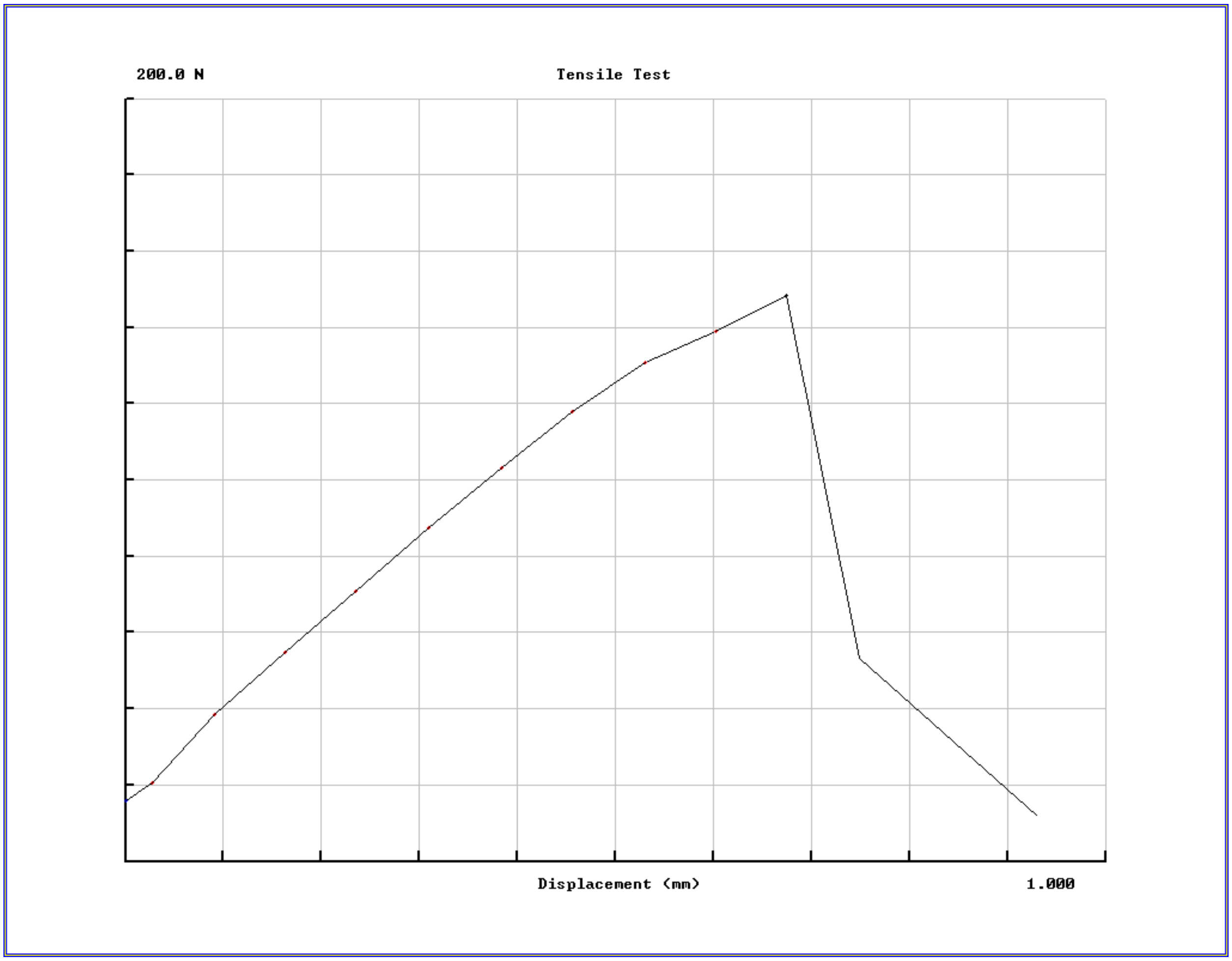


Figure 85: 0.4-U-50-8

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1104.5	148.43	5.34	0.4	0.93	Upright	6.4


0-4
U-5D-8
0-4
U-5D-8

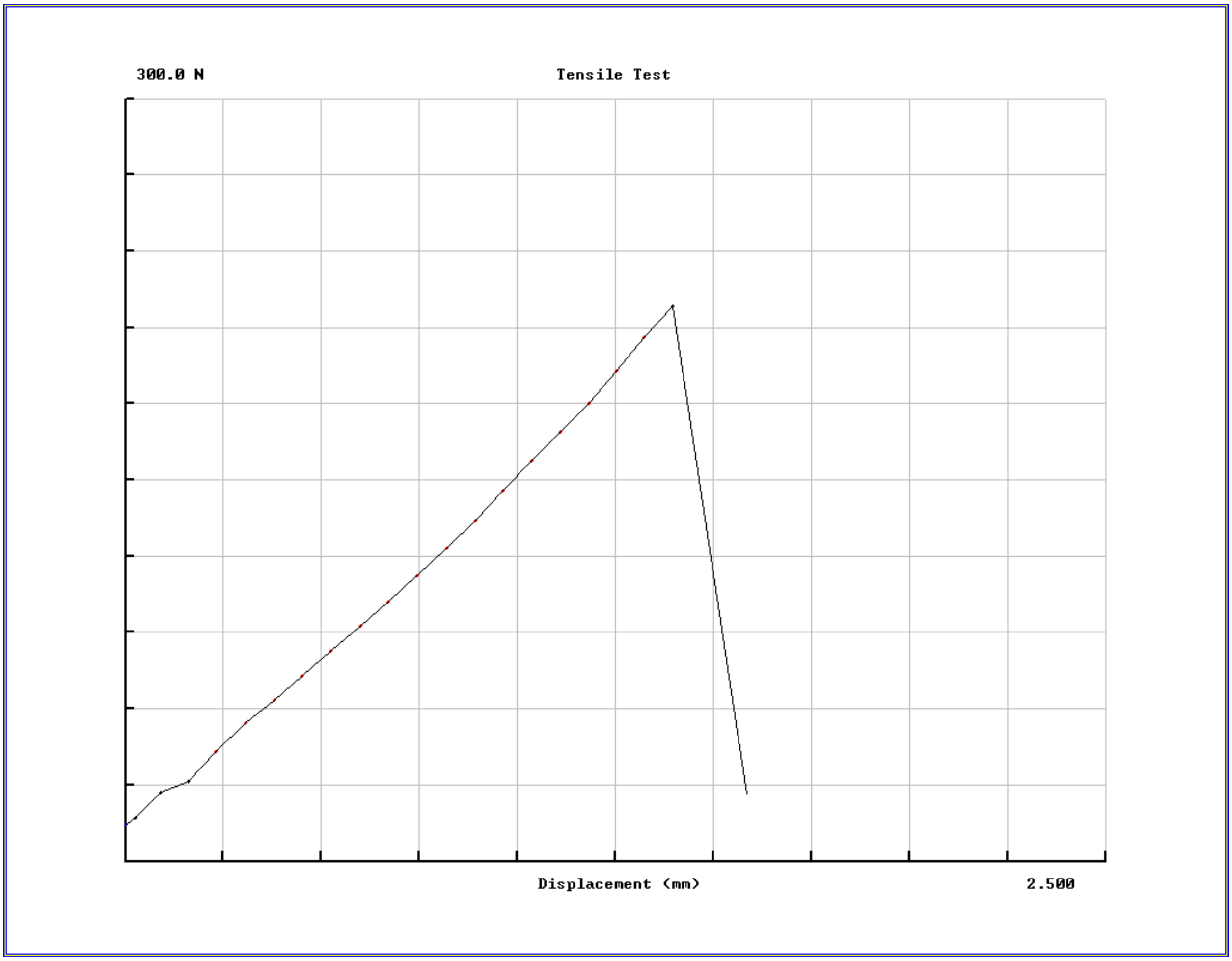
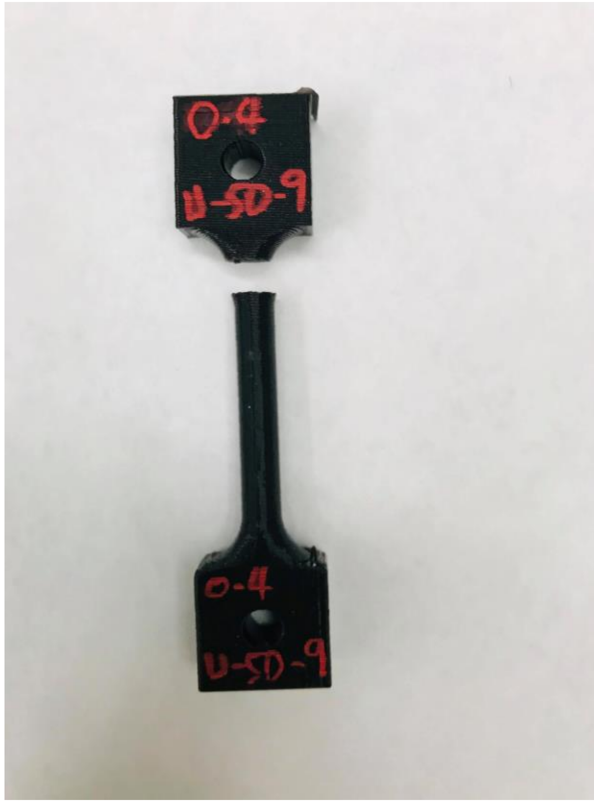
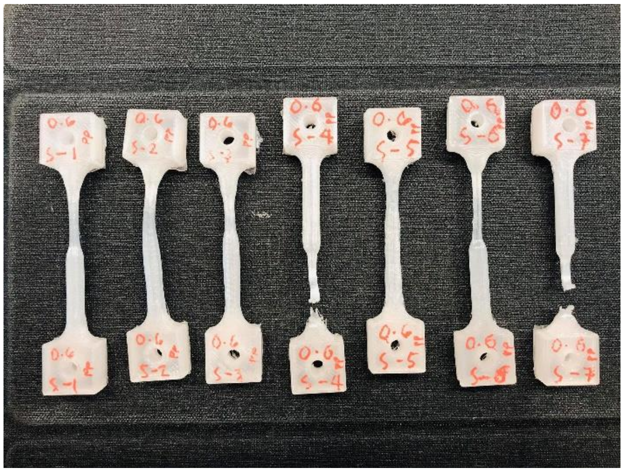


Figure 86: 0.4-U-50-9

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PLA	1237.39	218.34	7.88	0.4	1.59	Upright	6.41



N. PP, 0.6mm diameter nozzle, 100% Infill, Side printed



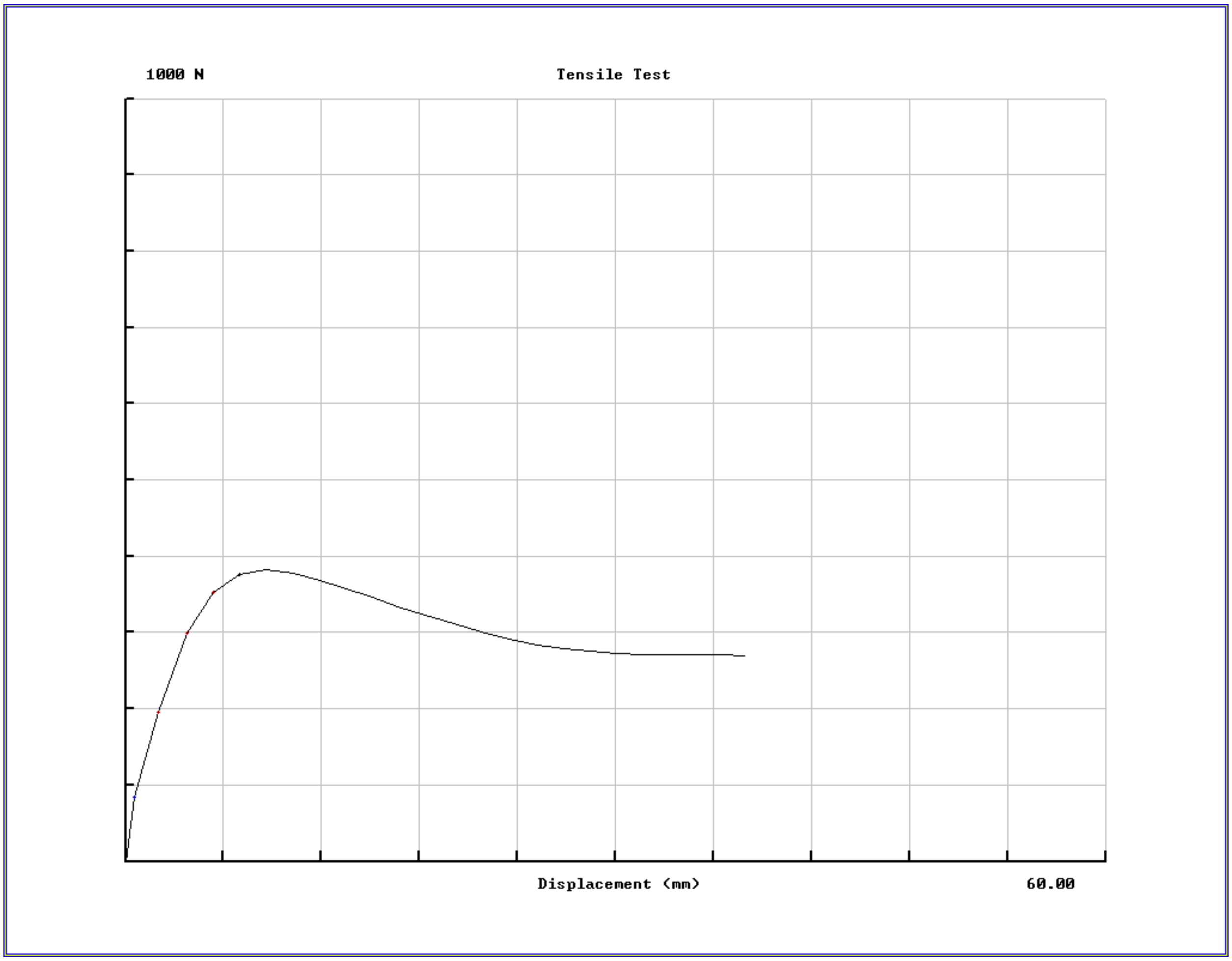
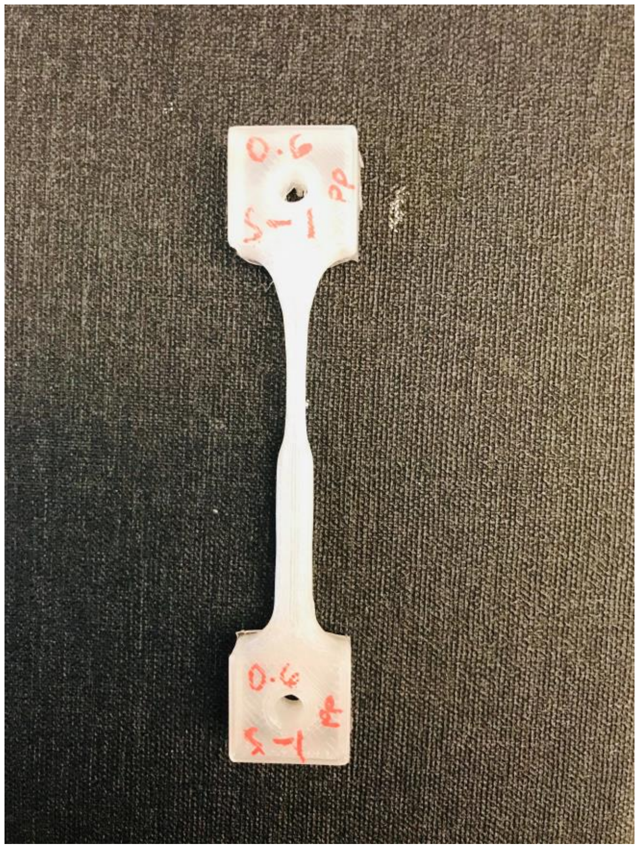


Figure 87: 0.6_PP-S-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	68.77	382.13	12.42	0.6	37.98	Side	6.26



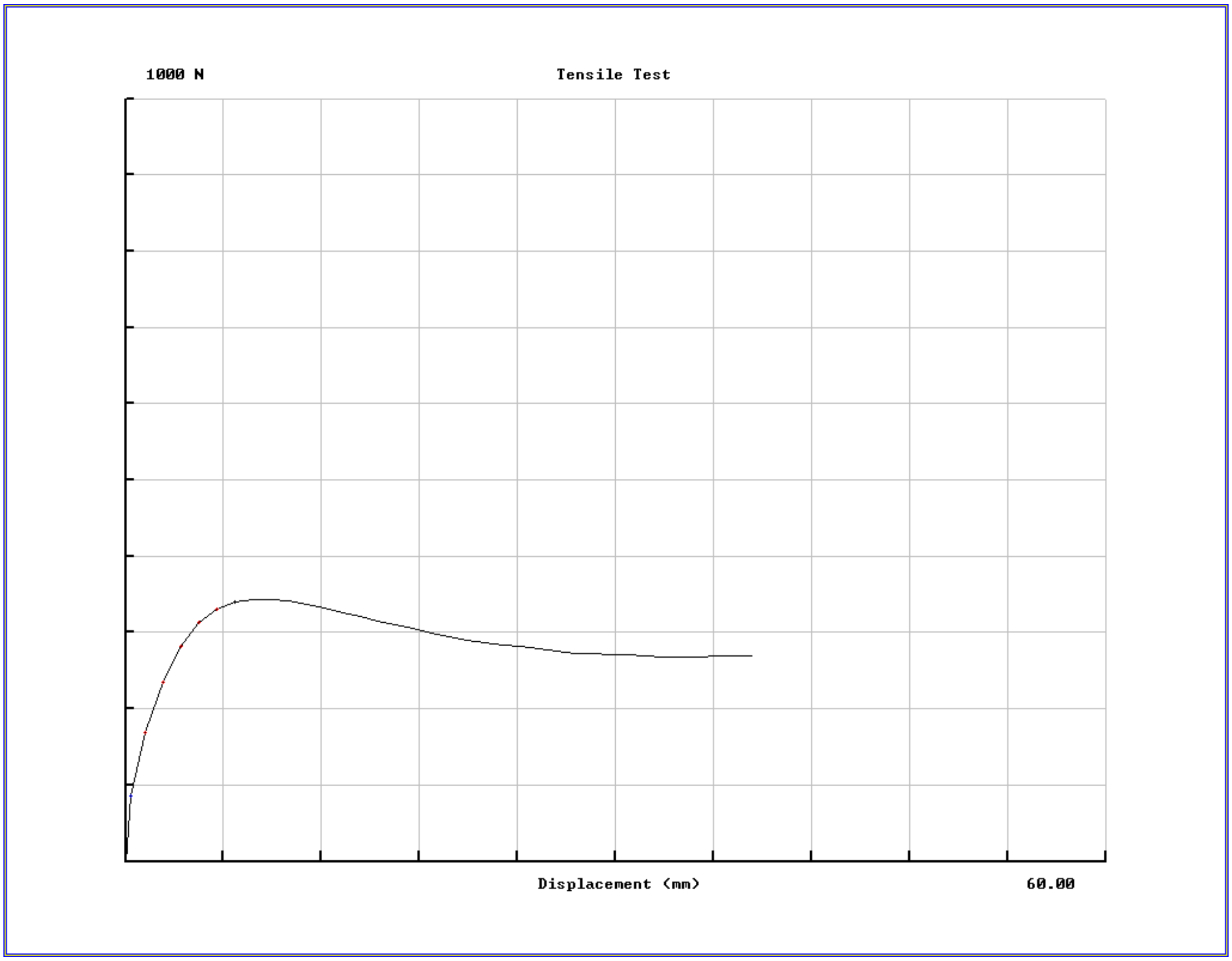
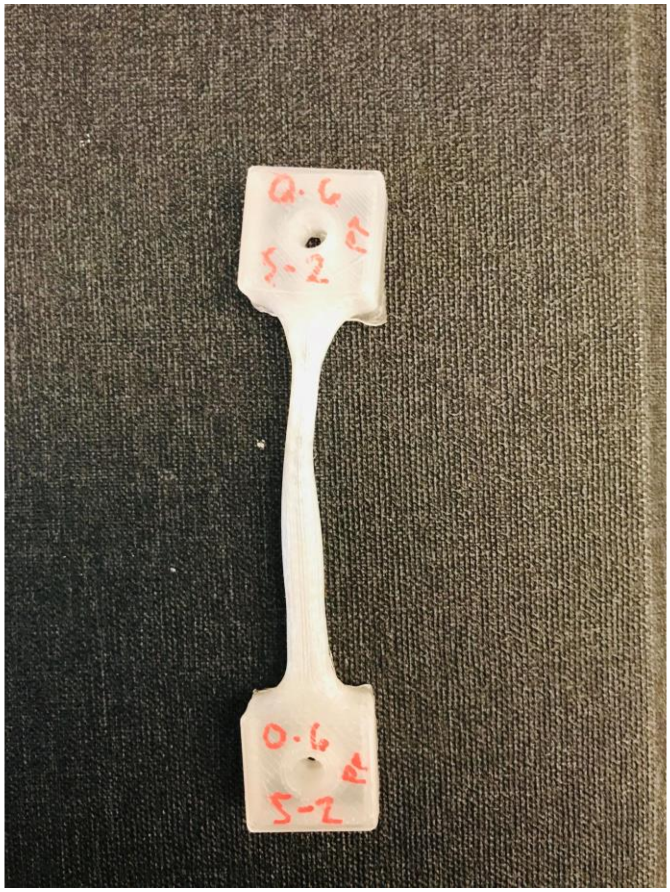


Figure 88: 0.6_PP-S-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	46.25	343.34	11.34	0.6	38.41	Side	6.21


5-2
0·6
5-2

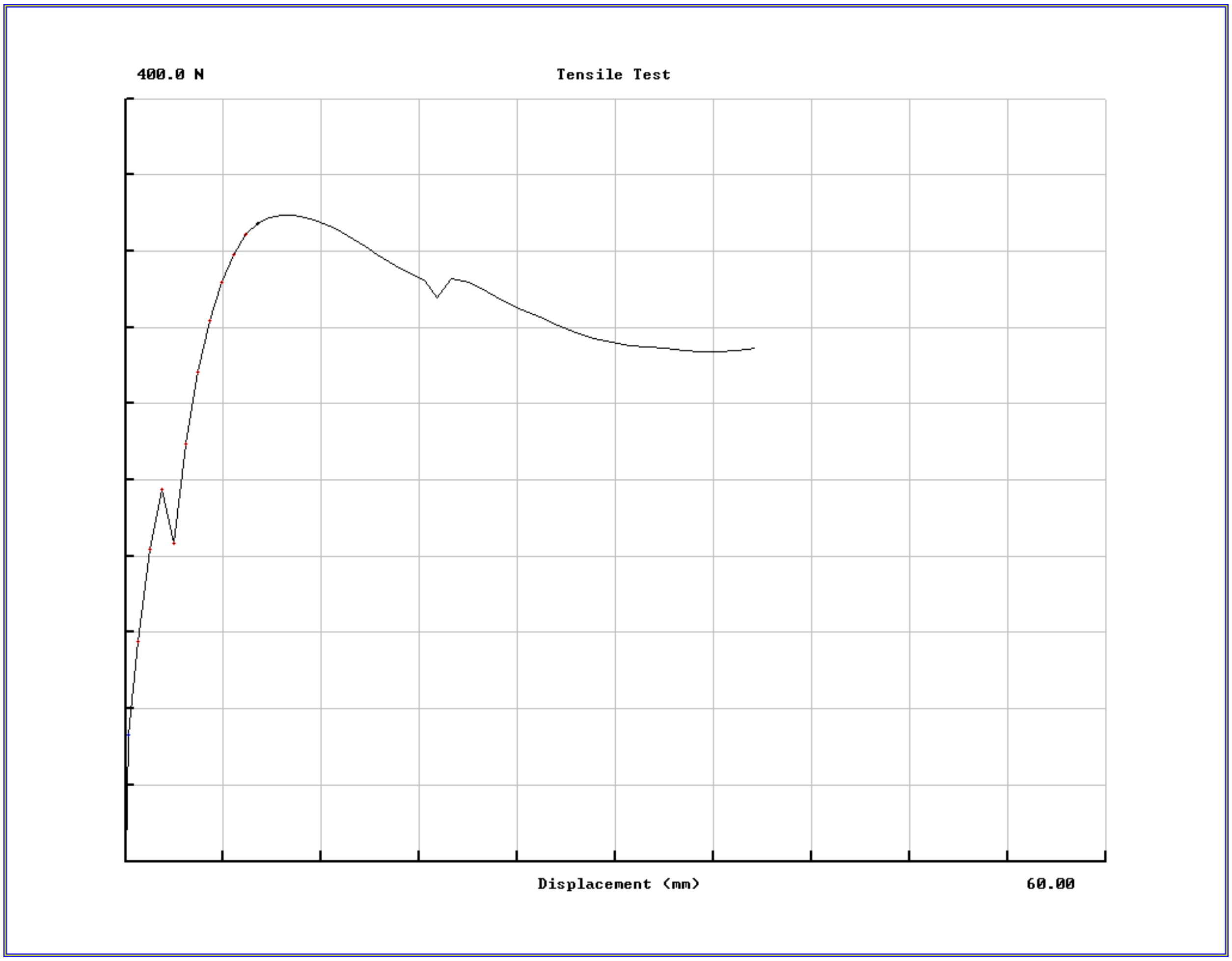
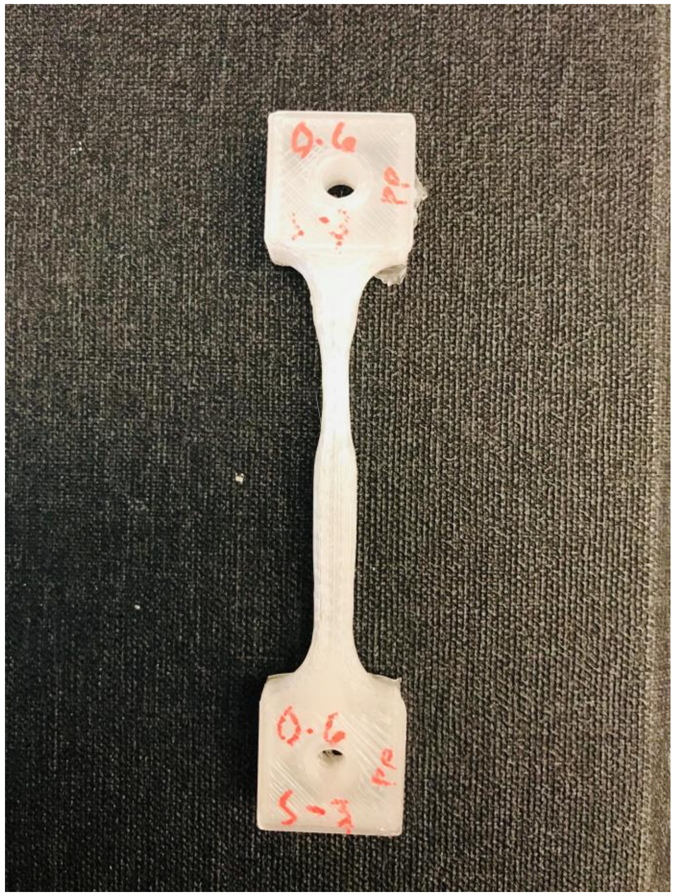


Figure 89: 0.6_PP-S-3

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	43.97	338.86	11.19	0.6	38.56	Side	6.22


0.6
PP
0.6
PP

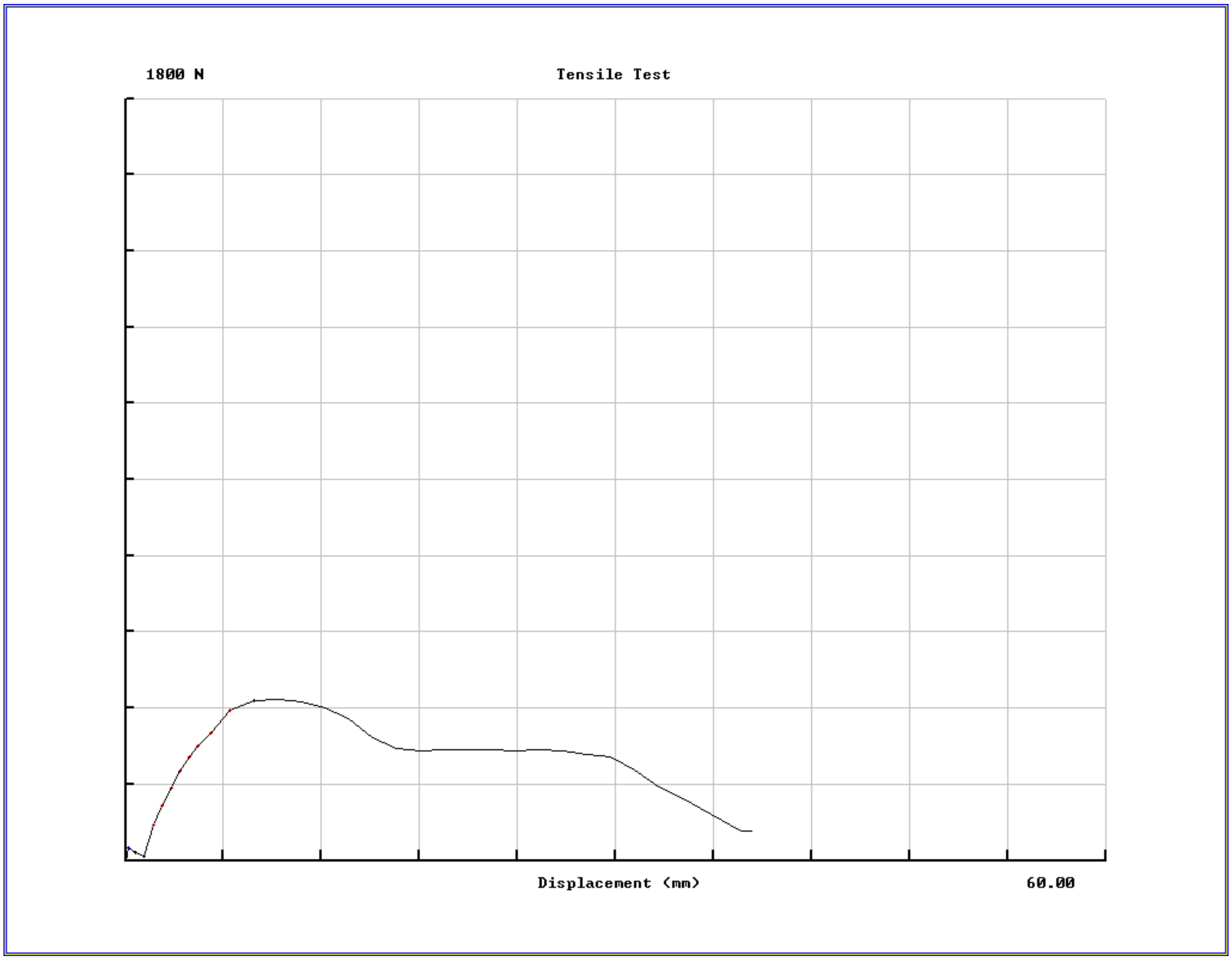


Figure 90: 0.6_PP-S-4

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	71.27	380.73	12.53	0.6	38.42376	Side	6.22


0.6
S-4
0.6
S-4

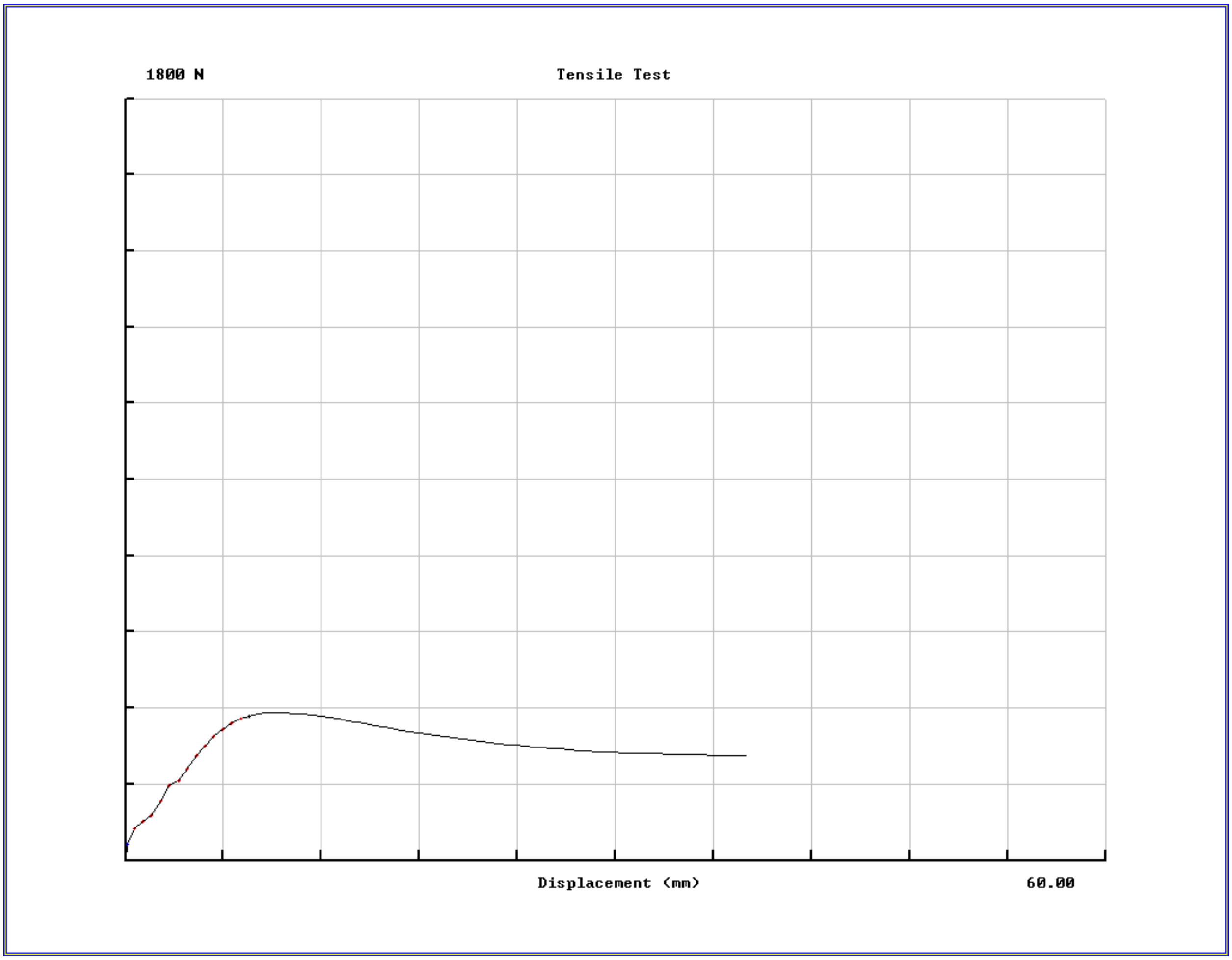


Figure 91: 0.6_PP-S-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	54.85	349.12	11.56	0.6	38.08966	Side	6.2

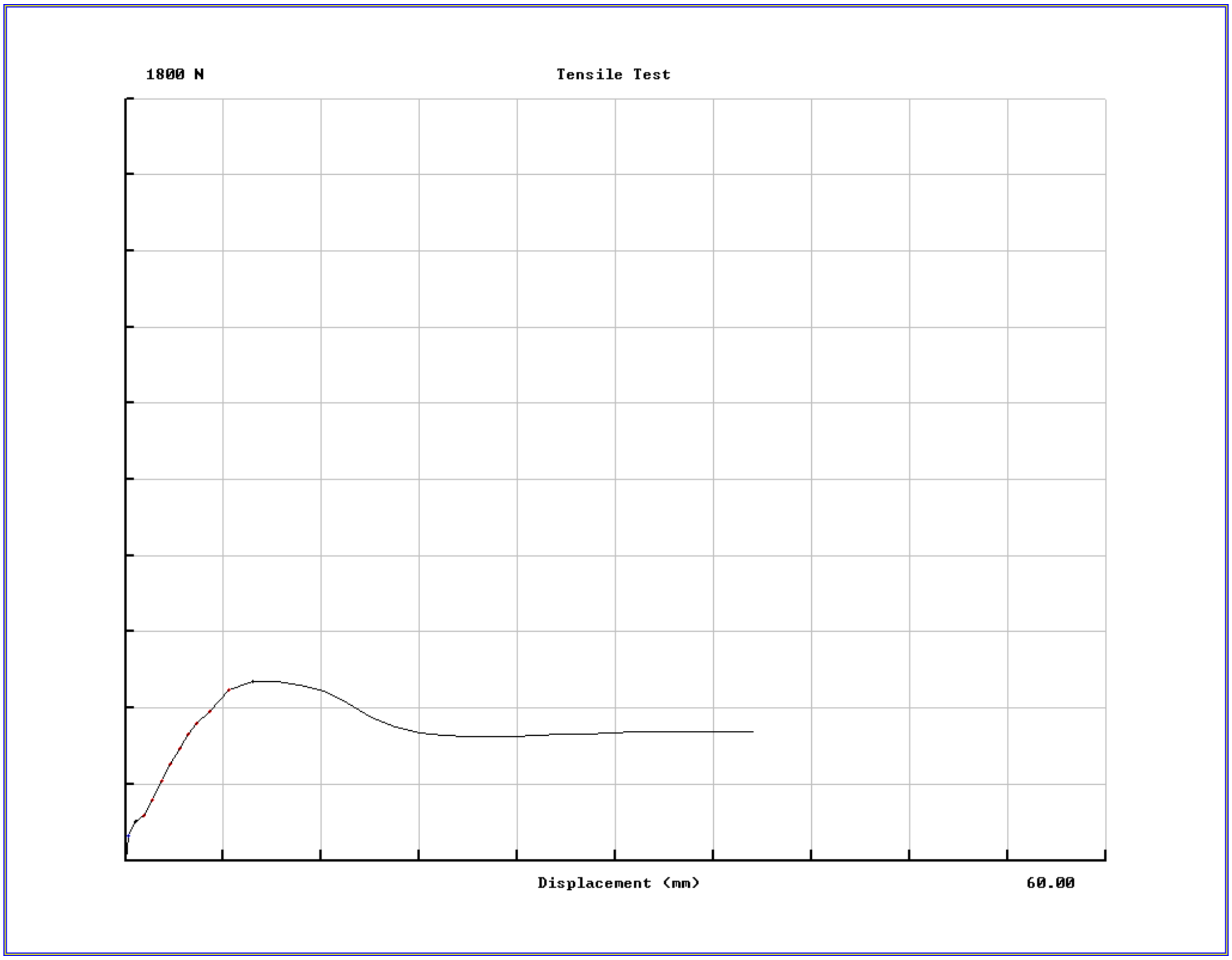


Figure 92: 0.6_PP-S-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	67.14	422.51	13.01	0.6	38.52981	Side	6.43


0.6

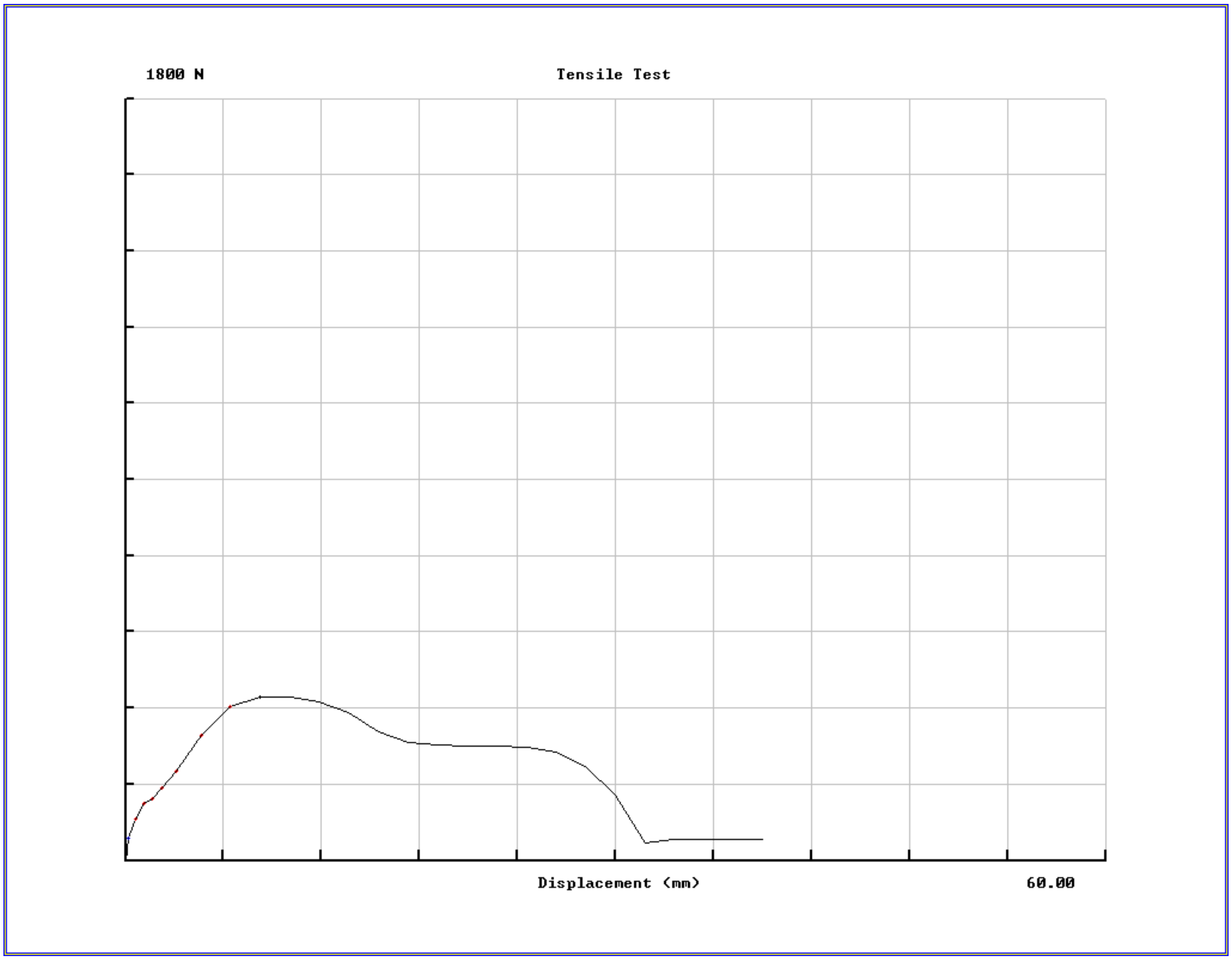
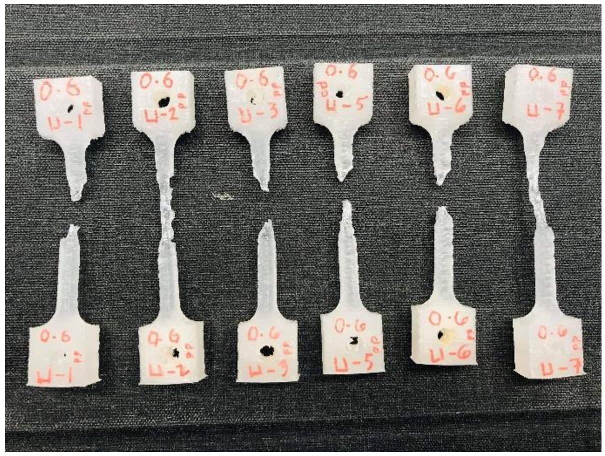


Figure 93: 0.6_PP-S-7

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	58.49	384.84	12.5	0.6	39.08136	Side	6.26

O. PP, 0.6mm diameter nozzle, 100% Infill, Upright printed



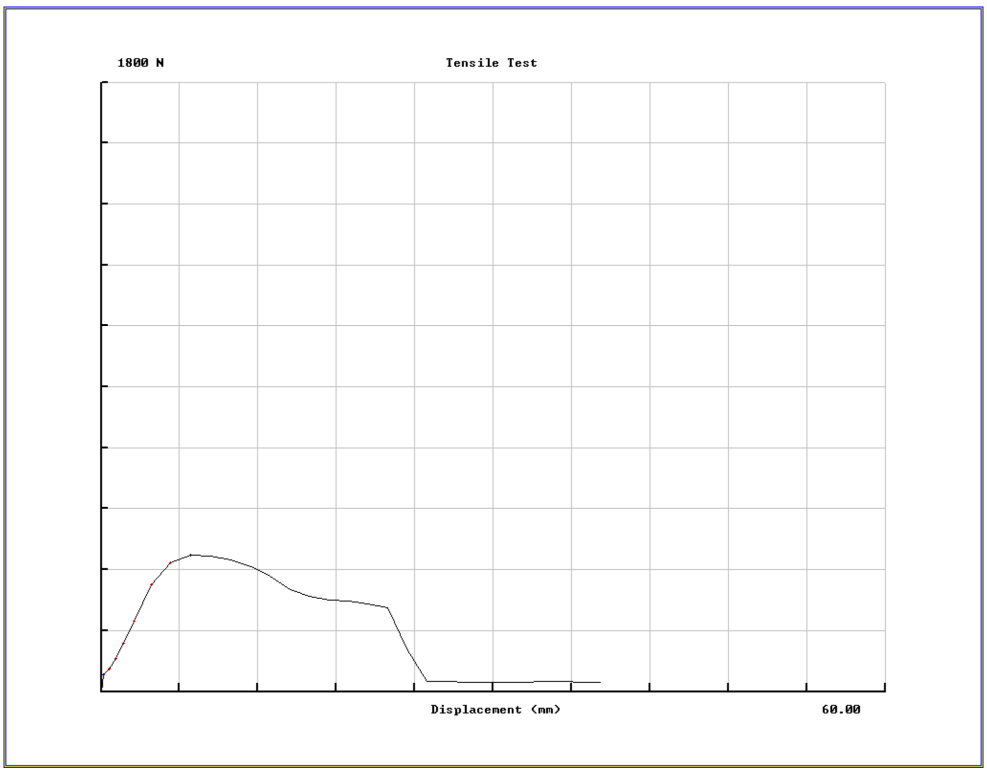
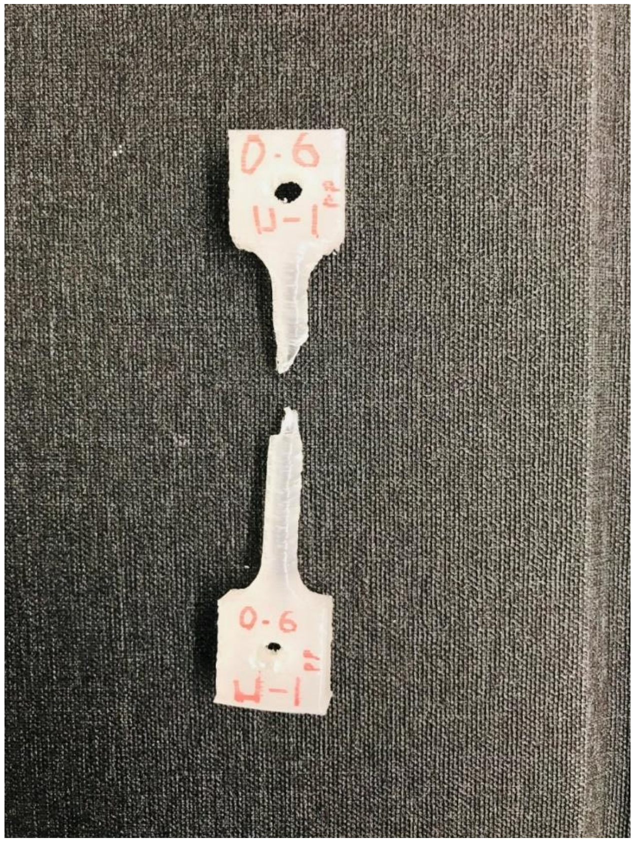


Figure 94: PP-U-1

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	85.46	402.75	13.09	0.6	38.25571	Upright	6.26



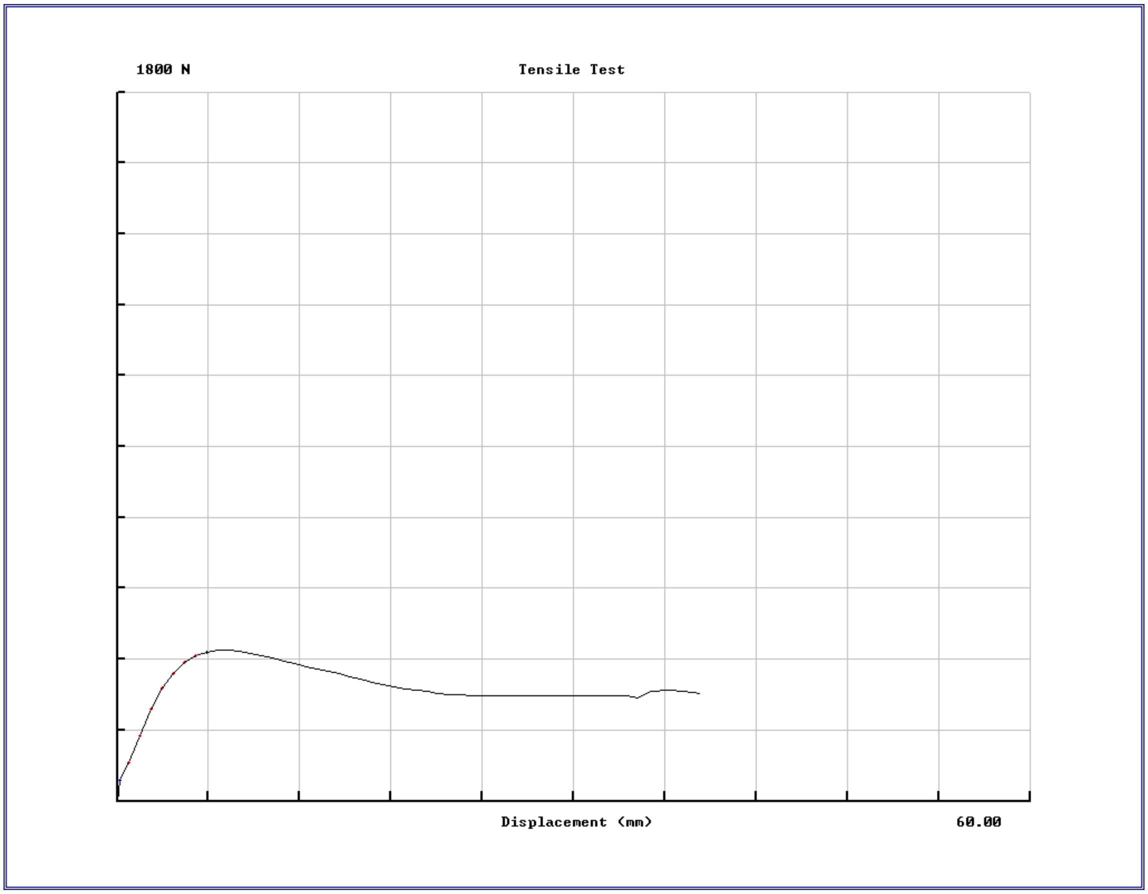
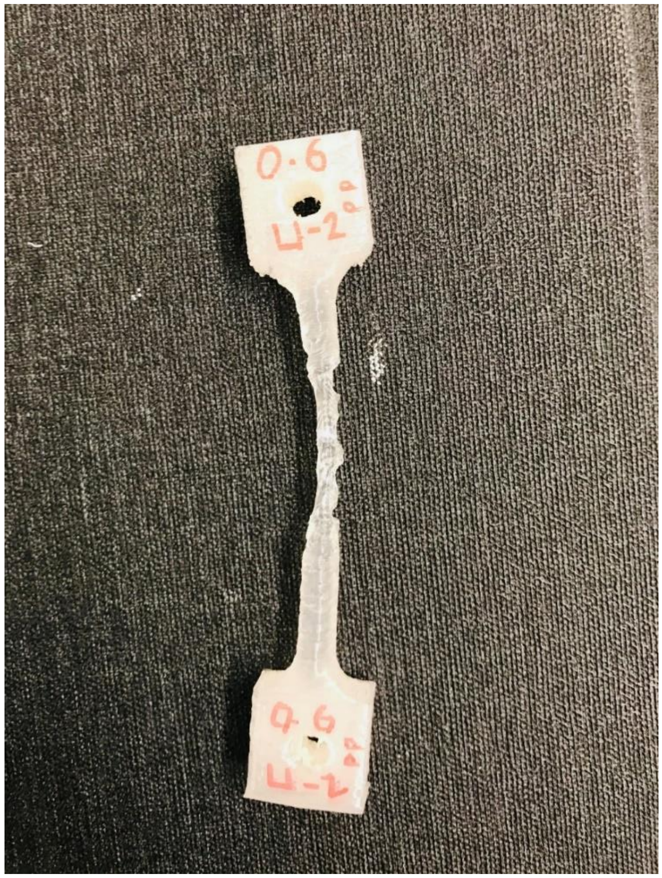


Figure 95: PP-U-2

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	83.8	382.54	12.67	0.6	38.36887	Upright	6.2



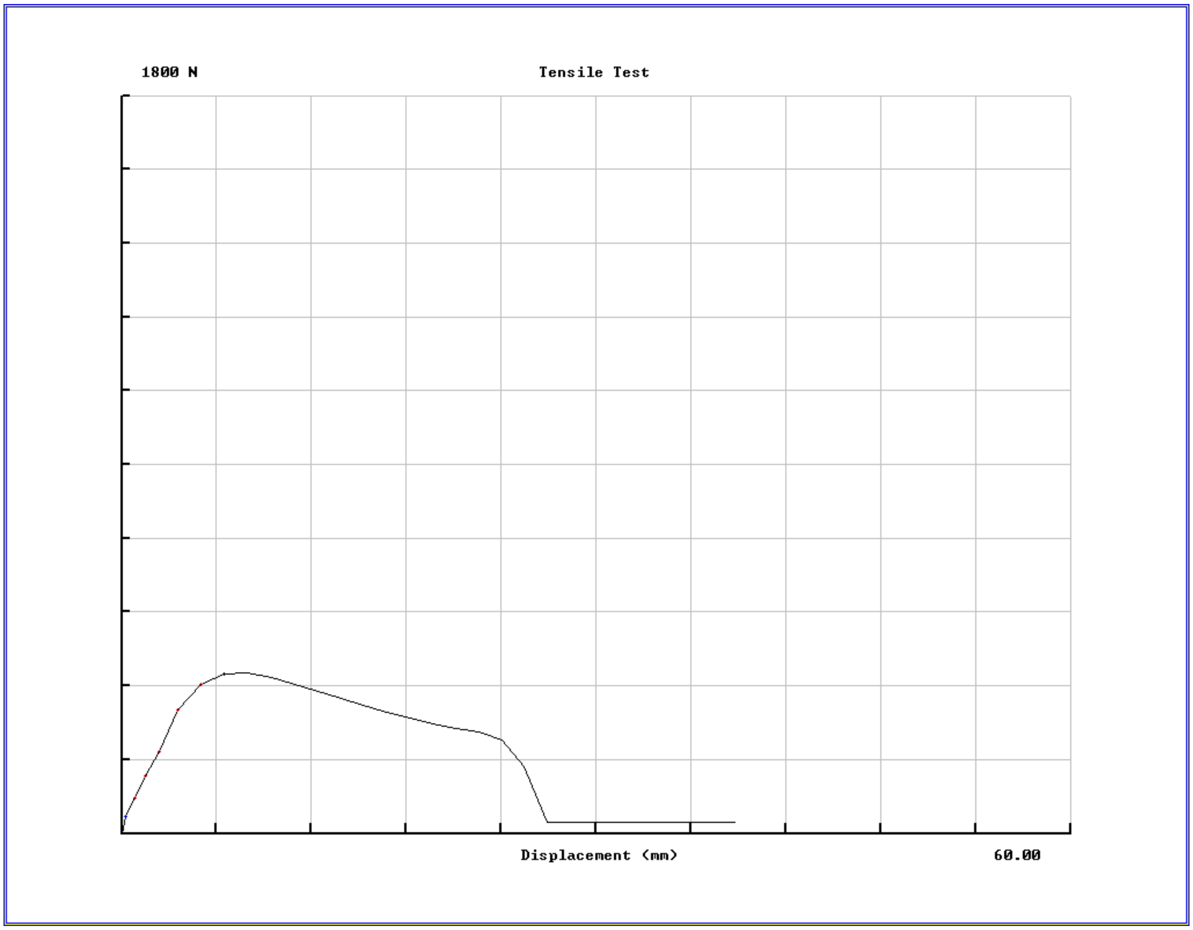
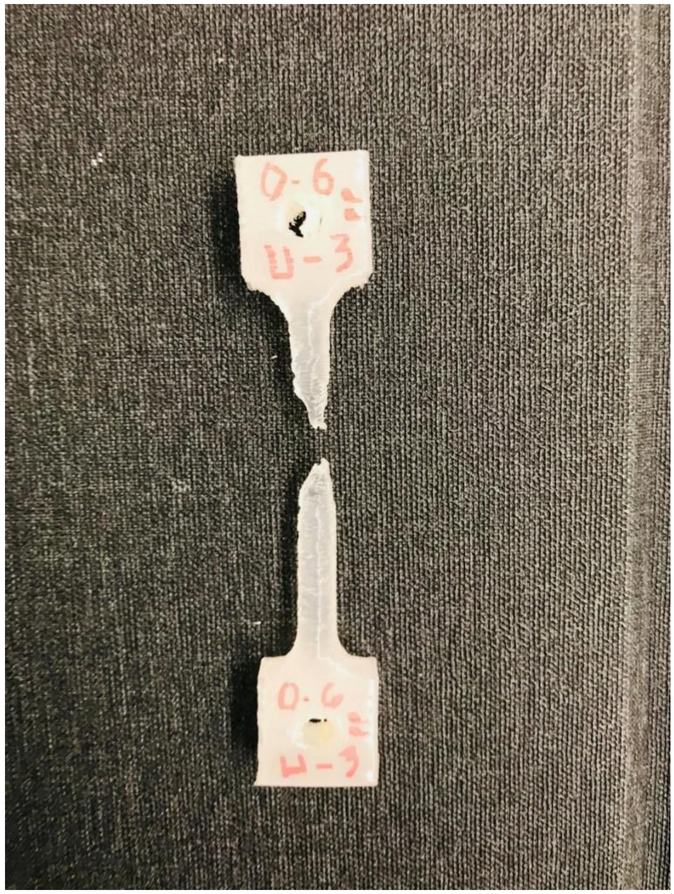


Figure 96: PP-U-3

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	86.5	390.82	12.94	0.6	38.85422	Upright	6.2


0-6
U-3
0-6
U-3

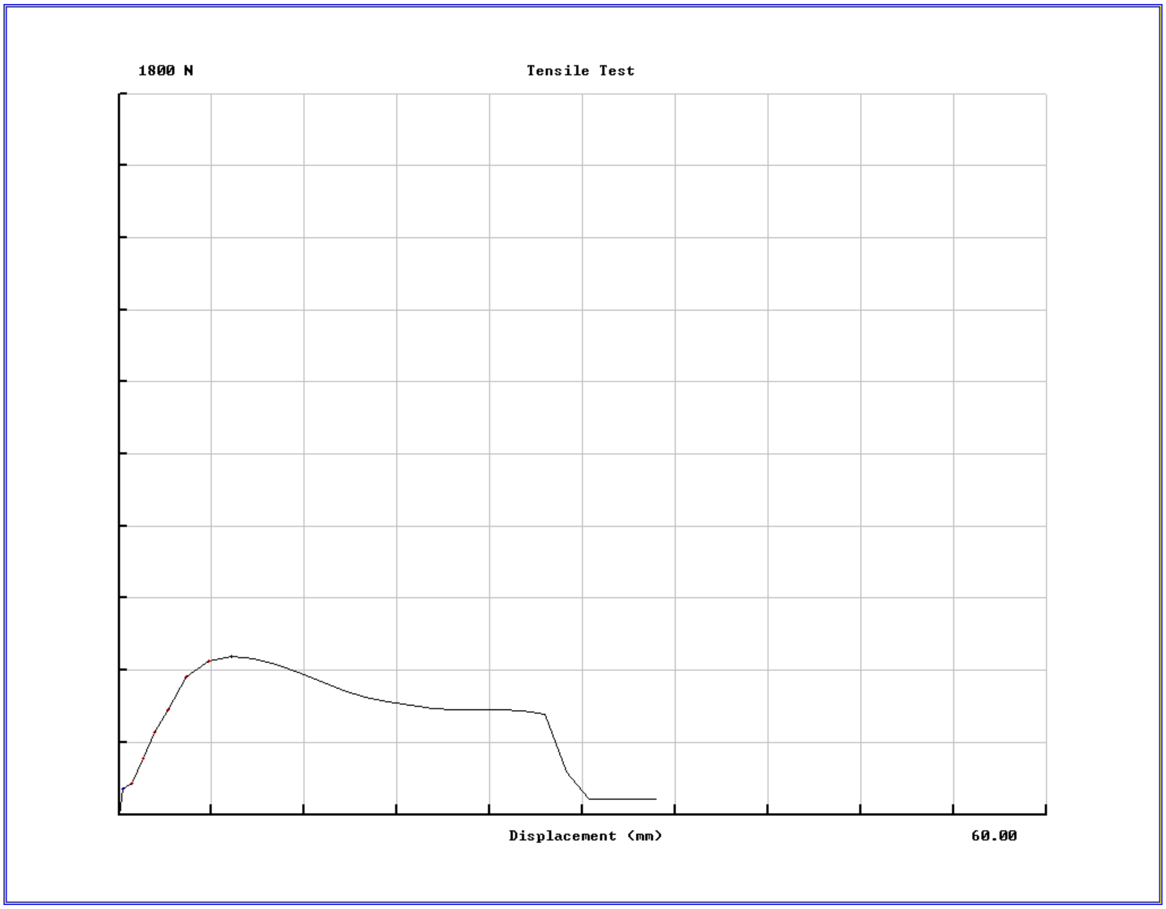
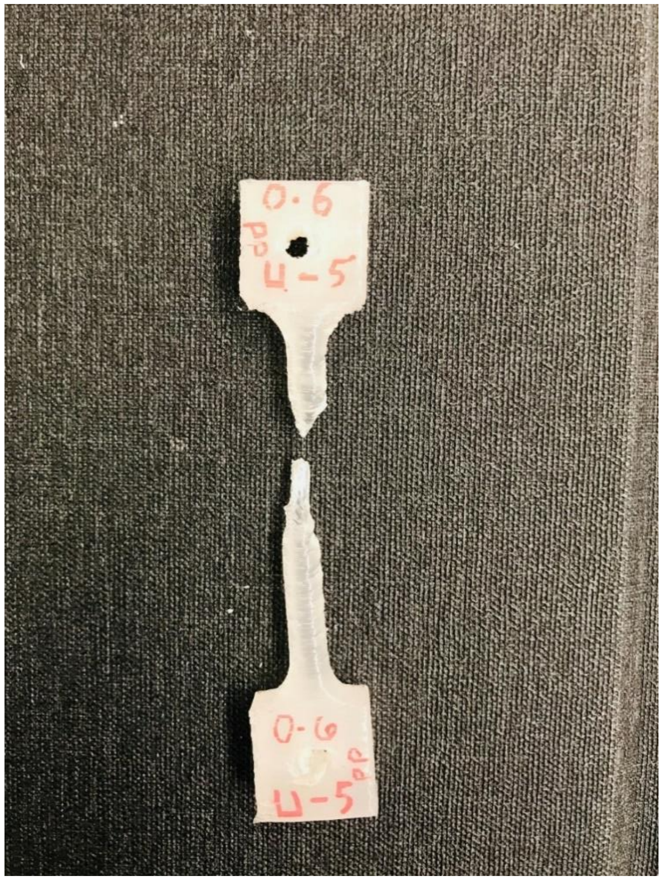


Figure 97: PP-U-5

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	76.46	393.39	12.74	0.6	34.80402	Upright	6.23


0·6
PP
U-5
0·6
U-5
PP

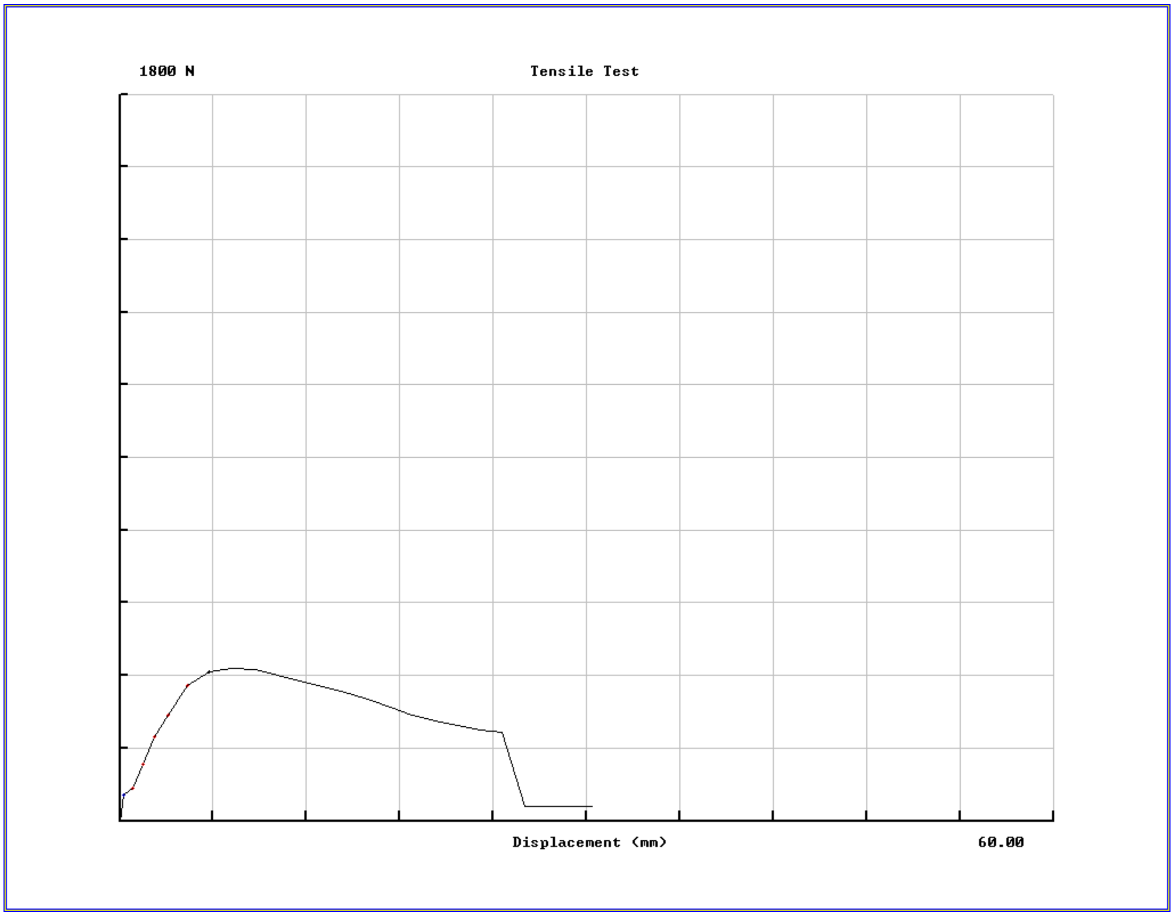
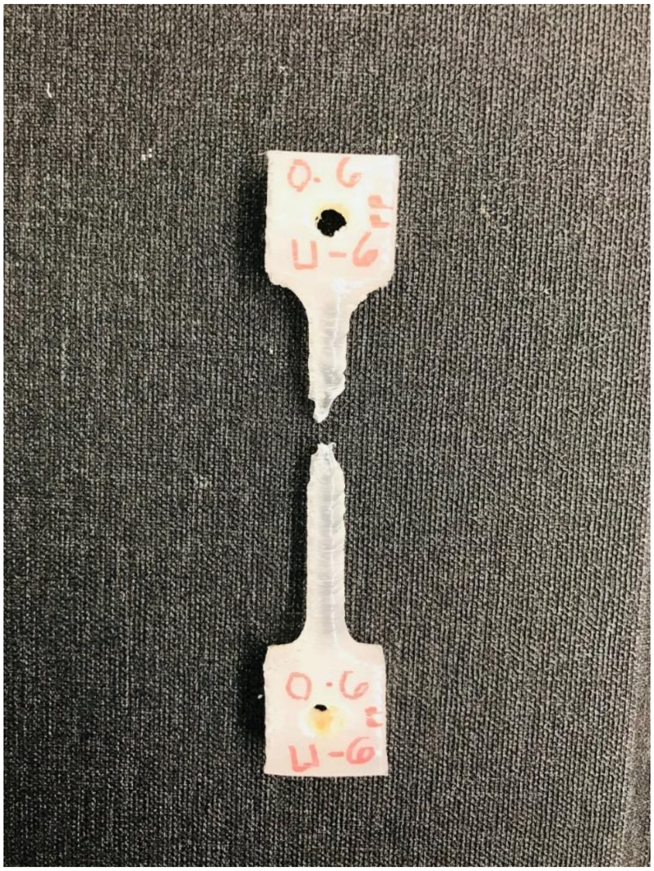


Figure 98: PP-U-6

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	88.77	378.22	12.33	0.6	30.43039	Upright	6.27



0-6
U-6
0-6
U-6

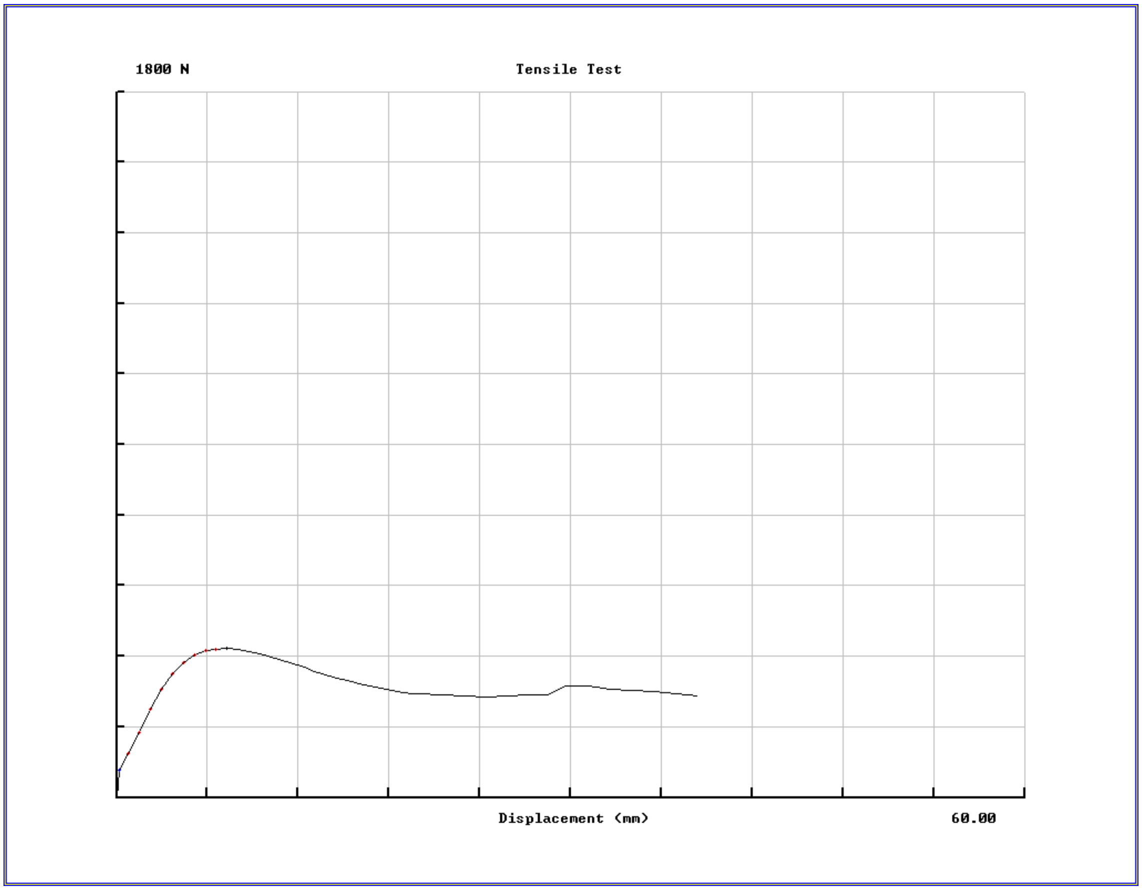
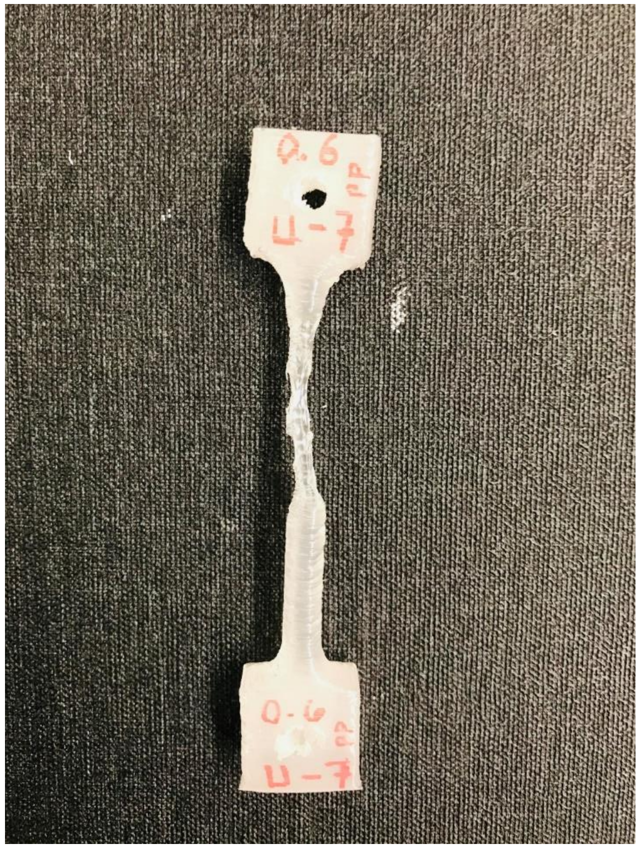


Figure 99: PP-U-7

Material	Young's Modulus (N/mm^2)	Rupture Force (N)	Ultimate Stress (N/mm^2)	Nozzle Size (mm)	Displacement (mm)	Print Orientation	Sample Diameter (mm)
PP	62.7	379.7	12.46	0.6	38.41562	Upright	6.25


0.6
PP
0.6
PP