<u>Tensile Testing of 3D Printed Materials for Scoliosis Brace</u>

by

Rahul Malik
Bachelor of Technology (Mechanical Engineering),
Maharshi Dayanand University, India
2012

A Report Submitted in Partial Fulfillment
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Supervisory Committee

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Dr. Nikolai Dechev (Supervisor)
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Department of Mechanical Engineering

Abstract

Tensile Testing of four different polymers was done to determine the best 3D printer material for developing a scoliosis brace using a 3D printer. Mechanical properties of various polymer materials have been studied to understand advantages and disadvantages, and to estimate the strength parameters. Four different polymers were eventually selected for testing: PLA, ABS, HDGlass (PETG) and Nylon. Test specimens were manufactured by 3D printing technology with specimens printed in side and upright orientations. Specimens were subjected to tensile testing to determine the properties of maximum tensile strength and Young's modulus. The superior material among these tested materials was PLA with a maximum tensile strength of 45.66 (N/mm^2) and the second strongest material was ABS with a maximum tensile strength of 35.44 (N/mm^2). The most flexible material was Nylon with low tensile strength of 22.06 (N/mm^2). PLA is considered to be the superior material from all other materials, with the next better material being ABS. Both Nylon and PETG are low strength materials when compared with PLA and ABS. The results achieved through these tests are of high significance in the development of a scoliosis brace.

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Acknowledgments

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Finally, I must express my very profound gratitude to my parents for providing me with unfailing help and support throughout my years of study and through the process of researching and writing this thesis report. This achievement would not have been possible without them. Thank you.

Dedication

I dedicate this thesis report to my family for providing me support and love throughout my years of study, without their constant support this would not have been possible.

CHAPTER 1

3D Printing (Additive Manufacturing)

1.1 3D Printing

3D printing (rapid prototyping) is a new advanced manufacturing process which manufactures functional products based upon a 3D CAD (Computer Aided Design) model. This CAD model is then further processed with a slicer software, such as CURA, that converts the CAD model into set of machine G-code instructions that are used to command the motors of a 3D printing machine. The 3D printing process can be used with different types of plastic materials. This new technology is most likely going to be the future manufacturing process to save time, money and efforts within certain industries and within research and development [1, 2, 3].

Recent developments in additive manufacturing (AM) or 3D printing have resulted in numerous applications toward the engineering sector and the medical sector. AM can offer the capacity to manufacture complex CAD shapes, to produce final product designs with specific chemical, physical, and mechanical properties. This has allowed the production of various medical implants and devices for medical applications [4].

1.1.1 How does it work?

The 3D printing machine (called a 3D printer) is an innovation that uses an x, y, z robotic stage combined with other deposition technologies, to print products from referenced 3D CAD models. The CAD model is created using CAD software such as Solidworks, Auto CAD, or other. This CAD model is then converted to the G-code using slicer software and sent to the 3D printer. The G-code is similar to a CNC programme which will move the printer material deposition system, to print the final product as per the instructions. The recent developments in this process can allow printing variety of materials including plastics and polymers, and in some cases metals, ceramics and non-metals [1, 2, 3].

1.1.2 Advantages

There are several advantages to 3D printing:

- No specialized tooling is needed, thus significantly reducing production time and cost.
- Small production batches are feasible and economical.
- Possibility to quickly change design.
- Easy to produce prototype products.
- Waste reduction.
- Shorter lead times for easy supply chain and lower inventories.
- Design customization.

The advantages described above also allow for personalized design of medical devices matched to individual body shapes. Hence, this technique has good application towards fabrication of spinal braces [1, 2, 3].

1.1.3 Applications

Due to the relative high cost of Additive Manufacturing (AM) technologies in comparison to injection molding, AM has limited adoption by manufacturers; however, in the engineering research and development sector, medical field, and in some construction industries they are gaining popularity.

There are many new AM opportunities available in the biomedical field regarding the 3D printing of custom-shaped orthopedic, dental implants, medical equipment and tissue scaffolds. CAD/CAM-based AM technologies for plastics, metals and non-metals have established many applications in the near net shape fabrication of complex geometries with tailored mechanical properties for biomedical sectors [1, 2, 3].

1.1.4 3D Printing Technologies

There are a variety of 3D printing techniques available in the market to fabricate plastic parts, where the most recommended and accepted are as follows: Fusion Deposition Modelling, Selective Laser Sintering, Inkjet 3D printing, Stereolithography and 3D plotting. In addition other 3D printing technologies for printing of metals, ceramics and composites are rarer in industrial use, or are still in the process of development.

Each technique has its own benefits and drawbacks during the manufacturing process.

The choice and selection of the fabrication technique depends on the selection of raw materials, requirement of processing speeds and resolution, cost and performance needs for the intended application. The established fast prototyping techniques are summarized in Table 1 [3].

Table 1. A summary of established rapid prototyping techniques [3]

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
SLA	Liquid photopolymer	Photocurable resin (epoxy or acrylate based resin)	Laser scanning and UV induced curing	High printing resolution	Material limitation, cytotoxicity, high cost
SLS	Powder	PCL and polyamide powder	Laser scanning and heat induced sintering	Good strength, easy removal of support powder	High cost, powdery surface
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
3D plotting	Liquid or paste	PCL, PLA, hydrogel	Pressurized extrusion, and heat or UV-assisted curing	High printing resolution, soft materials capability	Low mechanical strength, slow

Fused deposition modeling (FDM)

Fused deposition modeling (FDM) printers are the most commonly used printers for fabricating polymer structures. Polymer materials such as Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA), are generally used because of their low melting temperatures. FDM printers work by controlled extrusion of thermoplastic filament, as shown in Figure 1. In FDM, filaments are heated into a semi-fluid state within a chamber, and forced out of the chamber through a nozzle. The extruded plastic is then moved along the x-y plane to create a single layer 2D shape. Subsequent 2D layers are added on top of each other where layers are fused to solidify into final product. The quality of printed parts can be controlled by modifying printing parameters, for example, layer thickness, printing orientation, raster width, raster edge and air hole [5].

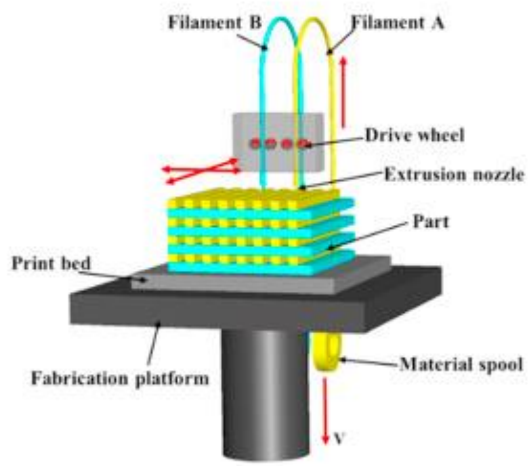


Figure 1. Graphic Illustration of a FDM setup [5]

One major drawback of FDM printing is that the composite materials need to be in a filament form to enable the extrusion process. It is difficult to homogeneously disperse reinforcements and remove the void formed amid the manufacturing of composite filaments. Another hindrance of FDM printers is that the usable material is restricted to thermoplastic polymers with reasonable melt viscosity. The liquid thickness ought to be sufficiently high to give auxiliary support and sufficiently low to facilitate the extrusion. In spite of from these downsides, FDM printers additionally offer points of interest, including minimal effort, fast print time, and ease of learning. Another preferred standpoint of FDM printing is the possibility to deposit different materials. More than one extrusion nozzles with different materials can be set up in FDM printers. Hence, the final printed parts can be a mixture of composition of materials if needed [5].

Powder bed and inkjet head 3D printing (3DP)

Powder bed and inkjet 3D printing innovation was first built at the Massachusetts Institute of Technology (MIT) in 1993 as a rapid prototyping advancement. This technology relies on powder handling, as shown in Figure 2. The process works as follows: Powders are first spread on the construct stage and then selectively joined into a designed layer by depositing a liquid binder through inkjet print head, which can move in X-Y direction. After a preferred 2D example is shaped, the construct stage is lowered and an additional layer of powder is spread, and then selectively joined by deposition of liquid binder. This procedure is repeated hundreds of times to produce the desire part. Finally, the non-binded powder is removed to get final products. The internal structure of the product can be controlled by altering the amount of deposited binder. Powder size, binder viscosity, interaction between the binder and powder, and the binder deposition speed are the major constituents that can decide the quality of final products. The main advantages of this technology are the flexibility of material choices and room temperature handling condition. Theoretically, any polymer materials in powder state could be printed by this technology. But the printing resolution for this technology is especially restricted [5].

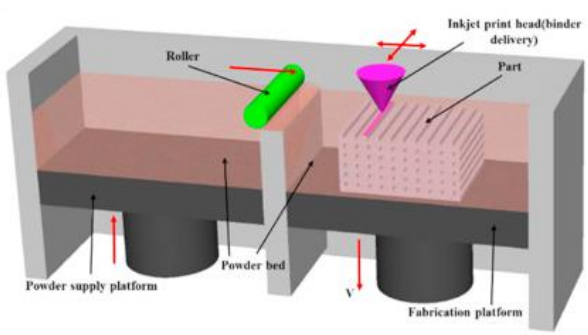


Figure 2. Graphic Illustration of a 3DP setup [5]

Stereolithography (SLA)

Stereolithography utilizes photopolymers that can be shaped by UV laser. A UV-laser is controlled in a desirable way to shoot in the resin pool, and the photocurable resin will polymerize into a 2D shape on the surface of its layer. After each layer is cured, the stage moves down by 1 layer height, and another layer of resin is prepared to be designed, as shown in Figure 3. The usual polymer materials utilized as parts of SLA are acrylic and epoxy materials [5].

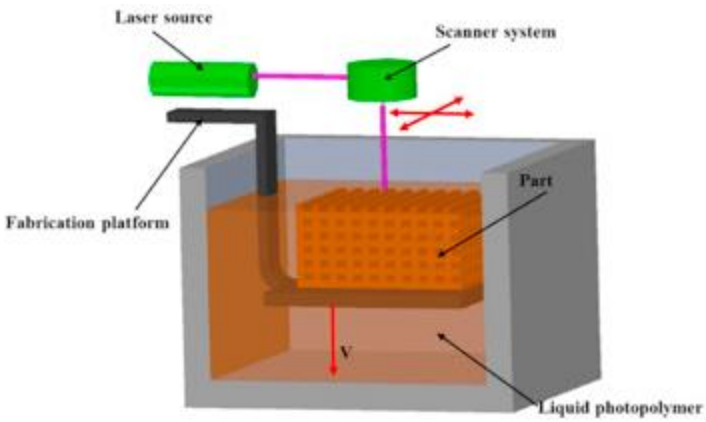


Figure 3. Graphic Illustration of SLA setup [5]

It is very critical to understand the curing reactions happening in the course of polymerization to control the quality of final printed parts. Force of laser power, scan speed and duration of contact influence the curing time and printing resolution. Photoinitiators and UV safeguards can be added to the resin to control the deepness of polymerization. The principle preferred standpoint of SLA printing technology is the capacity to print parts with high resolution. SLA is a nozzle free method; therefore, the problem of nozzle clogging can be eradicated. Even though SLA has these advantages, the high cost of this technology is a major drawback for modern application [5].

Selective Laser Sintering (SLS)

Selective laser sintering (SLS) strategy is similar to 3DP method and they are both based on powder processing. Rather than utilizing a liquid binder, in SLS, a laser beam with a controlled way scans the powders to sinter them by heating, as shown in Figure 4. Under high power lasers, neighboring powders are fused through atomic diffusion and afterward the printing of next layer begins and the uncontrolled powder will be removed to get final products. The resolution of the final products is decided by powder molecule size, laser control, scan spacing and speed. Even though in practice any thermoplastic polymer in powder form could be prepared by SLS procedure, but the intricate combined behavior and diffusion process during sintering have constrained the selection of materials utilized as a part of SLS process. To the date now, polycaprolactone (PCL) and polyamide (PA) is generally utilized laser sintering materials [5].

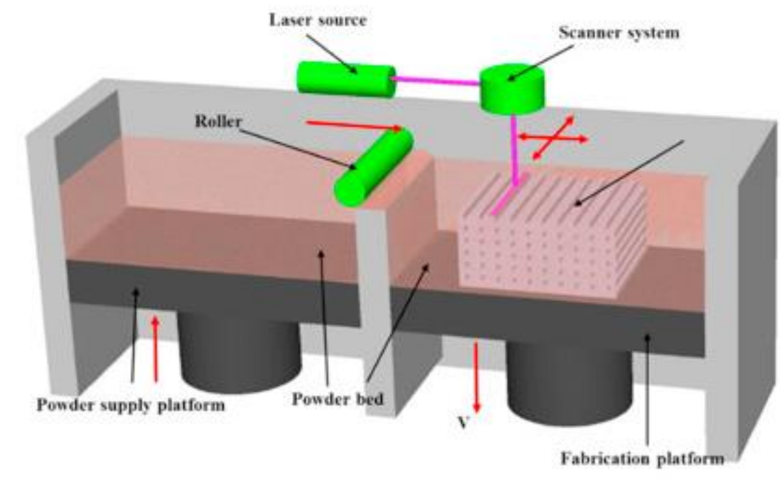


Figure 4. Graphic Illustration of SLS setup [5]

3D plotting/Direct-Write

3D plotting depends on expelling a thick material from a pressurized syringe to make 3D state of materials, as shown in Figure 5. The syringe head can move in three dimensions, while the stage keeps stationary where expelled materials are joined together layer by layer. Curing reactions can be done by providing two reactive segments utilizing mixing nozzles or be either by heat or UV light. Material viscosity and deposition speed associate with the quality of the final printed parts. The key preferred standpoint of this method is material adaptability [5].

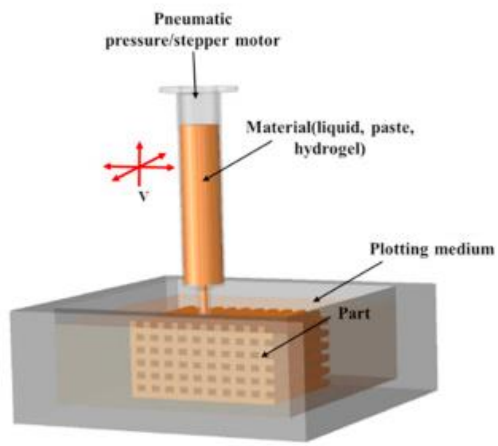


Figure 5. Graphic Illustration of 3D plotting setup [5]

Additional Techniques

In recent times, a few new strategies are produced for 3D printing of composites, for example, PolyJet which works by polymerization of the deposited droplets of photopolymer ink, digital light processing (DLP) which depends on particular polymerization of a whole surface of photopolymer by a projector light, liquid deposition modeling (LDM) which comprises in the additive deposition of material layers straightforwardly from a solution in a volatile solvent, and fiber encapsulation additive manufacturing (FEAM) which includes specifically summarize fiber from polymer matrix. When compared with traditional 3D printing systems, these strategies have either more material choices or less preparing time. However, because of their high cost and complexity, they are currently used in research procedures [5].

1.2 Thermoplastics or polymers used in 3D printing

For more than 30 years polymeric materials are used in the medical applications. A wide range of nondegradable and degradable materials have been approved by the Food and Drug Administration (FDA) for human use.

As 3D printing becomes more popular, and the cost of 3D printing machines drops down from the costs of only a few years ago, so the cost of feedstock also drops and at a time when the range of printing materials increases [4]. It is now possible to print utilizing different thermoplastic materials that can be melted and reformed to form complex shapes. A standout amongst the most widely recognized techniques for ease work area top printing is the Fused Filament Fabrication (FFF) prepare [4]. This technique utilizes a thin fiber of fusible thermoplastic to develop an item in layers. Each layer of the hot material welds onto the already set down and bit by bit creates the entire part. This is a straightforward process and one that can make parts of high solidity and complex shape. There are a number of prominent thermoplastics that can be used with this procedure, providing different results relying on their base properties. The primary materials as of now utilized incorporate Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyamide (PA), High Impact Polystyrene (HIPS) and Thermoplastic Elastomer (TPE) [4].

1.3 Well known 3D printing Polymers

1.3.1 Polylactic Acid (PLA)

Polylactic acid (PLA) is a kind of thermoplastic polyester used in 3D printing. It is made from renewable sources like corn starch, tapioca roots or sugarcane. An important aspect is that PLA degrades naturally when exposed to environmental conditions. Although PLA degrades when exposed to environment conditions, it is still very vigorous when utilized in some applications e.g. bottles, toys and biodegradable medical devices (rods, screws and pins and plates that are expected to biodegrade within 6-12 months). Thus, we can compare it to iron metal which when exposed to moisture and left outside overnight it could rust and become unstable quickly. But if it was kept away from moisture exposure in the environment it would remain stable for longer. Certainly, PLA is much weaker than iron metal [6].

PLA is currently applied in various industrial functions ranging from packaging of food materials and in some cases medical implants which include temporary tissue screws, sutures and tacks. Over a few weeks PLA will dissolve in the body. PLA can be classified in various grades which include scientific, food safe, medical and type used in PLA printing. The melting point for PLA is around 180ºC and is combined with other plastics to make it stronger when used in 3D printing. PLA is not thermally contractive and is normally efficient when used to print huge pieces. One key thing to note about PLA is that stiffness and hardness makes it more brittle than other tough plastics. In cases where the final product must endure sharp collisions then PLA may not be used as the printing material [6].

The other imperative thought when printing parts with PLA fiber is comprehending what sorts of temperatures the part will be subjected to. PLA plastic begins to soften like rubber at temperatures of 80°C and will disfigure if utilized in conditions that stay over those temperatures for any drawn-out time. In contrast ABS (described in next section) is tough, ductile material with wear resistance and heat tolerance [6].

Table 2. Specific properties of Polylactic acid (PLA) material [6]

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

1.3.2 Acrylonitrile Butadiene Styrene (ABS)

ABS (Acrylonitrile Butadiene Styrene) is an opaque thermoplastic and amorphous polymer used in 3D printing. ABS is normally created using an emulsion process for example similar to how emulsified milk products are made and since ABS is a thermoplastic material, it can be effectively recycled. It is used to make durable parts that can resist high temperatures. It is less brittle as compared to PLA filament, and it is much tougher. It can also be post-processed with acetone to offer a glossy varnish [7].

ABS is subject to more shrinking than PLA, hence it is more difficult to print for people less experienced, hence it is losing prevalence among 3D printing technology researchers. Part shrinkage must be taken in account for proper prints. Since ABS since is oil based, it is not considered to be eco- friendly like PLA When heated in a 3D printer for the manufacture procedure, ABS can emit fumes that may be harmful in high concentrations [7].

ABS has good physical properties and also it is more resistant to chemical damage. The machinability of ABS is poor and it has low melting temperature making it especially easy to use in mix products procedures or 3D imprinting on a FDM machine. ABS is additionally generally reasonable. ABS plastic is not ordinarily utilized as a part of high temperature applications because of its low melting point. Because of these properties ABS is being utilized as a part of different engineering applications [7]

Table 3. Specific properties of ABS material [7]

S No	Property	Value
1	Technical Name	Acrylonitrile butadiene styrene (ABS)
2	Chemical Formula	$(C_8H_8)_x \cdot (C_4H_6)_y \cdot (C_3H_3N)_z)$
3	Melting temperature	220-270 °C
4	Tensile Strength	46 MPa
5	Density	1.06 g/cm3

1.3.3 Polyamide (PA)

Polyamide is normally known as Nylon, this is a moderately strong and simple to utilize material that can be used to produce high quality parts. Polyamides (PA) are semi-crystalline polymers which are available in various grades**.** Nylon is tough, and flexible 3D printing material. It is adaptable when thin, yet with high between layer grip, nylon loans itself well to things like living pivots and other practical parts.

Nylon filament can integrate shading that is included in the post-processes with various fabric colour dyes. Nylon fiber contains some form of delicate dampness therefore drying measures should be considered to ensure quality printouts for instance using desiccant, vacuum and elevated temperatures.

Nylon is used in 3D printing of objects that need high exhaustion persistence, repetitive snap fits and contact fit accompaniments. Other applications include aerospace and automotive design which entail tailored creation tooling, jigs, fittings and other interior panelling, low-heat air intake devices and developing antenna covers. Nylons makes long lasting models for snap-fits panels and impact cover various apparatuses.

Table 4. Specific properties of Polyamide (PA) [8]

S No	Property	Value
1	Technical Name	Polyamide (PA)
2	Chemical formula	$C_{12}H_{26}N_2O_4$
3	Melting Temperature	220°C
4	Tensile Strength	76 MPa
5	Density	1.13 g/cm3

1.3.4 High Impact Polystyrene (HIPS)

High Impact Polystyrene (HIPS) is similar to ABS. It is an extreme, inflexible plastic material with high effect quality which can be glued, punched, sawn effectively, and is normally available in numerous collection of hues. It is commonly used for making toys, bundling, signs, kicking plates. In the instance when is interested in hued plastic with quality effect features then HIPS material will be considered. Polystyrene is commonly used for thermoforming thus it possesses the capabilities of developing different shapes and models. One unique feature of the HIPS plastic is that it can be decomposed using Limonene as a dissolvable thus making it significant when printing ABS with double expulsion printer. HIPS is quite simple to print 3D objects but however it is susceptible to bends.

Table 5. Specific properties of High Impact Polystyrene (HIPS) material [9]

S No	Property	Value
1	Technical Name	High Impact Polystyrene (HIPS)
2	Chemical Formula	(C8H8)N
3	Melting Temperature	210-249°C
4	Tensile strength	53 MPa
5	Density	1.04 g/cm3

1.3.5 Thermoplastic Elastomers (TPE)

Thermoplastic Elastomers (TPEs) are a class of polymers that have both thermoplastic and elastomeric properties. Inside their design limits, they have inclination to act like thermoset elastic at the same time, over their melt or softening temperatures, they carry on like thermoplastic. They can be easily reprocessed and remoulded. The capacity to handle these materials with thermoplastic techniques will consider for planning and easy manufacturing of thermoplastic elastomers (TPEs) that thermoset elastic does not offer [10].

Thermoplastic Elastomers (TPEs) have crystalline and amorphous structure. At the same time they can be with the mixture of crystalline and amorphous structures. It is the crystalline structure that gives TPEs their thermoplastic character and the amorphous structure that give them their elastomeric character. The crystalline structures are typically nominated as the "hard" phase and the amorphous structure as the "soft" stage. While both phases add to the general physical and mechanical properties of a TPE, some key properties might be related with one phase or the other in this way directing the choice of TPE materials applications [10].

TPE is mainly used in the production of household appliances automotive parts, weather sealing for windows and doors, medical supplies, electrical insulation, shoe soles, adhesives, wristbands and smart phone covers.

1.3.6 PETG (Copolyester)

PET (Polyethylene Terephthalate) is common polymers used in 3D printing in many current applications. It is used in food packaging, making water bottles and other plastic objects. PET comes in several modified forms (copolyesters) which include PETP, PET-P, PETG, GPET and PETT. The raw PET is not normally used in 3D printing instead the modified forms (copolyesters) are used. PETG is the most common form of PET used for 3D printing filament. The G stands for glycol-modified, and this makes the resulting resin clearer and less brittle than the original PET. It is used to make water bottles, food packaging, and countless other common plastic items. As a 3D printing filament, PETG has proven its worth as a durable material that is easy to use. It normally combines some significant features of ABS filament which include mechanical properties and rigidity with those of PLA materials [11].

Table 6. Specific properties of PET [11]

S No	Property	Value
1	Technical Name	PET
2	Chemical Formula	$(C_{10}H_8O_4)_n$
2	Melting Temperature	260°C
3	Tensile Strength	152 MPa
4	Density	1.56 g/cm3

1.4 Tensile Testing

A tensile test is an essential qualification test for all engineered materials. Under the tensile test the important strength parameters can be determined including rigidity, yield quality, % elongation, % reduction of area and Young's modulus. This tensile test is done by applying a load longitudinally (lengthways) on standard tensile specimen with known dimensions of the material. The tensile test is applied at a specific strain rate until the failure of the specimen. The applied load and expansion are recorded during the test to calculate the properties of Ultimate Tensile Strength, Yield Strength, Percentage Elongation and Percentage Reduction in Area [13].

A standard specimen used for tensile testing is the dog bone or dumbbell shape. For the tensile tests conducted for the four 3D printed materials, the specimen shape is shown in Figures 6(a), 6(b) and 6(c) illustrating the length 78.10 mm, width 19.05 mm and thickness 9.52 mm of the standard sample respectively, depending on the standard used.

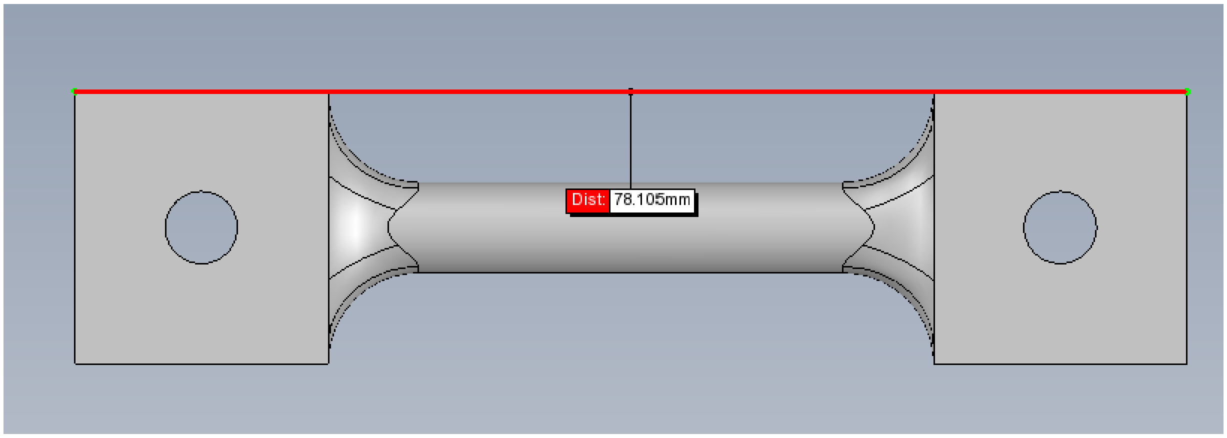
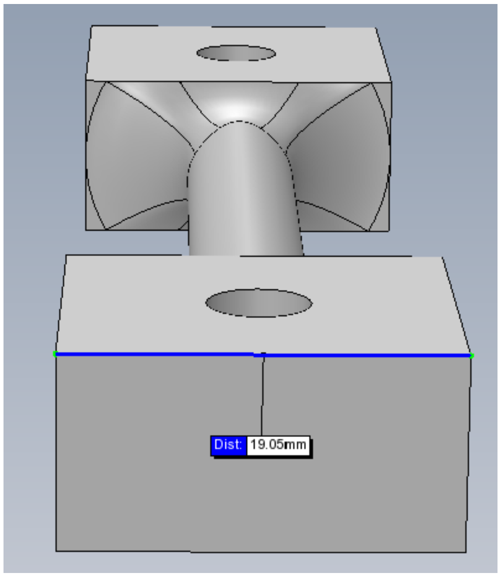


Figure 6(a). Specimen Length



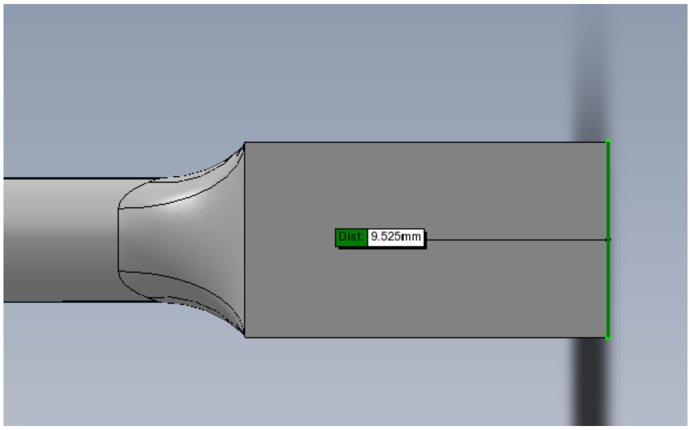


Figure 6(b). Specimen Width **Figure 6(c). Specimen Thickness**

Figure 6. Standard tensile test specimens

Tensile testing of materials including metals and plastics is the most essential test strategy to examine the mechanical properties. There are standard ASTM techniques are accessible for conducting the tensile test universally. This information is critical for both designers and quality professionals to precisely anticipate the execution of their end applications. This data is basic for developing new materials and broaden the applications [13].

1.4.1 Tensile tests on 3D printed materials by other researchers

Influence of printed internal structure on tensile strength by Muhammed Buğra

3D printed plastic parts are complex structures, having specific porosity and density in different layers within each part. If a 3D printed part has an internal structure it forms a different internal build pattern than the same shaped part without the internal structure. In this research, build orientation and the existence of an internal channel were assessed for their influence on tensile strength. This current research claims that the presence of internal structure within 3D printed materials doesn't have influence on the modulus of elasticity but can significantly reduce the ultimate tensile strength as illustrated by experiments by Muhammed Buğra a Metallurgical and Materials Engineering student at Middle East Technical University Ankara, Turkey**.** He conducted an experiment to evaluate the effect of internal structures on the tensile strength for the printed materials [14]. He conducted four experiments each containing eight replicates of tensile specimens involving solid density ABS. A summary of experimental groups that he used is shown below:

Experimental Group	**Build Orientation**	**Internal Structure**
1	Horizontal	None
2	Horizontal	Yes
3	Vertical	None
4	Vertical	Yes

Table 7. Experimental Groups Information [14]

The tensile tests were measured using an instron model at 74°F and 56% relative humidity. The tests were performed at a rate of 5 mm/min (0.2in/min) and measurements were taken at 20 points in every second.

Results

Experimental Group	Description of Group	Resulting Sample Size	Tensile Modulus E (MPa)	E Standard Deviation	Tensile Stress @UTS (MPa)	Sress@UTS Std. Dev.	Tensile Strain	Tensile Strain Std. Deviation
1	Horizontal, No Channel	8	409.27	13.0	16.54	0.27	6.00	0.43
2	Horizontal, With Channel	8	418.71	17.7	16.12	0.25	6.10	0.15
3	Vertical, No Channel	8	463.23	25.2	19.55	0.25	5.10	0.50
4	Vertical, With Channel	6	456.92	15.6	18.08	0.34	5.33	0.86

Table 8. Experimental Results [14]

The experimental results show that vertical build orientation produced more tensile strength than the horizontal orientation. On the other hand, the ultimate tensile strength of materials without an internal channel was noted to be higher than those containing internal channels [14]. The analysis of the experiment concluded that the presence of internal structures on 3D printed materials doesn't have influence on the modulus of elasticity but can significantly reduce the ultimate tensile strength.

Influence of processing factors on the tensile strength of 3D-printed models by Tomislav Galet

Experiments and research conducted by Tomislav Galet aimed at determining the impact of processing factors on the tensile strength of the 3D materials. He also aimed at finding the combination of factors that will provide the highest strength. His experiments involved preparation of samples on a 3D printer with variation in layer of thickness, infiltrant type and build orientation [15].

The following processing factors shown in the table were considered:

Layer thickness	0.1 mm						0.0875 mm					
Infiltrant	Wax		Epoxy resin		Cyanoacrylate		Wax		Epoxy resin		Cyanoacrylate	
Orientation	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Experiment label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC

Table 9. Processing Factors [15]

The samples were printed after which they were left to dry before they were infiltrated with various infiltrants including normal-wax Cera Alba, epoxy-resin based Loctite Hysol and cyanoacrylate-based Loctite. The tensile tests were then carried out using a ZMGi 250 tensile testing machine with the jaw-motion speed of 1 mm/min [15].

Tensile test results showed that the strength of 3D-printed materials normally come from the infiltrants. Whereas, it can be enhanced by various combination of two other processing factors. The experimental outcomes also confirmed impact of the infiltration types on the materials, placing epoxy resin as the strongest one [15]. If the maximum tensile strength is needed, it can be obtained by selecting the best combination of the other two processing factors.

CHAPTER 2

What is Scoliosis?

Scoliosis is a spinal disfigurement comprising of parallel bend, rotation of the vertebrae and an adaptable or inflexible deformation in the frontal plane. It was first identified by Hippocrates and the expression "scoliosis" was first utilized by Galen (AD 131-201). For the most part, scoliosis patients have a spinal deformation or more likely trunk divider and back asymmetry. There are various sorts of scoliosis, each having its own particular aspects. The fundamental type is adolescent idiopathic scoliosis (AIS), which represents around 80% of diagnosed scoliosis cases. Other than AIS, other known types of scoliosis are intrinsic (10%) and neuromuscular (5-7%) [16].

Prevalence of scoliosis in the general population is 0.3-1.6%. The major difference in the reported prevalence is because of different diagnosis procedures, samples and definitions of scoliosis. The prevalence of AIS is 2-3% in youth within 10-16 years old. The ratio of females to males varies with age. The ratio is one-to-one in adolescents with spinal curvatures of 10^{o} or less, the ratio increases to 10 females to every male for curvatures greater than 30^{o}. Scoliosis in females tends to advance more commonly. In adolescents who are diagnosed to have mild AIS with a Cobb angle $< 25^{o}$, they have 10-15% progressive curves and only 2-4% of the diagnosed patients advance to extreme scoliosis with Cobb angle $> 45^{o}$ [16].

In spite of the fact that the clinical demonstrations of AIS have been well described, the causes and the manner of development of AIS still remains unknown. Recent investigations related to the cause of AIS have primarily focussed on the structural components of the spine, spinal musculature, collagenous structures, the endocrine framework, focal sensory system, and hereditary factors. [16].

Inherited factors are one of the primary reasons for Scoliosis, as observed in twin studies and singleton multigenerational families. A similar curve pattern was observed in twins with scoliosis. A present examination of monozygotic and dizygotic twins from the Swedish twin registry assessed that general inherited effects accounted to 38% of the observed phenotypic variance, leaving the remaining 62% to environmental factors. [16]. Different moderate treatments of AIS are available; however proof of their viability and adequacy is still unknown. Current medical literature tends to support wearing braces amid the critical body growth period to control the severity of spine deformity [16].

2.1 Why Scoliosis Braces are used?

Scoliosis is seen as any horizontal (sideways) recurrent displacement of the spine. This recurrent pattern of spine displacement is measured by the Cobb angle. This Cobb angle can be measured from an x-ray of the human torso. For cases where the measured Cobb angle is more than 10 degrees yet under 25 degrees, the commonly preferred approach is observation. A scoliosis specialist will take x-ray images every 4 to 6 months to check whether the curve is progressing or not [17].

Scoliosis braces will routinely be prescribed if either of the following two conditions are met:

• Cobb angle has reached at least 25 degrees and the adolescent still has significant growth left until skeletal development [17]

• Cobb angle is less than 25 degrees however has quickly progressed at least 5 degrees at the 4-to 6-month follow-up appointment [17]

If an adolescent with scoliosis is at, or close to full skeletal development, bracing is likely not recommended, because of the fact that it would at no time in future be convincing.

2.1.1 Brace Usage

The spine distortion resulting from scoliosis does not recuperate without surgical correction. However, medical studies and therapeutic reviews demonstrate that wearing a scoliosis brace during growth periods of children and adolescents (as recommended) can keep the progression of scoliosis in check. Wearing a brace can be a useful way to keep a scoliosis curve's Cobb angle relatively small. A scoliosis bend of 50 degrees or more when an adolescent reaches skeletal development (about age 14 or 15 for young girls and 16 or 17 for young boys), will continue advancing all through adulthood. These sorts of spinal bends will likely end up causing severe disfigurement that requires surgery. Hence, the goal of spinal braces is to avoid a big surgery by either stopping the bend development inside or probably avoiding it from reaching 40 or 50 degrees during the period of skeletal development [17].

2.1.2 How Bracing works?

Bracing treatment intends to apply restorative strengths on the spine to discharge stack on the inward (internal) some portion of the bend and increment stack on the raised (external) some portion of the bend. The idea is that a bone encountering pressure will become less and a bone encountering diversion (less or no pressure) may develop more. Bracing tries to back off the scoliosis bend's bone development as an afterthought that should be prevented, and accelerate development as an afterthought that necessities to accelerate. While bracing won't regularly invert or remedy the scoliosis, it can moderate or decrease any movement of the bend until the child/adolescent achieves skeletal development. After this point, the bones fairly set so the bend is probably not going to advance (if it is less than 40 degrees) [17].

The correct components of bracing are still under scrutiny. But, research shows that the brace should be rigid (hard) so that it can apply strong and consistent pressure on the scoliosis bend to have an impact. [17].

2.2 Types of Scoliosis Braces

There are a number of non-bending back braces available today to treat scoliosis. These braces can shift in how weight is connected to the spine and ribs to keep a scoliosis bend from advancing. Some non-bending braces require full-time wear, regularly in the proximity of 16 and 23 hours a day, though others are just worn around 8-10 hours for each night while resting [17].

2.2.1 Boston Brace

The most commonly used brace for scoliosis today is the Boston brace. Large number of people know the Boston brace as a kind of thoracic-lumbar-sacral orthosis (TLSO). Different kinds of Boston brace models are available, for instance, a CTLSO (TLSO with a neck augmentation) for a high thoracic bend, but they are not as common.

The Boston brace works by applying restorative weight on the angled (outside) side of the curve and removing contrasting zones of assistance on the inward (interior) side of the bend so the spine can advance toward that path [17].

Figure 7. Boston Brace [18]

2.2.2 Wilmington Brace

Wilmington brace is another commonly available brace for Thoracic-Lumbar-Sacral Orthosis (TLSO). However, the Wilmington brace is quite different from Boston brace. It is custom-fitted based on a replica taken from the patient back curvature. After having the replica, the counteractive forces are designed to the specific requirements of the patient's spinal curvature. This support goes onto the body like a tight coat and is known as a full contact TLSO brace due to its lack of gaps or open spots [17].

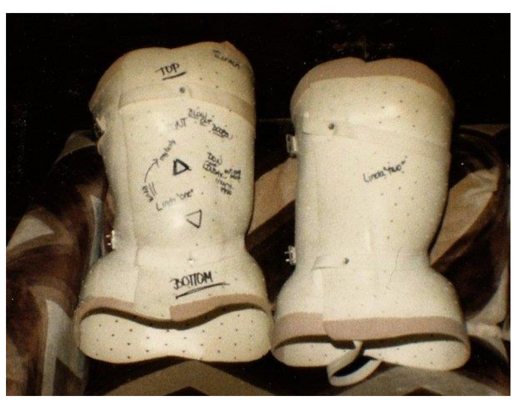


Figure 8. Wilmington Brace [19]

2.2.3 Milwaukee Brace

The Milwaukee brace, which is the first Cervico-Thoracic-Lumbar-Sacral Orthosis (CTLSO) designed in the 1940s, is a more established and bulkier brace. Because of the adequacy and relative comfort of today's more present-day braces, the Milwaukee brace is not used any longer. But still it can be utilized for curves higher in the thoracic or cervical spine. In principle, Wilmington brace and Boston brace are effective full-time bracing options for scoliosis curves at (mid-back or base of the shoulder bone) or lower [17].

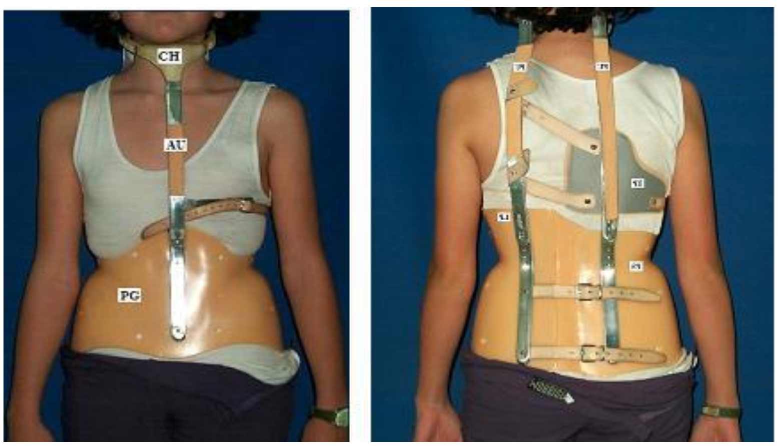


Figure 9. Milwaukee Brace [20]

2.2.4 Charleston Brace

The most regularly recommended nighttime brace is the Charleston bending brace. It is specially made from the replica of the patient's middle. After the replica is made, the remedial forces are included to the brace based on the measurements taken from the spine x-ray [17].

Figure 10. Charleston Brace [21]

2.2.5 Providence Brace

Like the Charleston brace, the Providence brace applies a hyper corrective constrain on the spine that is just practical while setting down and resting during the night. Having said that, rather than bowing the spine's bend the other way like the Charleston brace, the Providence brace marginally raises one shoulder and specifically applies horizontal and rotational powers on the bend (or both bends on the off chance that it is a twofold bend).

The Providence brace is equipped for pushing the bend toward the midline or past in some cases. Sometimes, specialists have more knowledge of either Charleston bending brace or Providence brace, and have an individual preference for recommending either [17].

Figure 11. Providence Brace [22]

2.3 Summary of Chapter 2

Different strategies for treatment have been used for patients with adolescent idiopathic scoliosis (AIS) to reduce spinal curvature progression. One of these is spinal orthotic treatment, has been suggested in skeletally young patients with curvatures ranging from 25 to 45 degrees. Different kinds of spinal braces are generally used for patients with AIS, and they can be differentiated by various mechanisms of preventing curve progression based on individual design characteristics. The majority of commonly used concepts of spinal braces are Cheneau concept, SPoRT concept and Boston brace systems which have distinctive external corrective force application methods by utilizing rigid, semi-rigid braces or flexible bands and everyday brace wear durations [4].

CHAPTER 3

Design of Experiment

3.1 Design of Samples

In this research study, the mechanical properties of the 3D printed materials PLA, ABS, Nylon and HDGlass (PETG) were investigated. The results are shown, and conclusions are drawn on the mechanical properties of experimental materials.

Tensile testing of plastics is generally done according to ASTM D638 standard where this standard is industrially utilized, and it is a critical tensile test technique. This test technique utilizes standard "dumbell" or "dogbone" formed specimens, which are 9.5 mm of thickness.

3.2 Why dog bone shape specimen and why that size?

The standard "dumbell" or "dogbone" shaped specimens are used, so that the deformation is confined to the narrow center region and to reduce the possibility of fracture to occur at the ends of the specimen. Avoiding failure at the ends (where the specimen is gripped) is crucial. Moreover, grips of tensile testing machines have teeth to attain a fairly strong grip that can resist the forces required to deform the specimen longitudinally. The teeth usually cause plastic deformation of the gripped portion of the specimen. Material properties may change because of plastic deformation, but it indeed changes the specimen geometry. The stress concentrations in the gripped region is created as the specimen geometry changes. If a failure occurred at the grips in a cylindrical or bar specimen without enlarged ends, then both the changes would lead to an incorrect measurement [23]. Dog-bone shape is also crucial as it determines another property called Elongation, which is usually measured at the same time. Elongation is measured by placing a gauge on the reduced section and for the measurements to be accurate, the elongation should occur in this area [23]. Any plastic deformation resulting due to the movement of the machine grips will add to the measurement of elongation.

With reference to the size, these are controlled by standards which are universally accepted. For example, tensile testing of plastics is done by following the guidelines of the ASTM D638 standard.
A total of 26 specimens and minimum three specimens of each material were printed following the guidelines of the ASTM D638 standard. All specimens were printed with 100% fill density with different printing temperatures depending on the material.

3.3 Fabrication of samples and materials

In this experimental investigation, we used 4 different materials for testing which were: Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyamide (Nylon) and HDGlass (PETG). The specimens were printed with two different print orientations: side print and upright print. These four materials are popular among all the other thermoplastics with good mechanical properties and they also are easily available. And, therefore they were considered for this investigation. The 3D printing parameters and operating temperatures for all the materials used are summarized in Table 7, such as layer height, shell thickness, fill density and print speed.

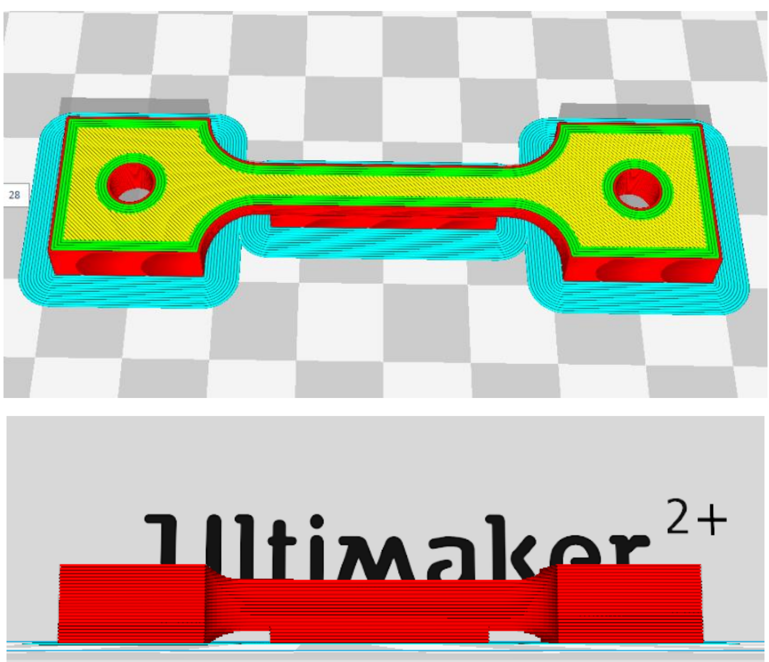


Figure 12. Graphic Illustration of Side Print

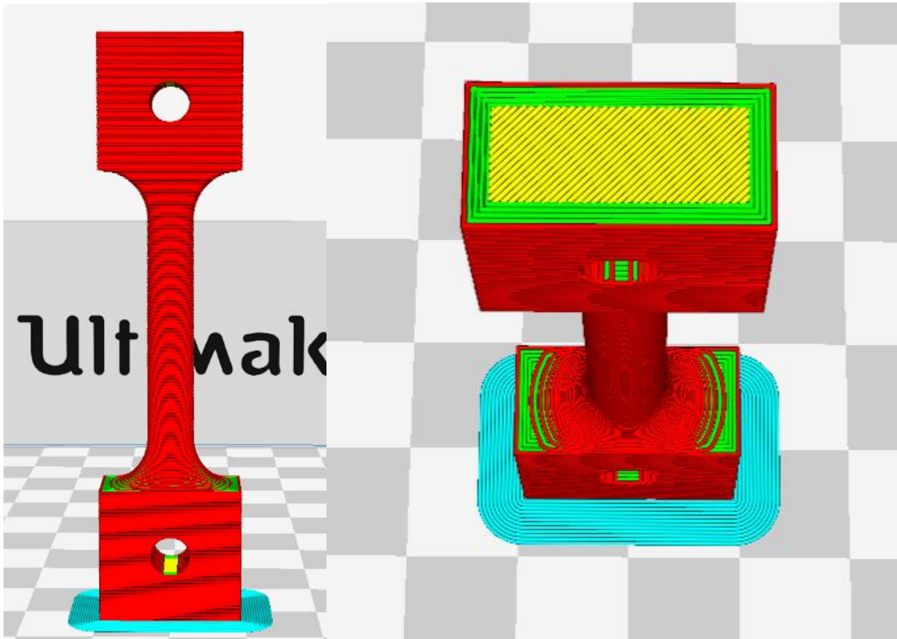


Figure 13. Graphic Illustration of Upright Print

3.4 Tensile testing Machine

The test specimens had an average diameter of 6.35 mm as measured by Vernier scale and shown in Figure 14. The printed tensile samples for each material were then subjected to tensile testing following the guidelines of the ASTM D638 standard. The specimens were tested for tensile strength on a MTI machine with a 10kN load cell for measurement. Figure 15 shows the MTI machine set up used for tensile testing of the experimental materials and Figure 16 shows the sample arrangement and break point during the test.

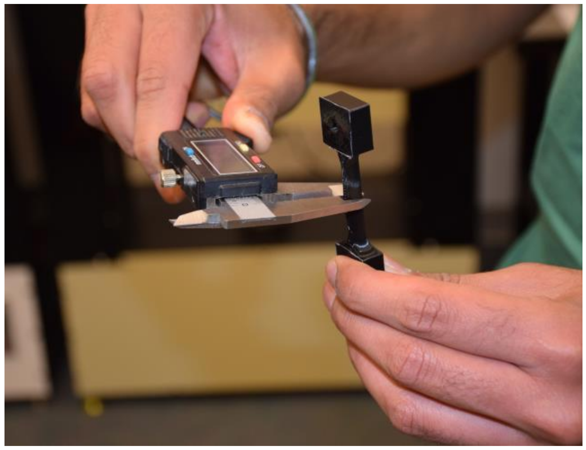


Figure 14. Sample diameter measurement using Vernier scale

Figure 15. MTI-10K machine setup used for tensile testing

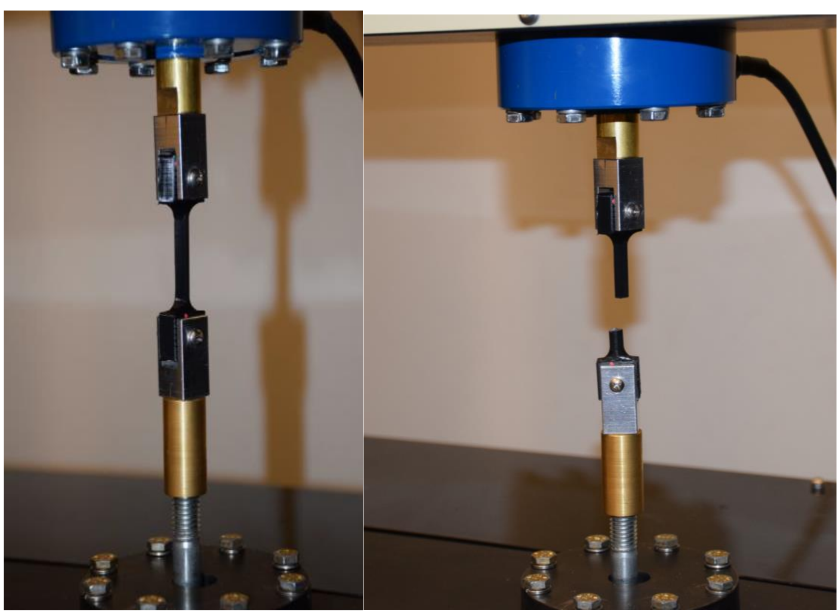


Figure 16. Sample arrangement on MTI-10K machine for tensile testing

CHAPTER 4

Results

4.1 Process Parameters

The process parameters used for 3D printing are summarized in Table 10.

Table 10. 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	210
ABS	0.2	0.8	100	50	255
Nylon	0.2	0.8	100	50	250
HDGlass (PETG)	0.2	0.8	100	50	225

4.2 Tensile Test Results

The results of the tensile tests for the 3D printed materials are summarized in Table 11 and 12 for side print and upright print specimens, respectively.

Table 11. Displacement (mm), Rupture Force (N), Sample Diameter (mm), Ultimate Stress (N/mm²) and Young's Modulus (N/mm²) for all the side printed materials.

Material with Specimen #	Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
PLA-S-6	Side	2.98	1412.23	6.25	45.66	1141.55
PLA-S-7	Side	2.76	1328.77	6.37	40.81	995.36
PLA-S-8	Side	2.69	1254.9	6.41	37.98	949.61
PETG-S-1	Side	4.21	843.05	6.2	26.18	494.05
PETG-S-2	Side	4.14	842.53	6.22	27.65	553.17
PETG-S-3	Side	2.95	809.81	6.24	25.85	369.29
PETG-S-4	Side	3.39	838.26	6.22	26.01	650.31
PETG-S-5	Side	3	854.29	6.17	28.78	394.27
NY-S-2	Side	13.09	669.15	6.22	22.06	183.84
NY-S-3	Side	15.01	712.95	6.24	23.23	185.84
ABS-S-1	Side	2.34	1146.8	6.78	31.87	910.57
ABS-S-2	Side	3.31	1169.09	6.7	32.28	1241.83
ABS-S-2	Side	3.06	1186.39	6.72	35.44	720.75

Table 12. Displacement (mm), Rupture Force (N), Sample Diameter (mm), Ultimate Stress (N/mm²) and Young's Modulus (N/mm²) for all the upright printed materials.

Material	Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
PLA-U-6	Upright	1.59	881.8	6.45	26.03	964.21
PLA-U-7	Upright	1.58	791.01	6.4	24.1	892.8
PLA-U-8	Upright	1.5	881.59	6.35	27.64	1063.31
PETG-U-2	Upright	14.85	632.27	6.14	21.12	1408.13
PETG-U-3	Upright	13.07	565.82	6.14	19.6	753.84
ABS-U-2	Upright	1.53	656.53	6.52	19.47	778.8
ABS-U-3	Upright	2.39	734.08	6.5	21.1	781.48

4.3 Result Comparisons

4.3.1 Side Print

The individual comparison result for Ultimate stress and Young's modulus of the side printed materials are shown in the Figure 17 and 18.

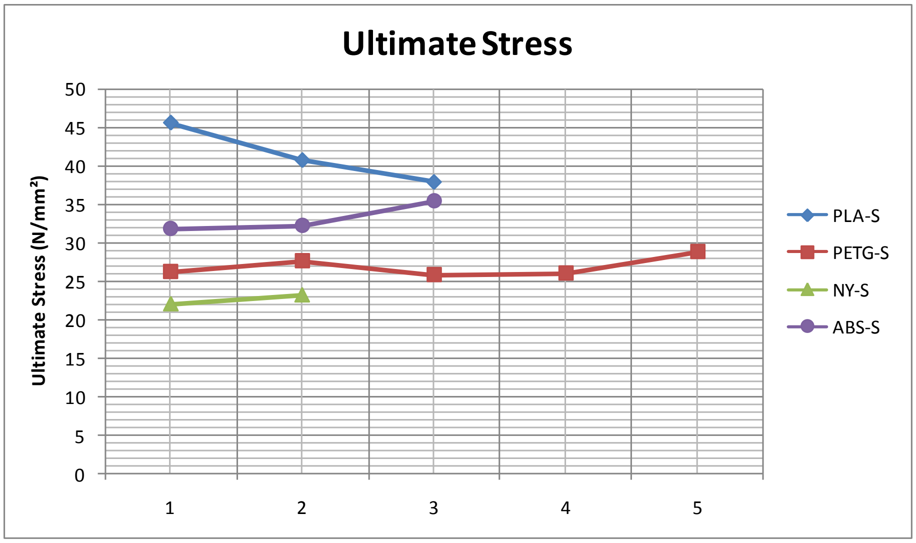


Figure 17. Ultimate tensile stress of side print materials (N/mm²)

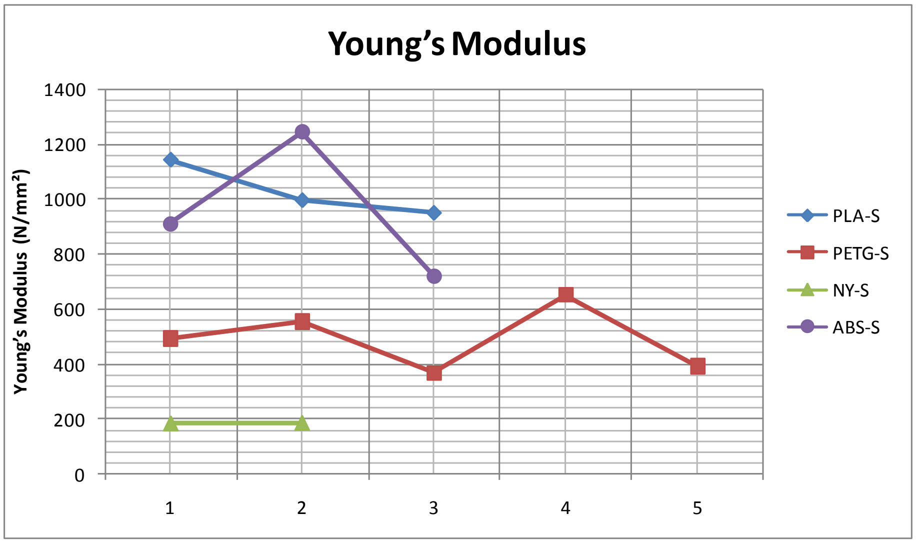


Figure 18. Young’s Modulus of side print materials (N/mm²)

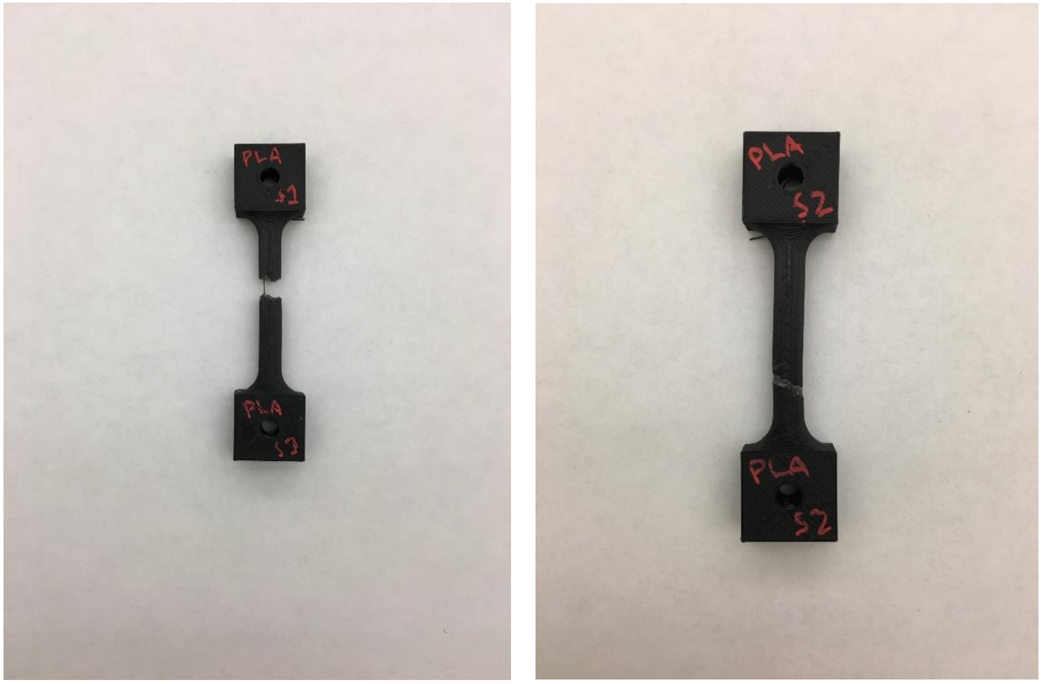


Figure 19. PLA Side Print Fractured Samples

4.3.2 Upright Print

The individual comparison result for Ultimate stress and Young's modulus of the upright printed materials are shown in the Figure 20 and 21.

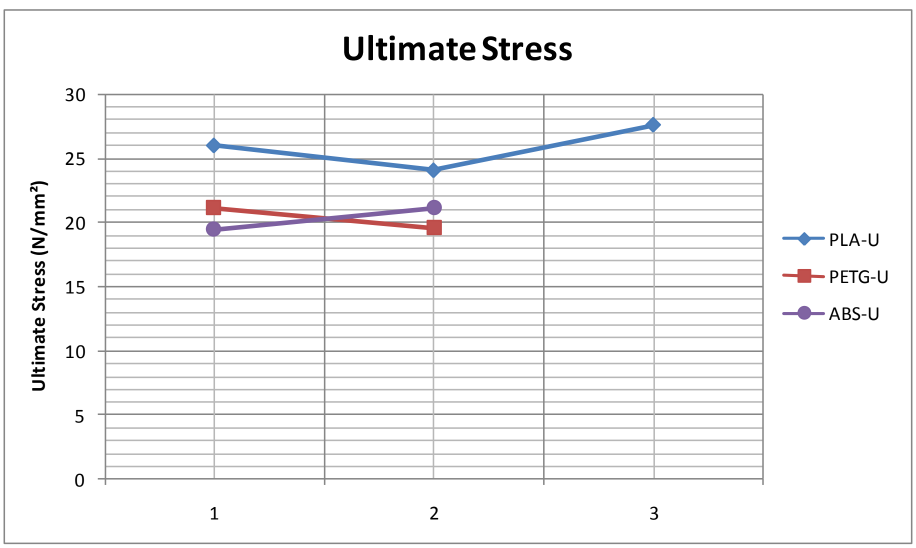


Figure 20. Ultimate tensile stress of upright printed materials (N/mm²)

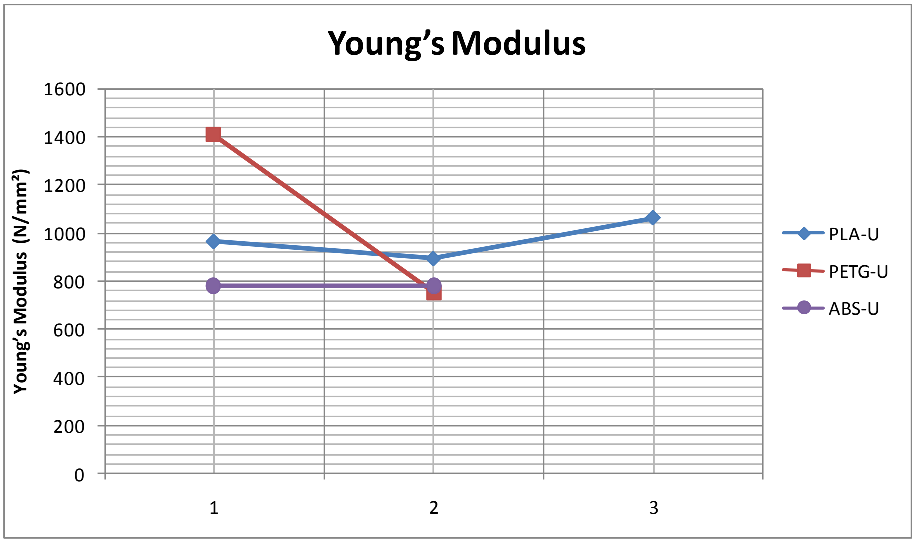


Figure 21. Young's Modulus of upright printed materials (N/mm²)

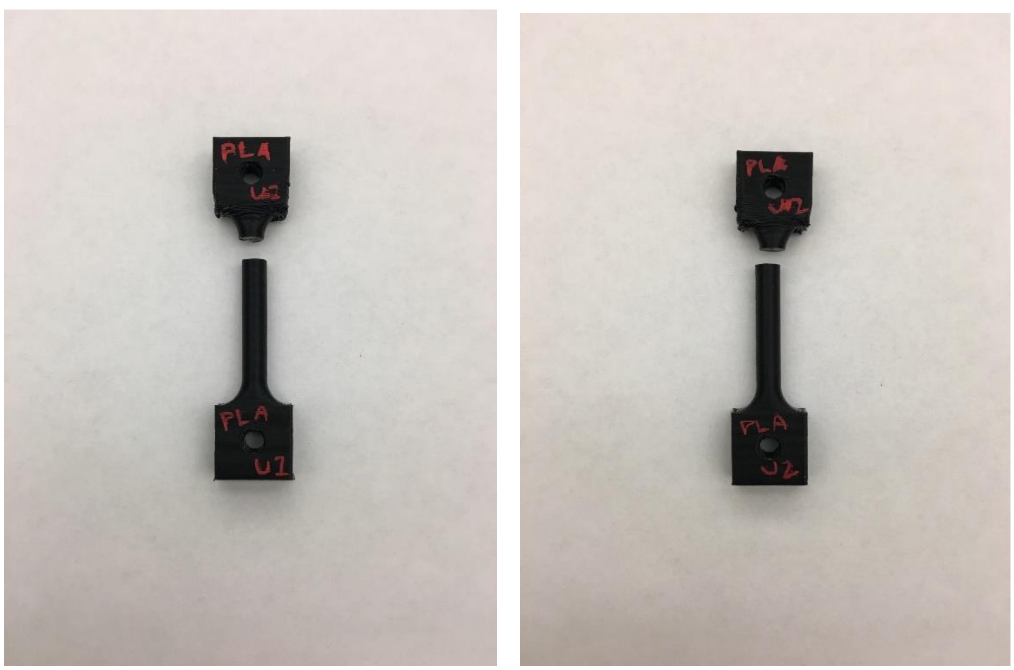


Figure 22. PLA Upright Print Fractured Samples

4.3.3 Comparisons of Side and Upright

The combined comparison result for Ultimate stress and Young's modulus of side and upright printed materials are shown in the Figure 23 and 24. In summary, all the tabulated results were compared with respect to the print orientations. Both individual plots and combined plots of the tensile results are analyzed and detailed discussions are presented in chapter 5.

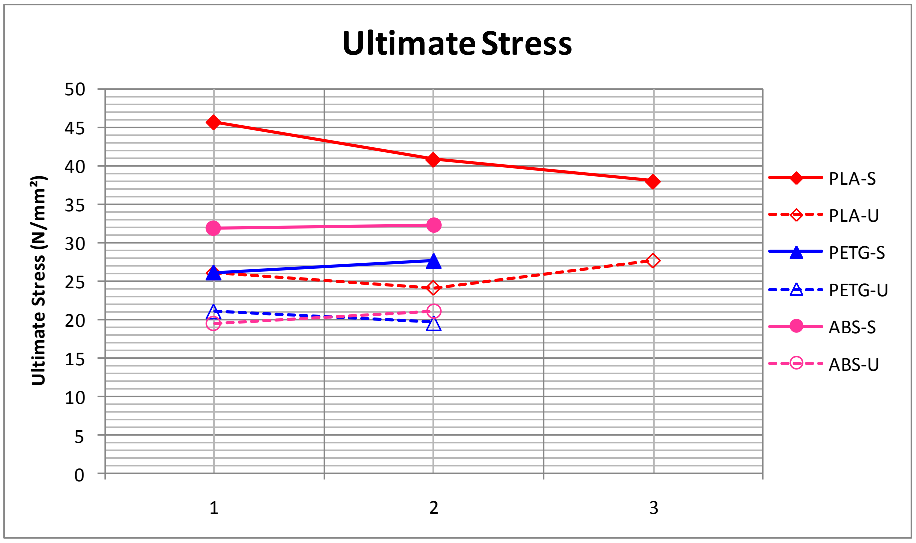


Figure 23. Ultimate stress of side and upright printed materials (N/mm²)

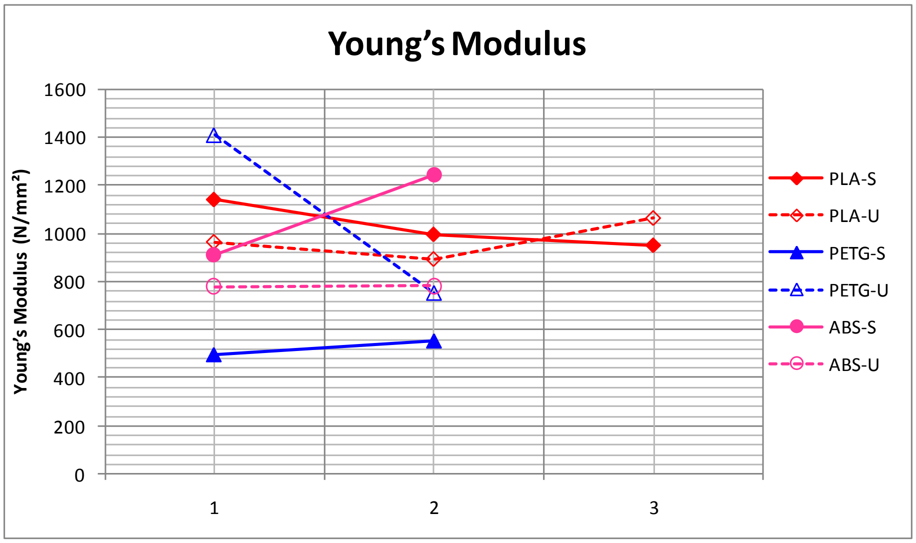


Figure 24. Young's modulus of side and upright printed materials (N/mm²)

CHAPTER 5

Discussion

5.1 Side Print

As shown in Table 6 for the side print orientations, there are 3 samples for PLA, 5 samples for PETG, 2 samples for Nylon and 3 samples for ABS with a total of 13 samples have been tested. The individual comparison result for Ultimate stress and Young’s modulus of the side printed materials are shown in the Figure 17 and 18. As seen from Figure 17 it is clear that PLA has the superior results with highest tensile strength of 45.66 N/mm^2, followed by ABS at 35.44 N/mm^2, PETG at 28.78 N/mm^2, and Nylon at 23.23 N/mm^2 respectively.

As seen from Figure 18 it is apparent that PLA and ABS has achieved highest modulus of 1141.55 N/mm^2 and 1241.83 N/mm^2 respectively. The lowest modulus was achieved by Nylon at 183.84 N/mm^2 respectively.

5.2 Upright Print

The individual comparison result for Ultimate stress and Young’s modulus of the upright printed materials are shown in the Figure 20 and 21. As seen from Figure 20 it is clear that PLA has achieved the highest tensile strength of 27.64 N/mm^2, and both PETG and ABS achieved almost the similar results of tensile strength of 21.12 N/mm^2 and 21.1 N/mm^2 respectively.

As seen from Figure 21, although the highest level of modulus achieved by PETG at 1408.13 N/mm^2 and at the same time it also achieved lowest of 753.84 N/mm^2. But PLA and ABS showed steady level of modulus. PLA has achieved highest modulus value of 1063.31 N/mm^2 and whereas ABS has 781.48 N/mm^2.

5.3 Comparison of Print Orientations

Figure 23 and 24 shows the comparison of Ultimate stress and Young’s modulus results with respect to the side and upright print orientations respectively.

As seen from the comparison graphs, it is clear that the print orientation has significant impact on the tensile properties obtained in this experiment. Analysis of ultimate stress for all the materials shows a significant relation between print orientation of the specimen and the ultimate stress. There is a significant decrease, approximately 40% in ultimate stress for upright printed materials over side print. However, this trend is not observed in young's modulus and considerable variation is observed in modulus in both type of samples as shown in Figure 23 and 24.

5.4 Analysis of results in comparison to needs for scoliosis brace

Based on the results obtained from the experiment, it is clear that side print orientation is having better mechanical properties over printing on upright and the following conclusions can be drawn.

1. The general properties of Poly-lactic Acid (PLA) manufactured by traditional methods are in the range of 40-50 N/mm² and at the same time PLA material from this experiment manufactured by 3D printing has achieved approximately 45 N/mm². It is reasonable to use this material for intended application of Scoliosis braces by 3D printing as this process can give many advantages over traditional manufacturing.

2. Acrylonitrile Butadiene Styrene (ABS) general properties show that they can be having a maximum of tensile strength of 46 N/mm². However, in this experiment with 3D printing we have achieved 35 N/mm². The achieved results seem to be reasonable to make it use on brace applications.

3. The general specific properties of PETG material show that they can be having a maximum tensile strength of 28 N/mm². However, in this experiment with 3D printing we have achieved equal value of 28 N/mm². The achieved results seem to be reasonable to make it use on brace applications where lower strengths are required.

4. With careful study of this experiment results, the other material Nylon has achieved least properties. The general properties of Nylon indicate that they can be with 90-180 N/mm², whereas with 3D printing we achieved only 22 N/mm². However, several grades are available for Nylon, so it is recommended to compare particular grade material. But with these results achieved it is not recommended to use this material for brace applications.

5.5 Recommendations and Future Work

Further to have few recommendations on this work, it is always interesting to see the failure mechanism of these samples under high resolution microscopes (scanning electron microscope) to understand the structure and properties better. This can enable future modifications of materials to have desired properties. It would also be interesting to prepare the samples with different fill densities to correlate the mechanical properties with respect to fill density.

Heat-treatment is the part of material science and engineering to improve the mechanical properties of materials. So, I strongly recommend conducting annealing (heat-treatment) of the samples to investigate the mechanical properties and improvements.

CHAPTER 6

Conclusion

This research work demonstrates that the strength and elasticity of a 3D printed sample depends generally on the print orientation for a given material. The strongest material among the tested samples was Poly-lactic acid (PLA) with a maximum tensile strength of 45.66 (N/mm^2) and the second strongest material was Acrylonitrile Butadiene Styrene (ABS) with a maximum tensile strength of 35.44 (N/mm^2). The most flexible material was Nylon with a minimum tensile strength of 22.06 (N/mm^2).

In summary, based on the experimental results it is recommended using Poly-lactic acid (PLA) or Acrylonitrile Butadiene Styrene (ABS), because they both exhibit excellent tensile strength as compared to HDGlass (PETG) and Nylon. Additionally, Poly-lactic acid (PLA) has some advantages over Acrylonitrile Butadiene Styrene (ABS) as follows:

- It is biodegradable thermoplastic, made from renewable resources.
- It is easy to print.
- It provides shinier and smoother appearance.

- It is already being used in the medical industry for application such as medical implants.
- It doesn't produce harmful fumes during printing.

There are also some drawbacks of PLA which definitely need to be considered, and these are:

- PLA is not as tough as ABS, meaning it is more brittle and cannot take impact forces well.
- PLA has a lower melting temperature, therefore it can deform because of heat.

Overall, Poly-lactic Acid (PLA) seems to be a very viable option for the application of scoliosis braces.

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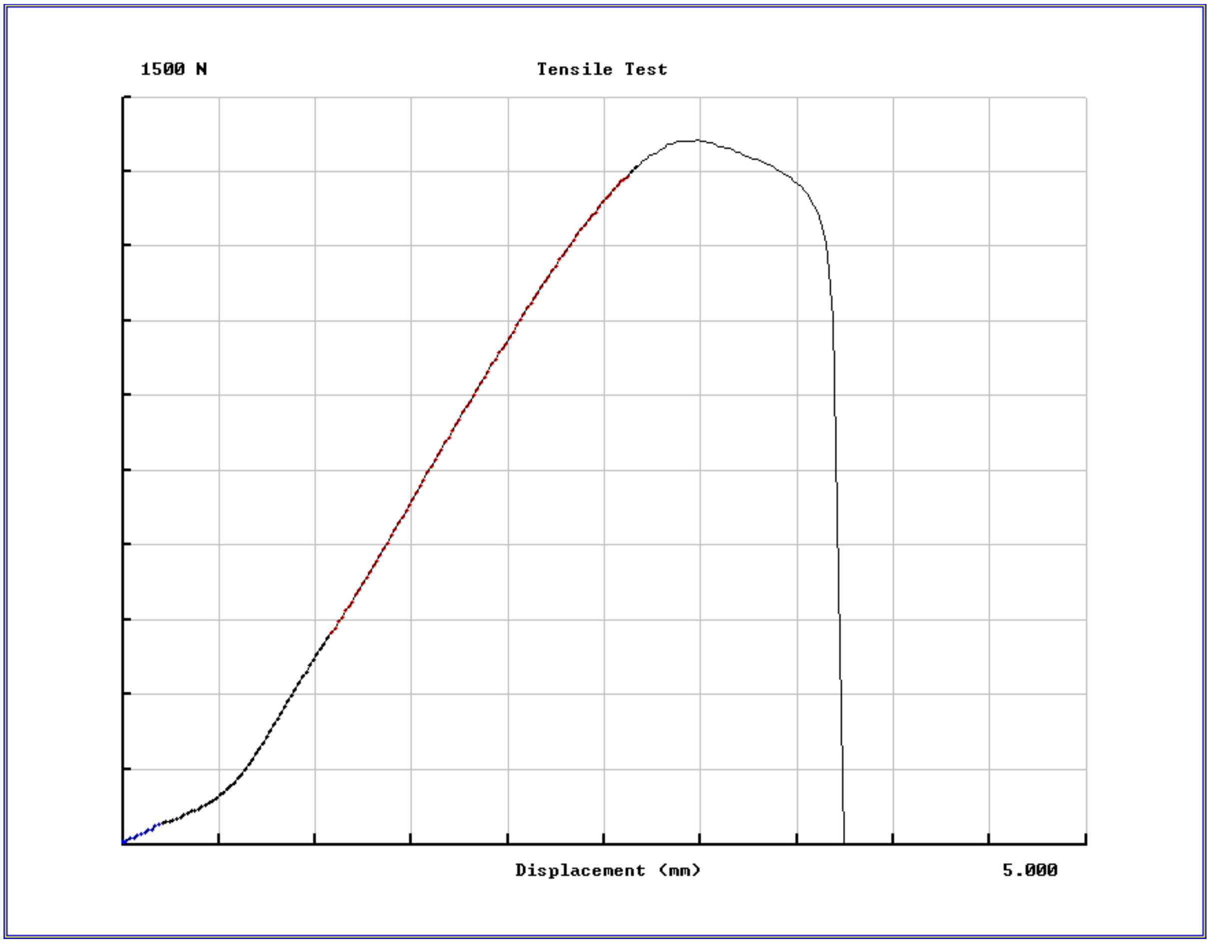
Appendix

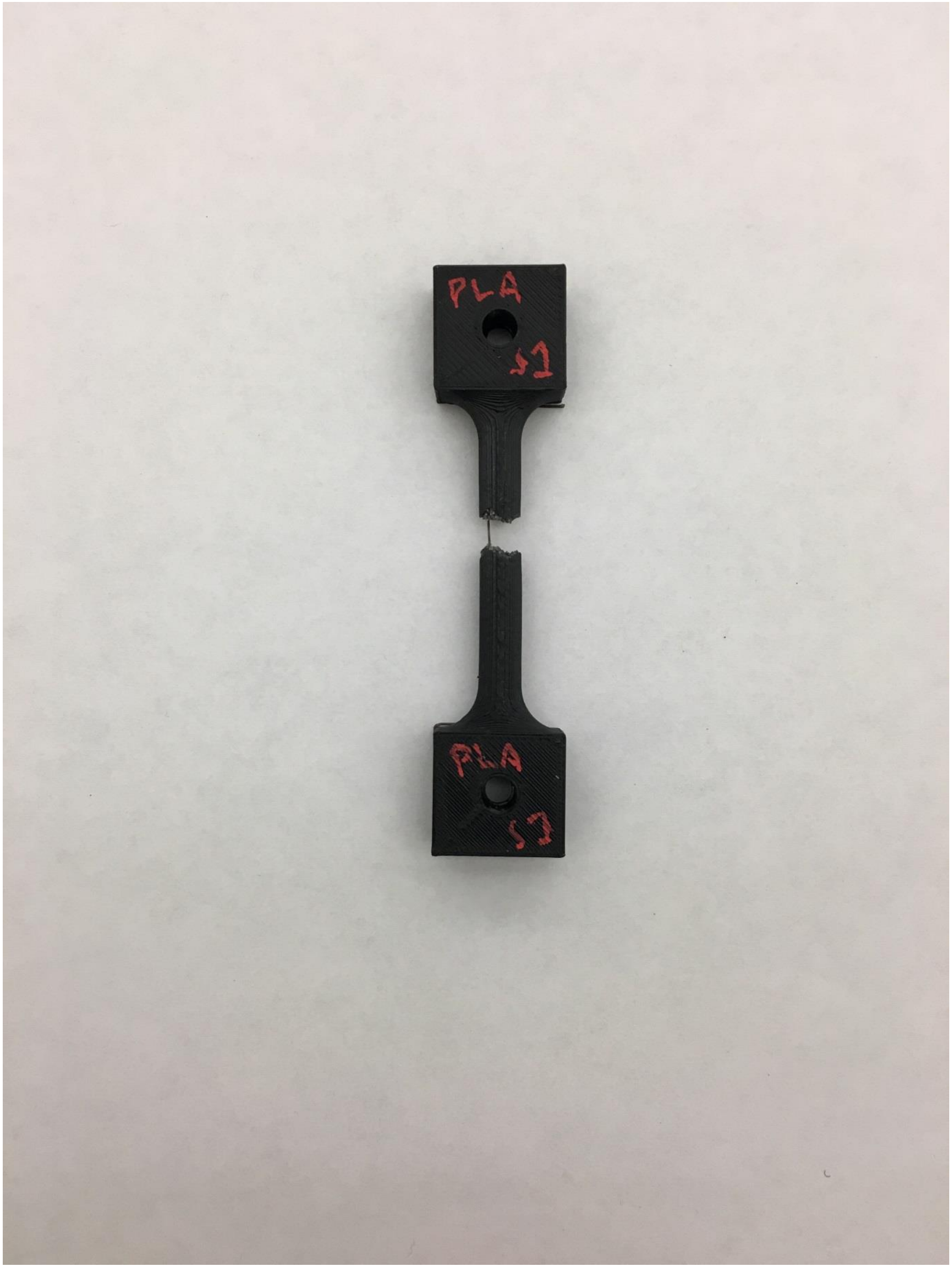
Tensile Test Graphs

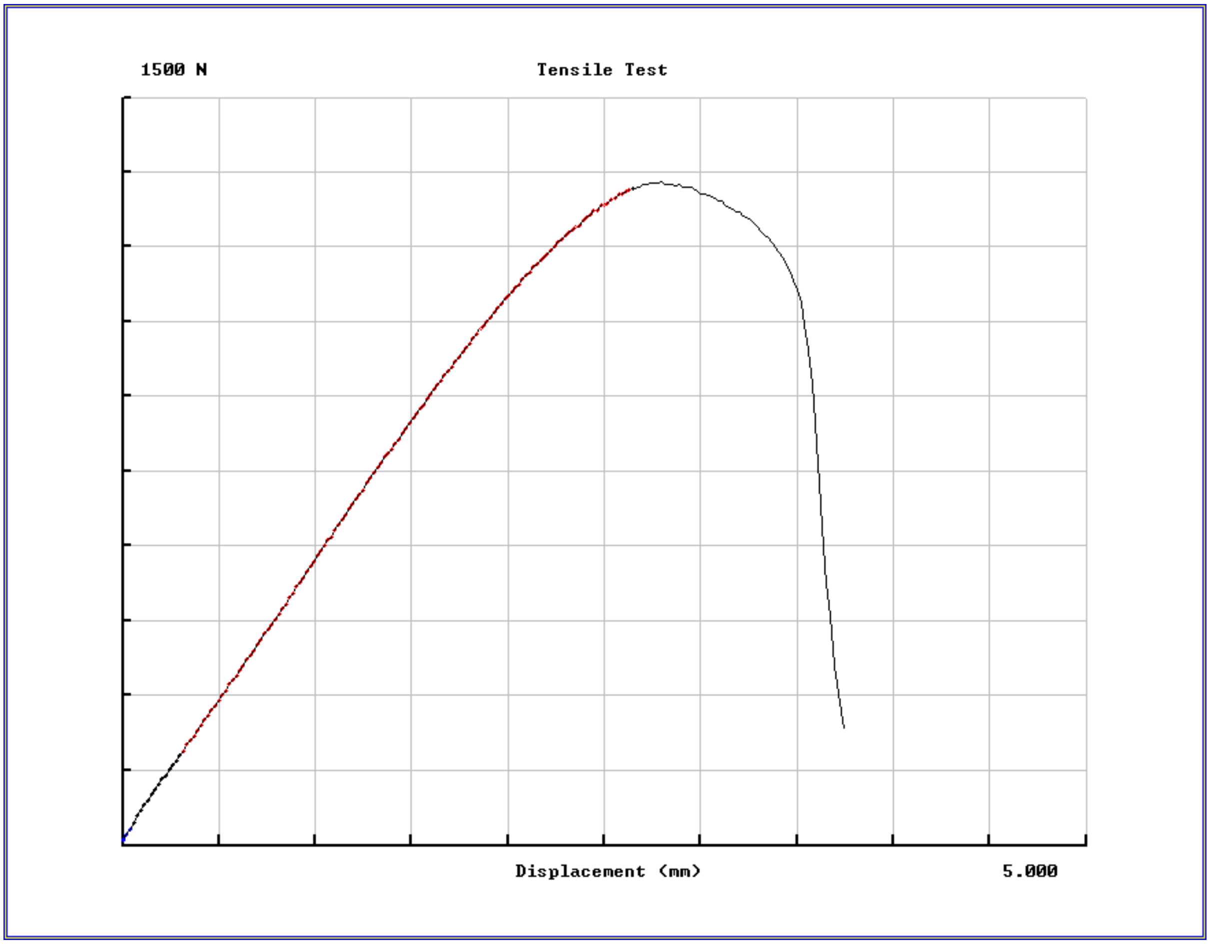
A.1 PLA



PLA-S-6

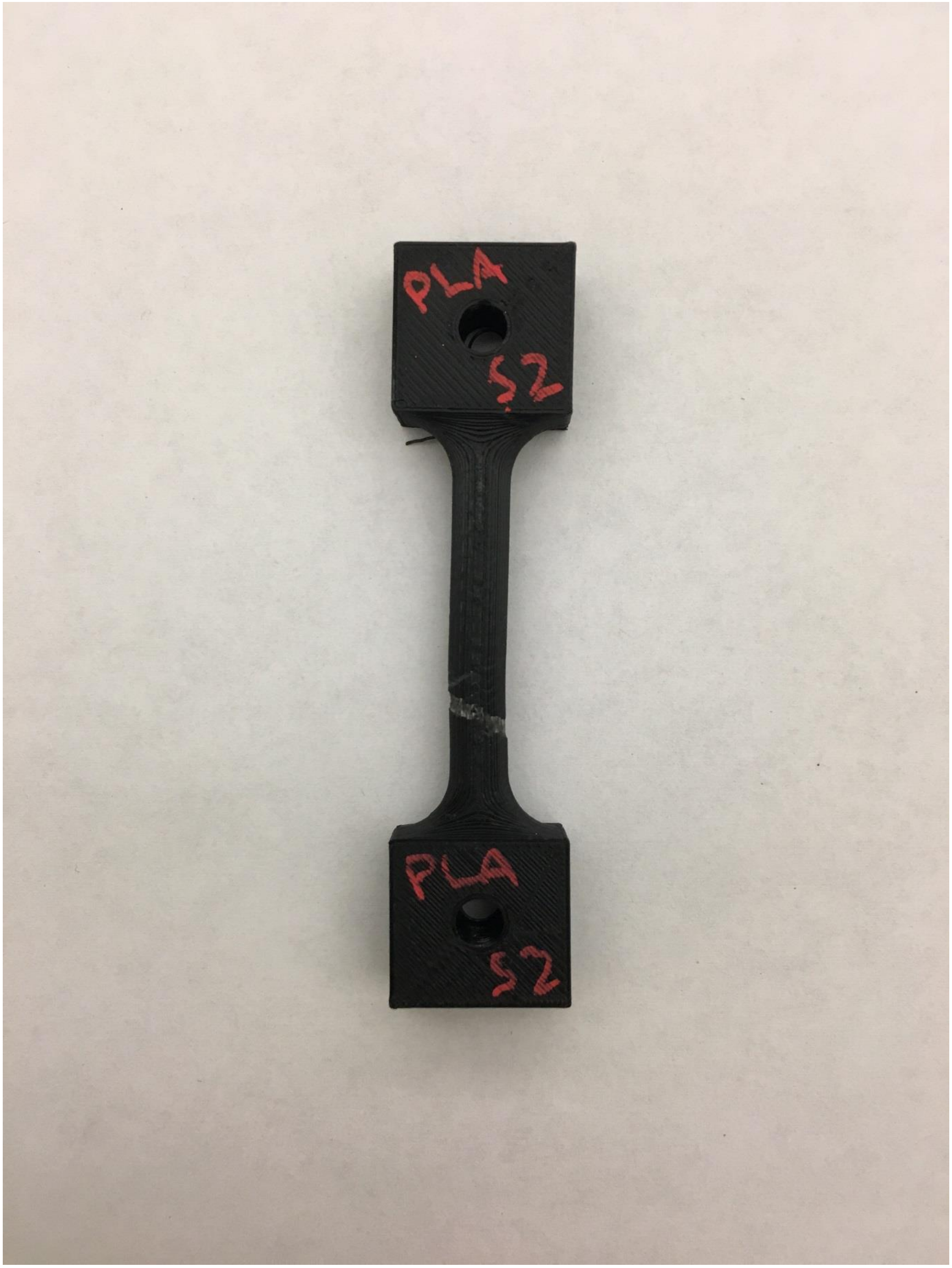
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	**2.98**	**1412.23**	**6.25**	**45.66**	**1141.55**

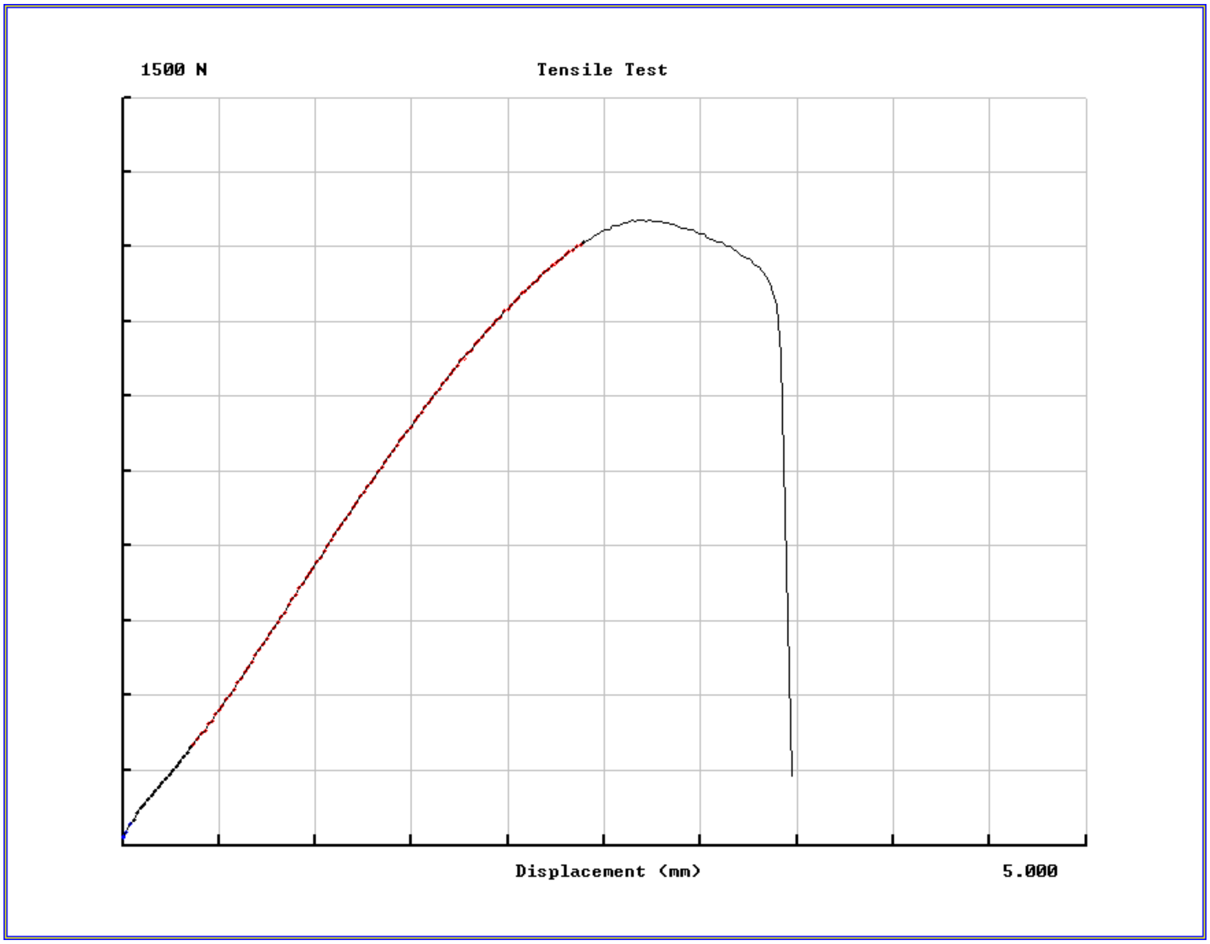

PLA
PLA



PLA-S-7

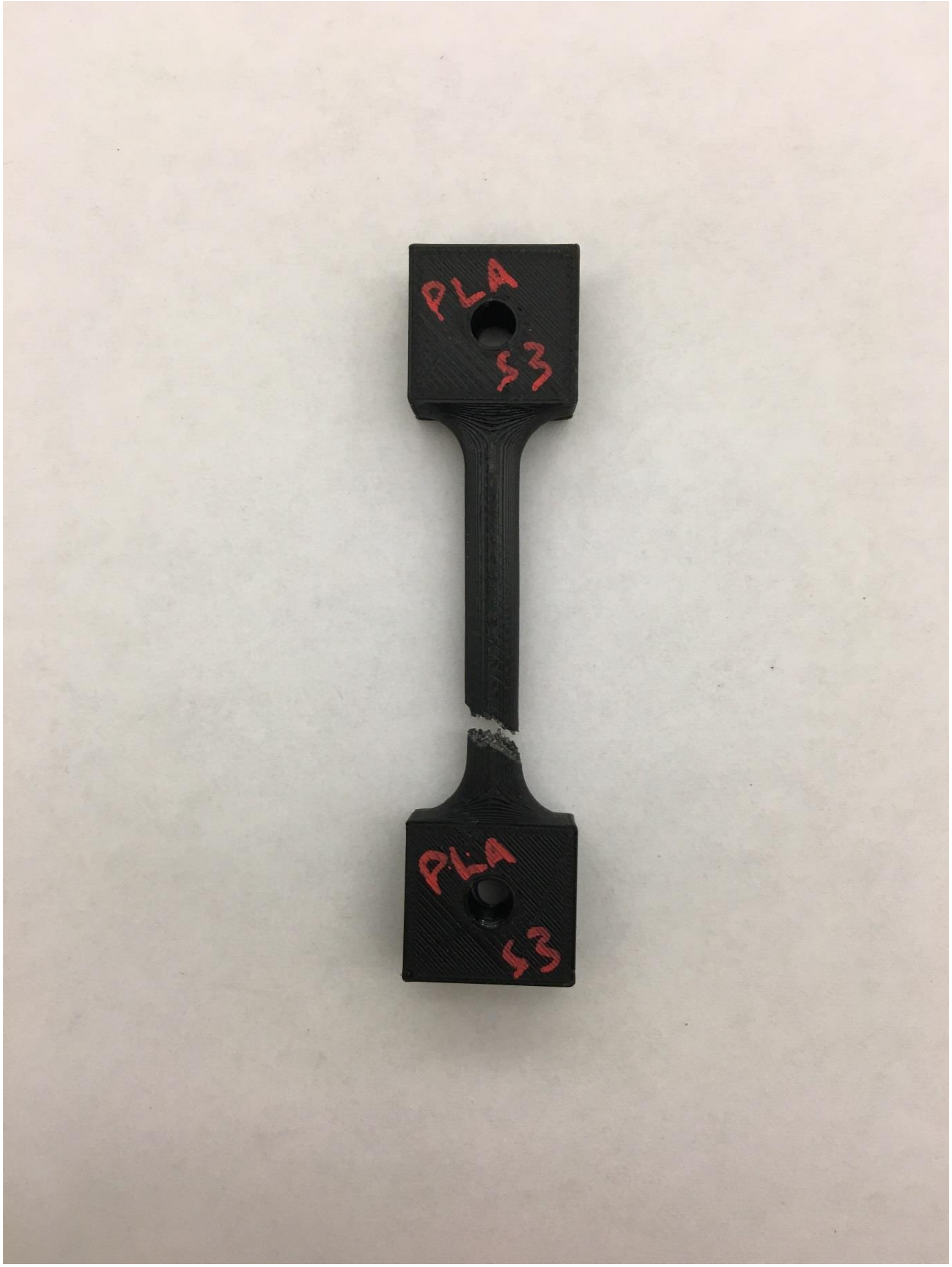
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	2.76	1328.77	6.37	40.81	995.36

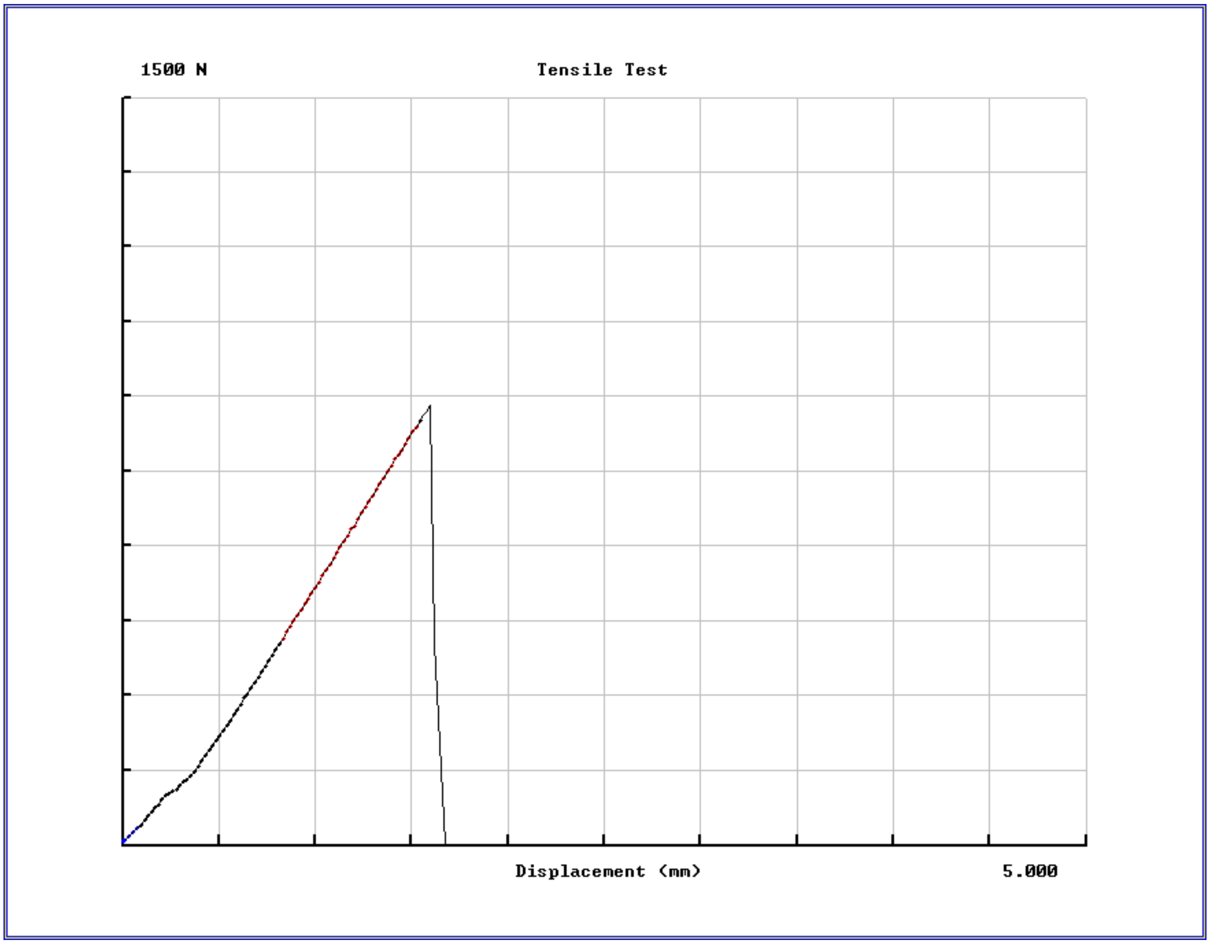

PLA
S2
PLA
S2



PLA-S-8

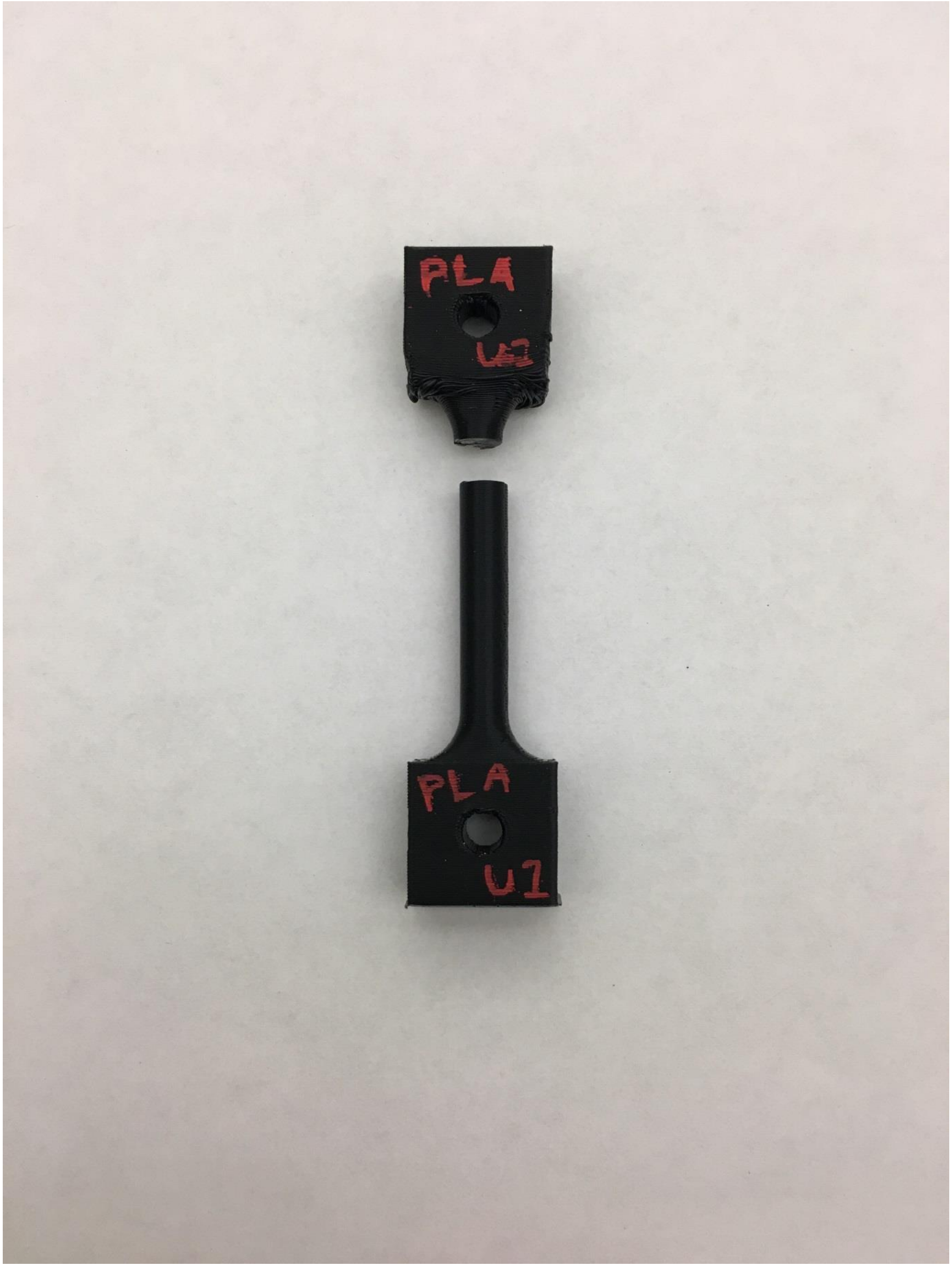
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed on Side	2.69	1254.9	6.41	37.98	949.61

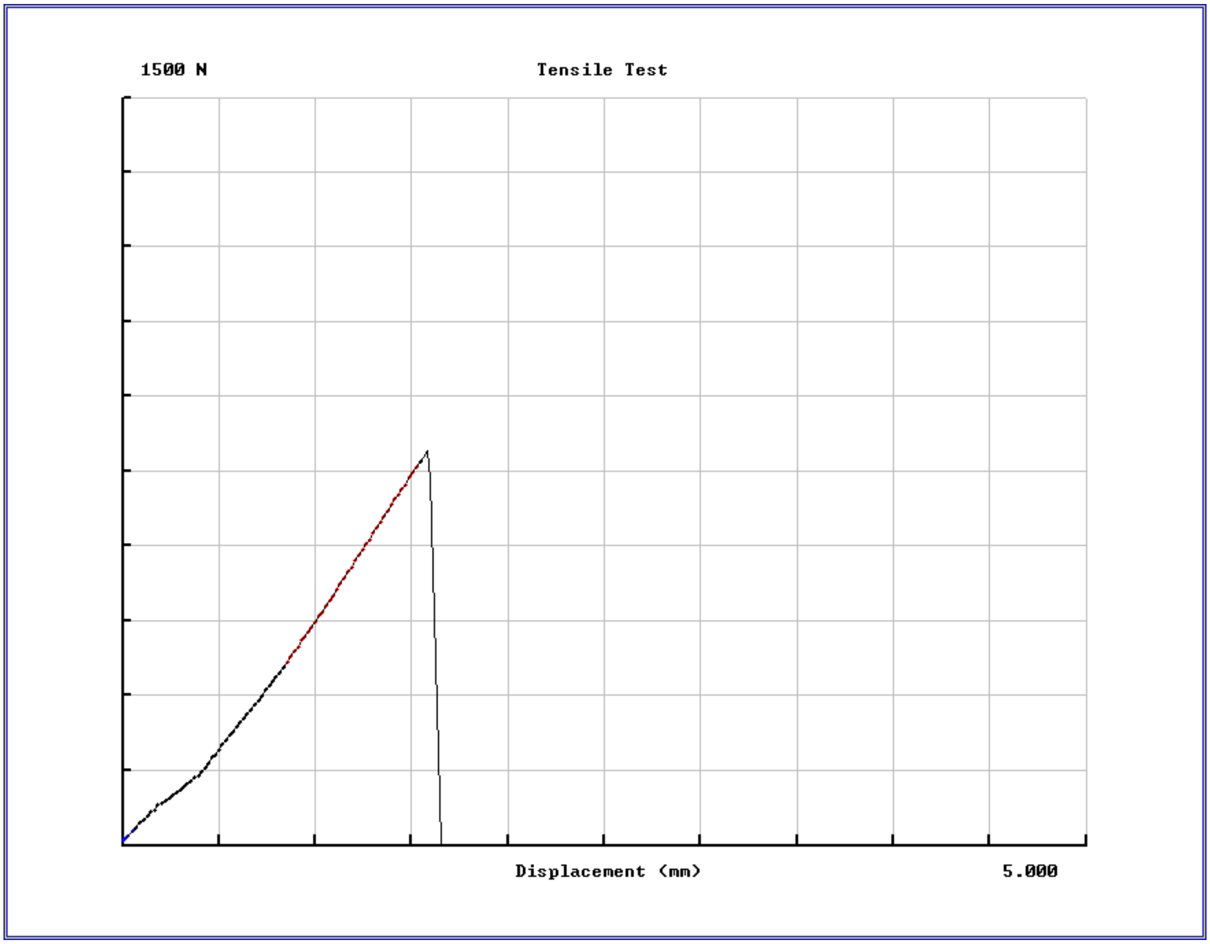

PLA
S3
PLA
S3



PLA-U-6

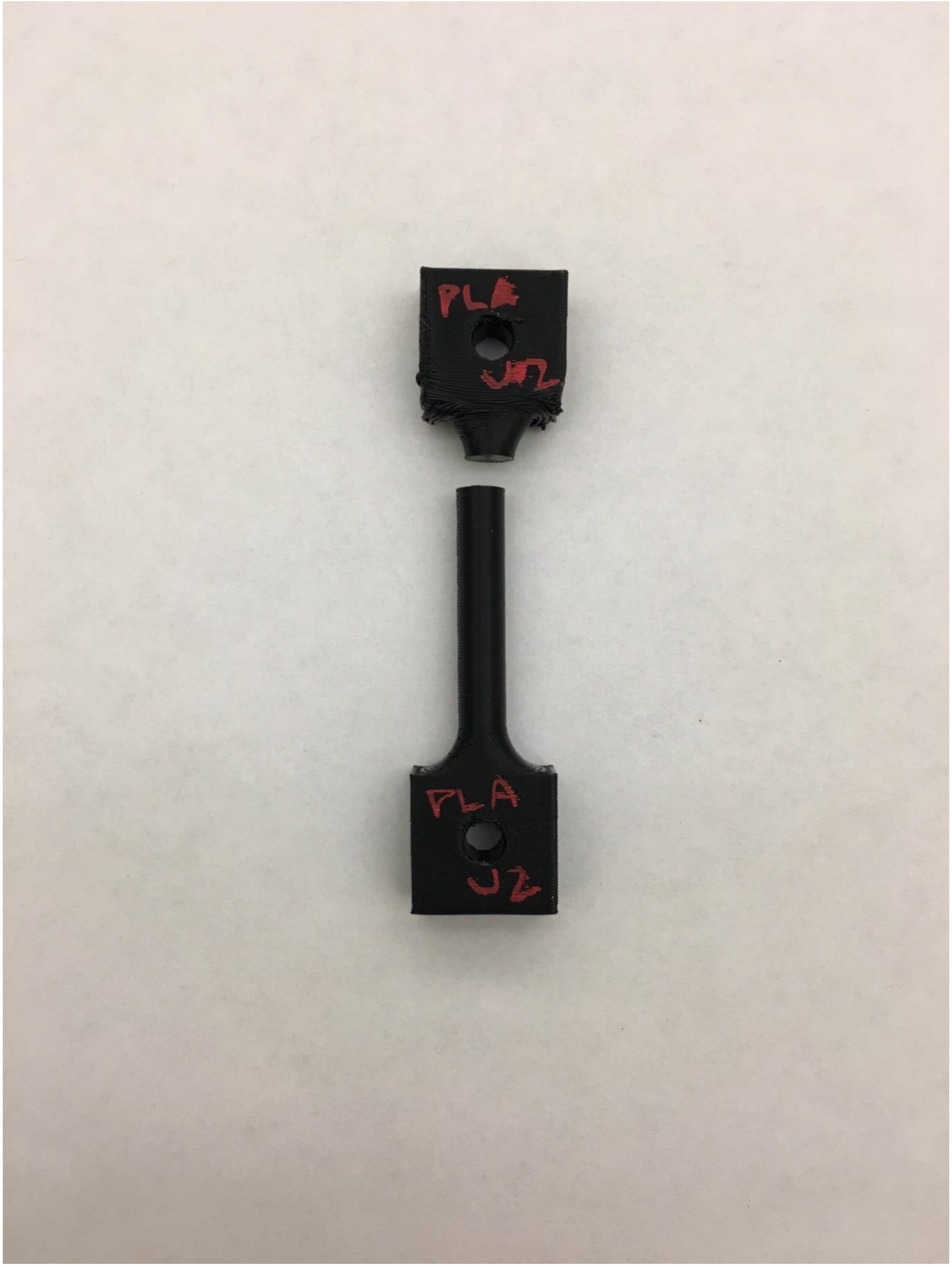
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	**1.59**	**881.8**	**6.45**	**26.03**	**964.21**

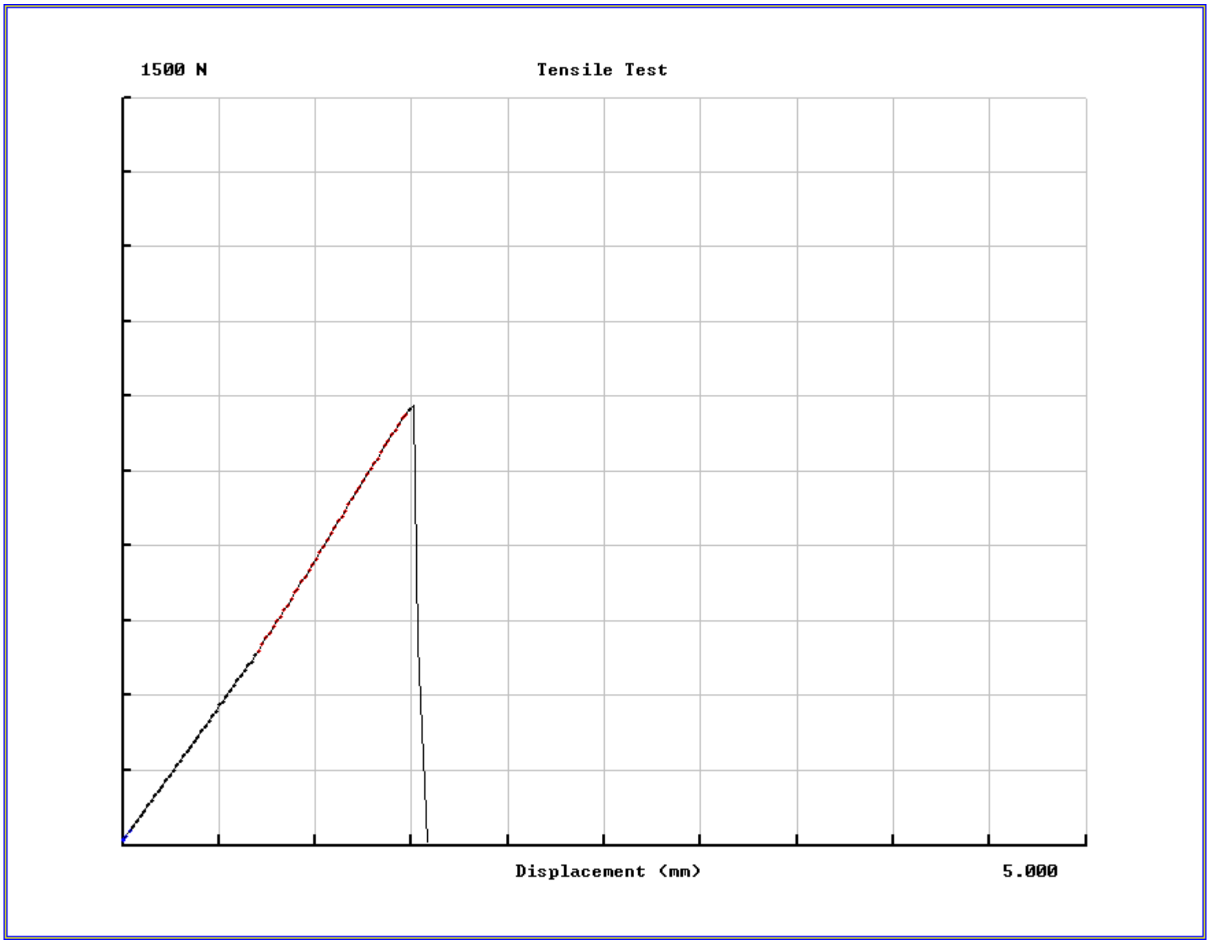

PLA
U1
PLA
U1



PLA-U-7

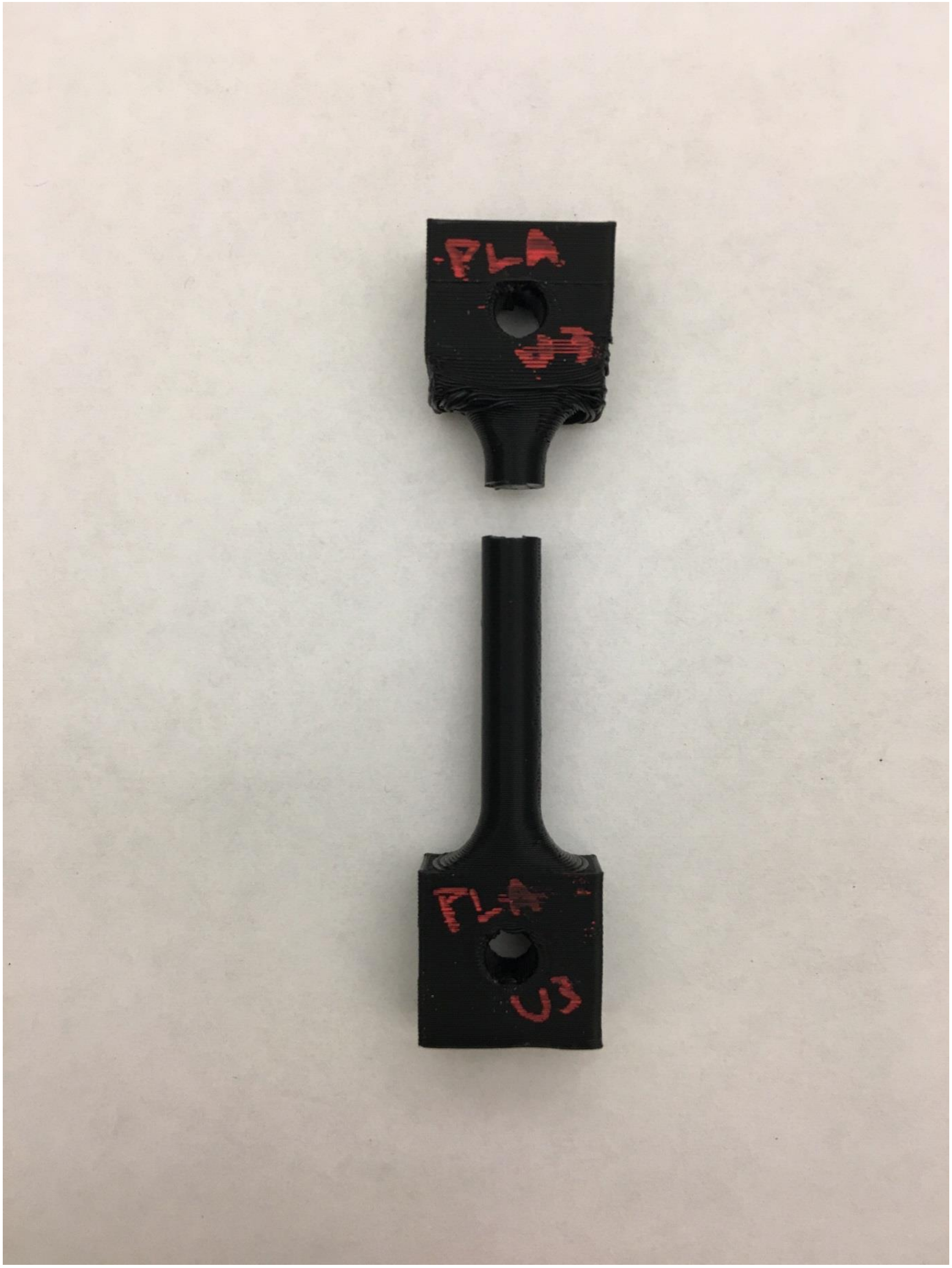
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	1.58	791.01	6.4	24.10	892.80


PLA
JZ
PLA
JZ

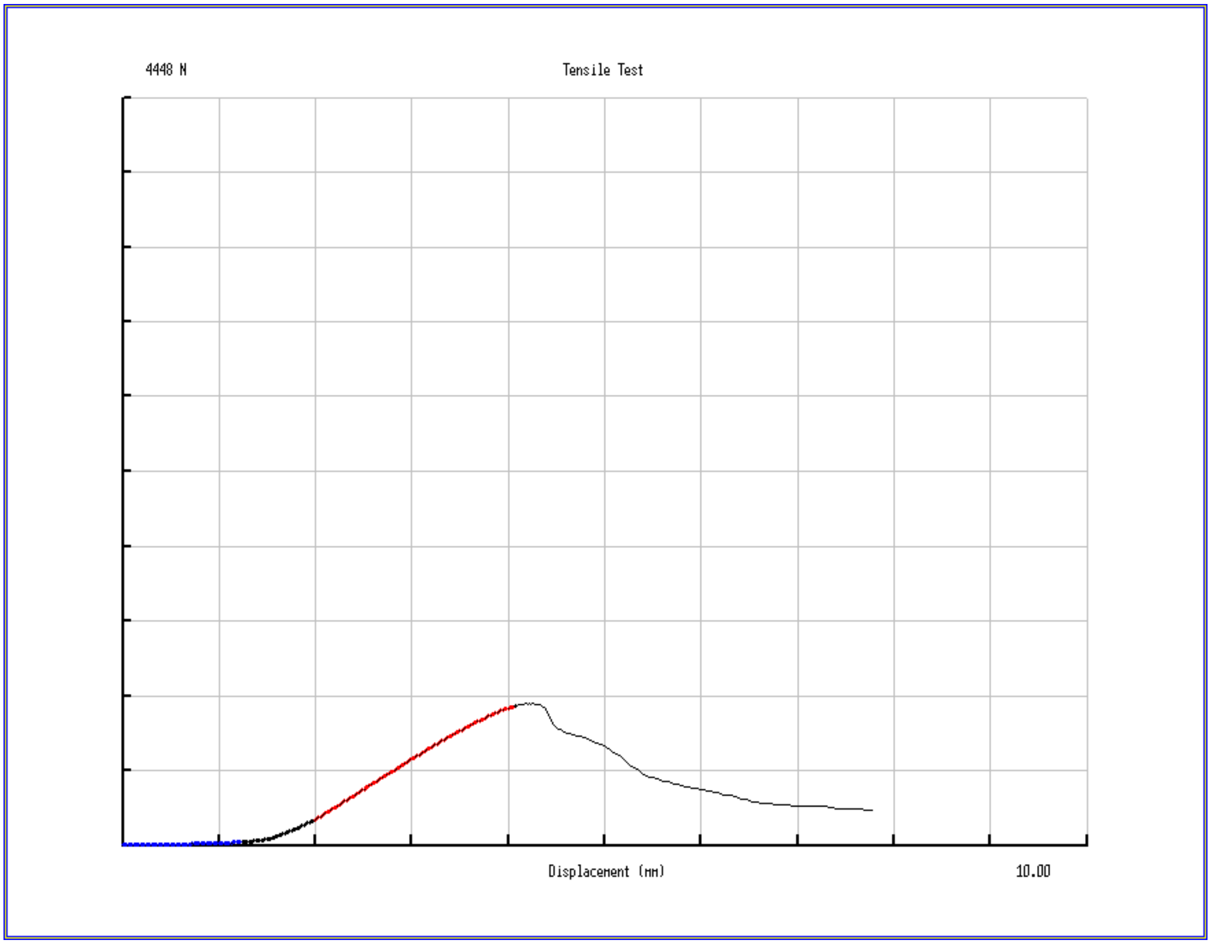


PLA-U-8

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed Upright	1.5	881.59	6.35	27.64	1063.31

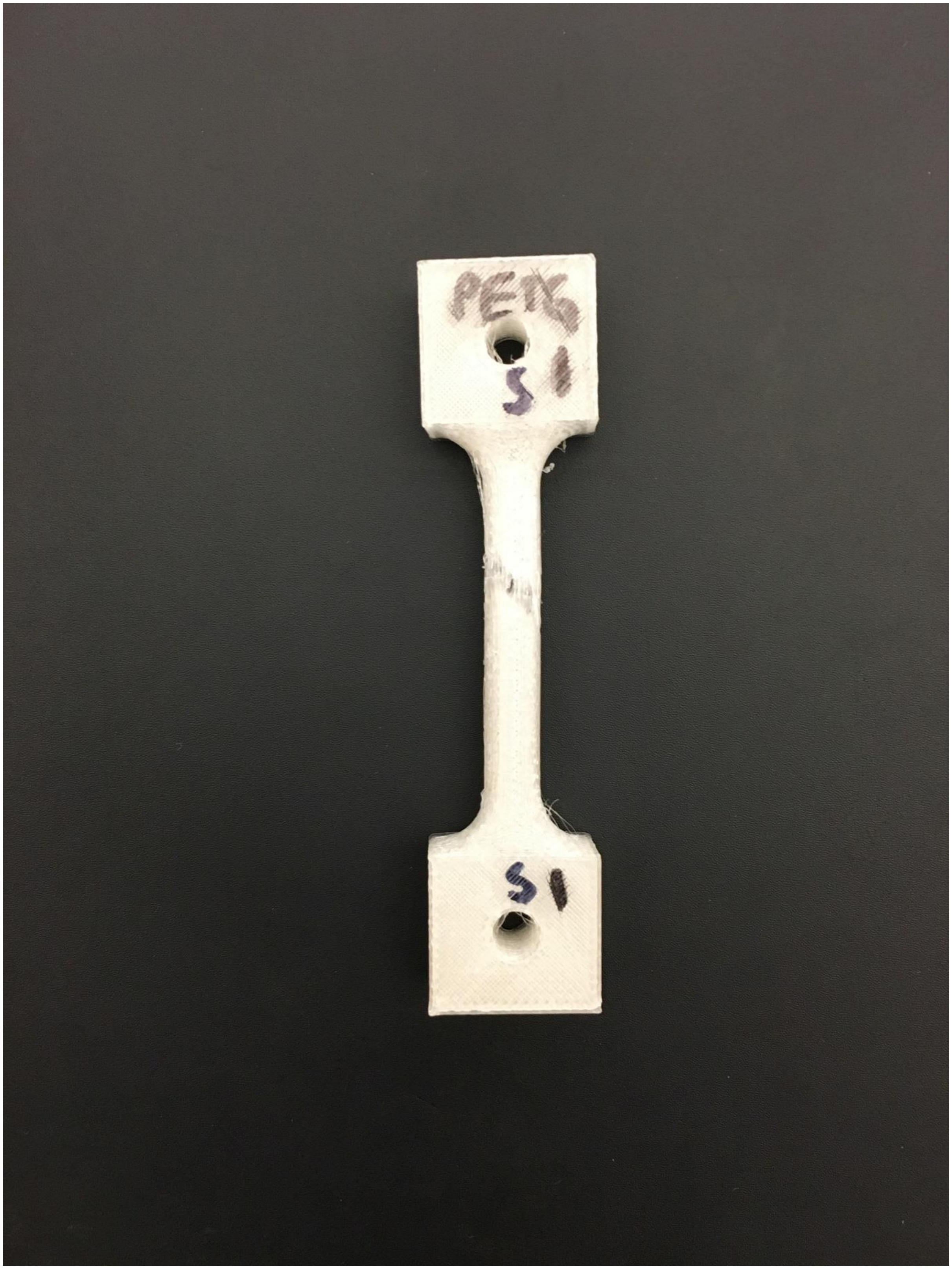

PLA
PLA
U3

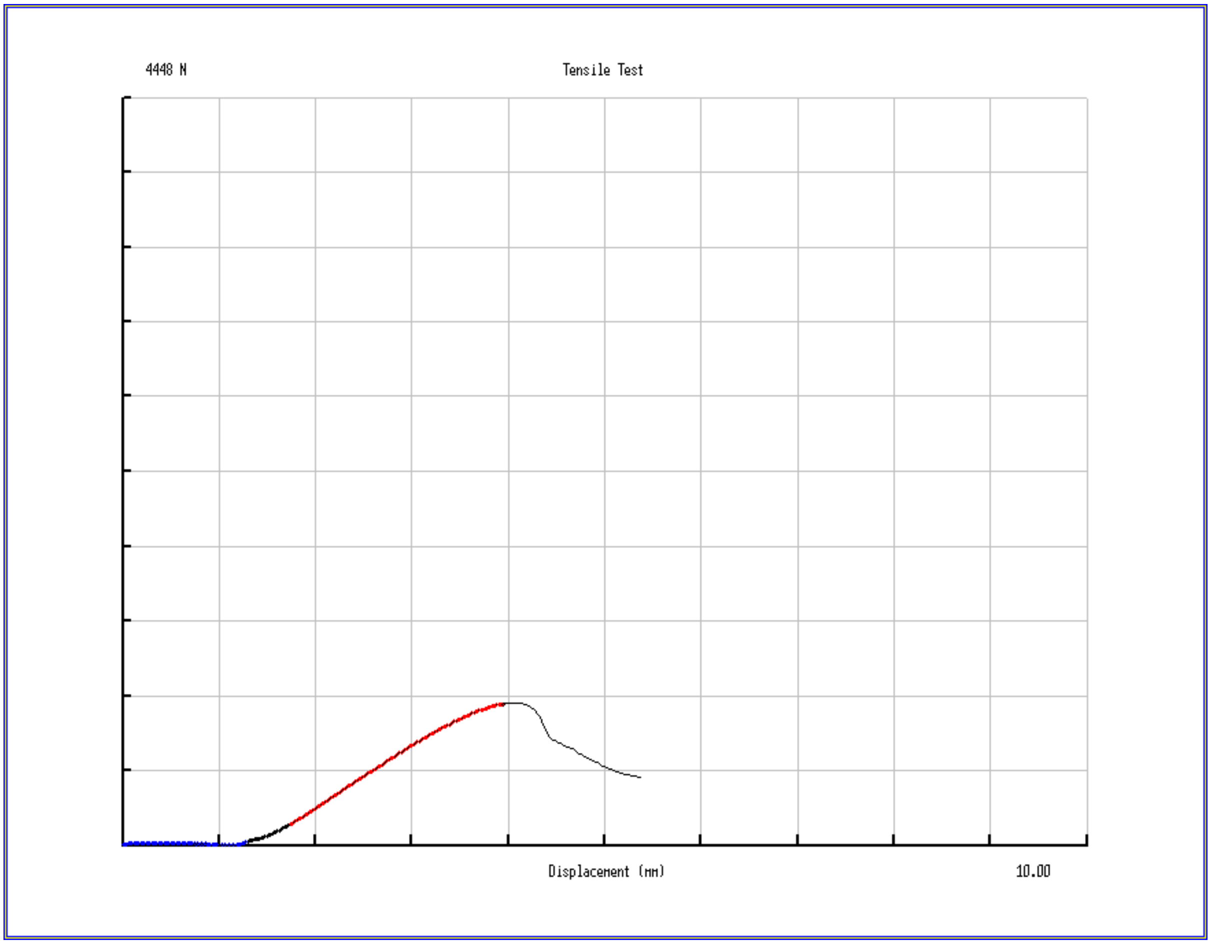
A2. HD Glass (PETG)



PETG-S-1

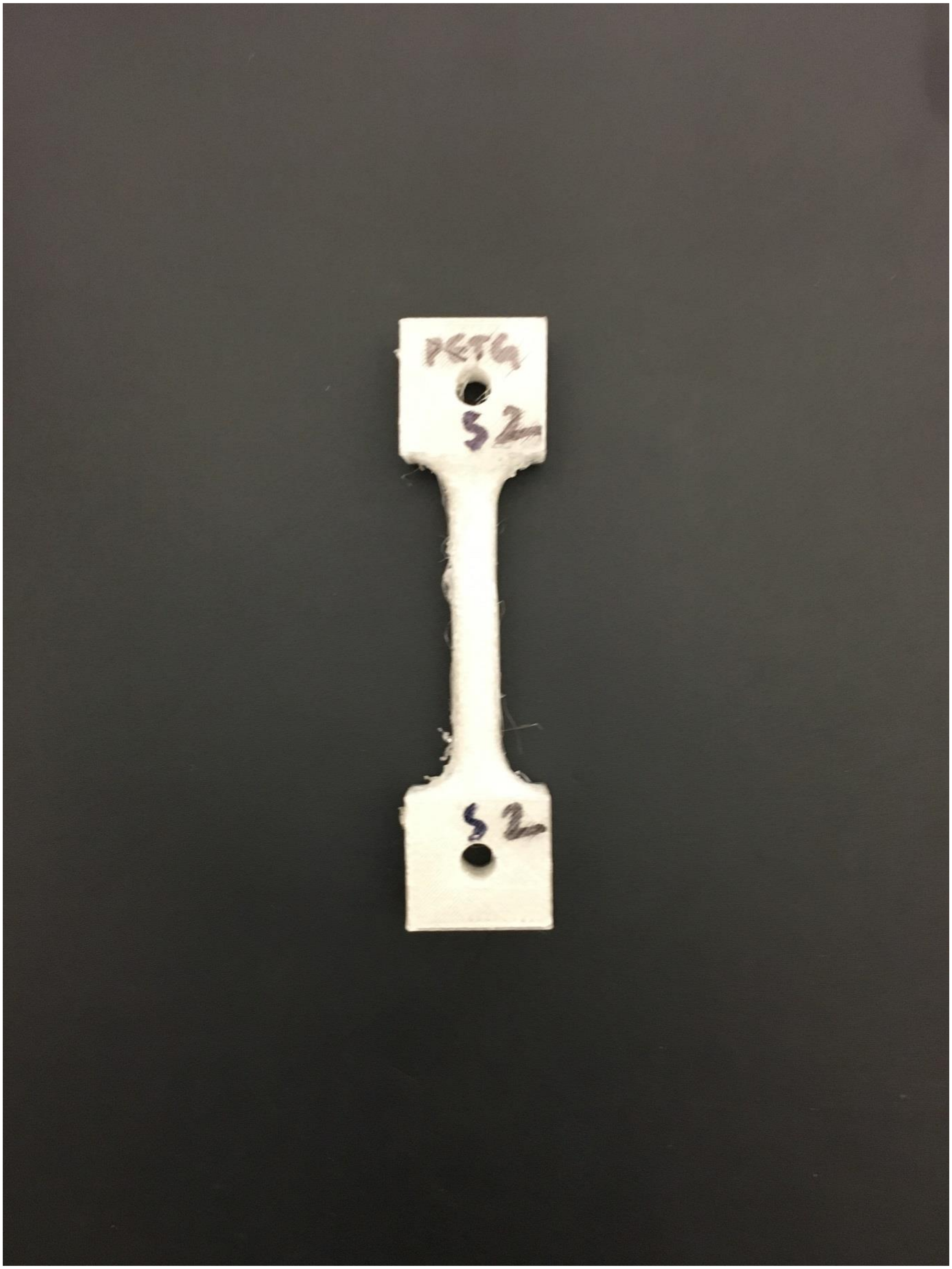
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed on Side	**4.21**	**843.05**	**6.2**	**26.18**	**494.05**

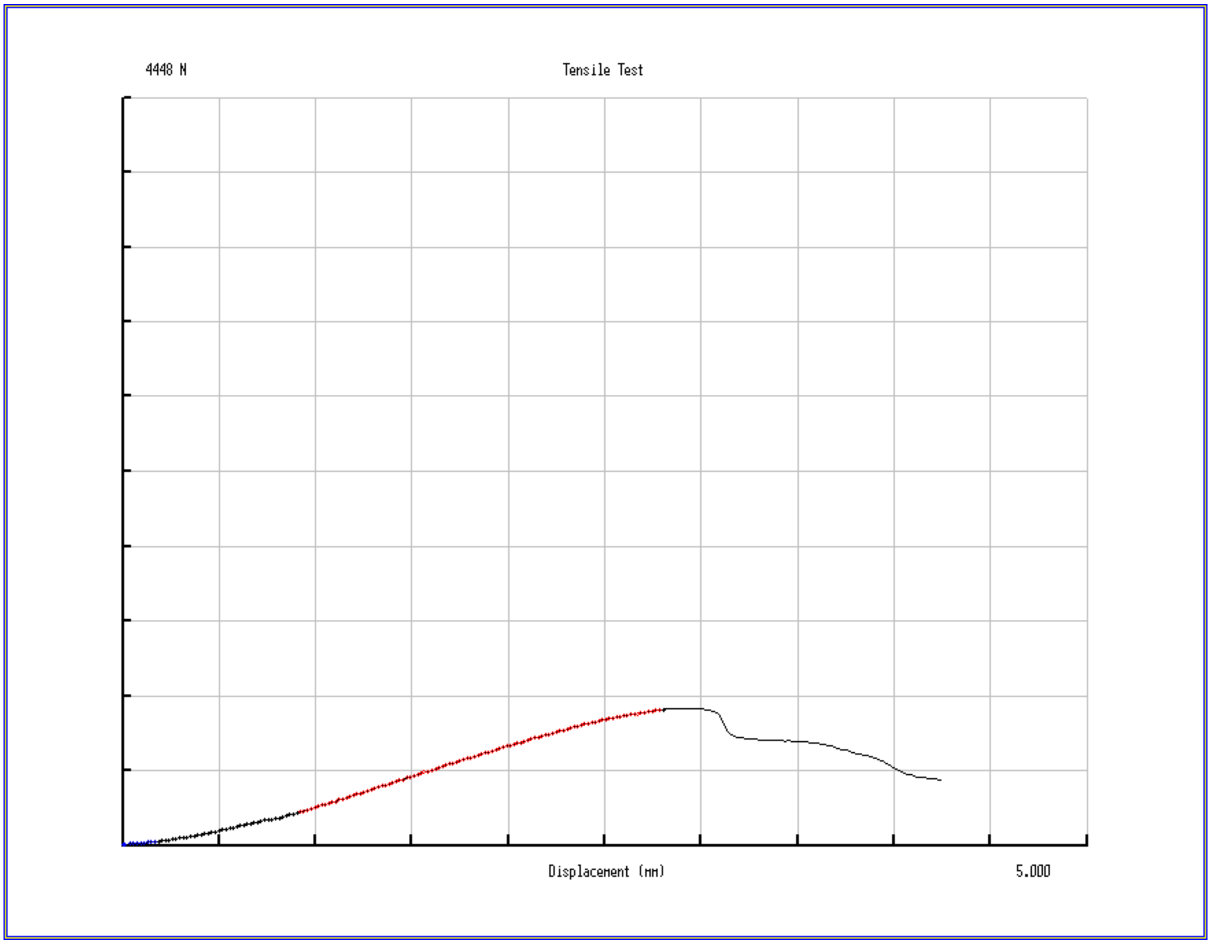

PETG
S1
S1



PETG-S-2

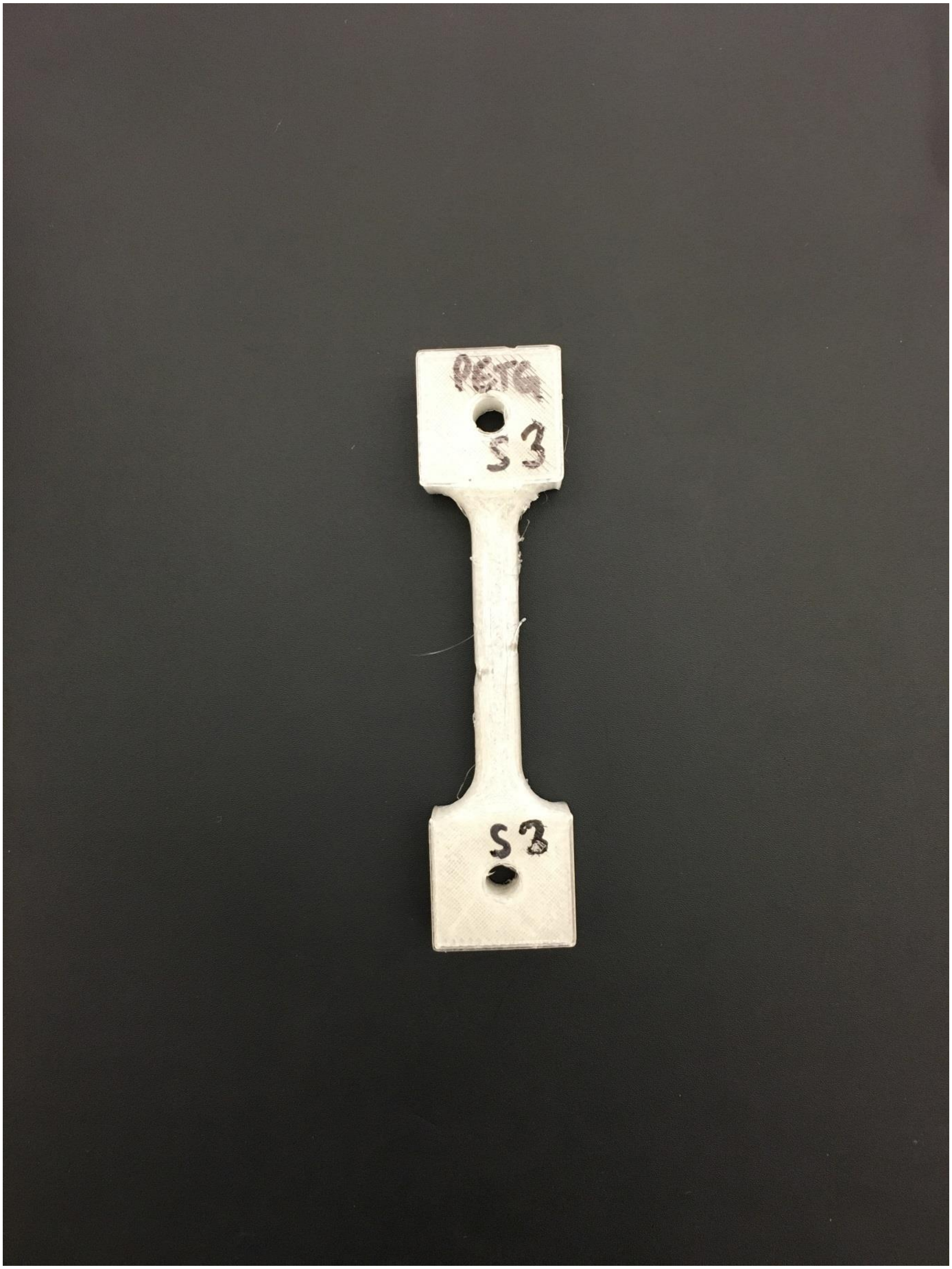
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	**4.14**	**842.53**	**6.22**	**27.65**	**553.17**

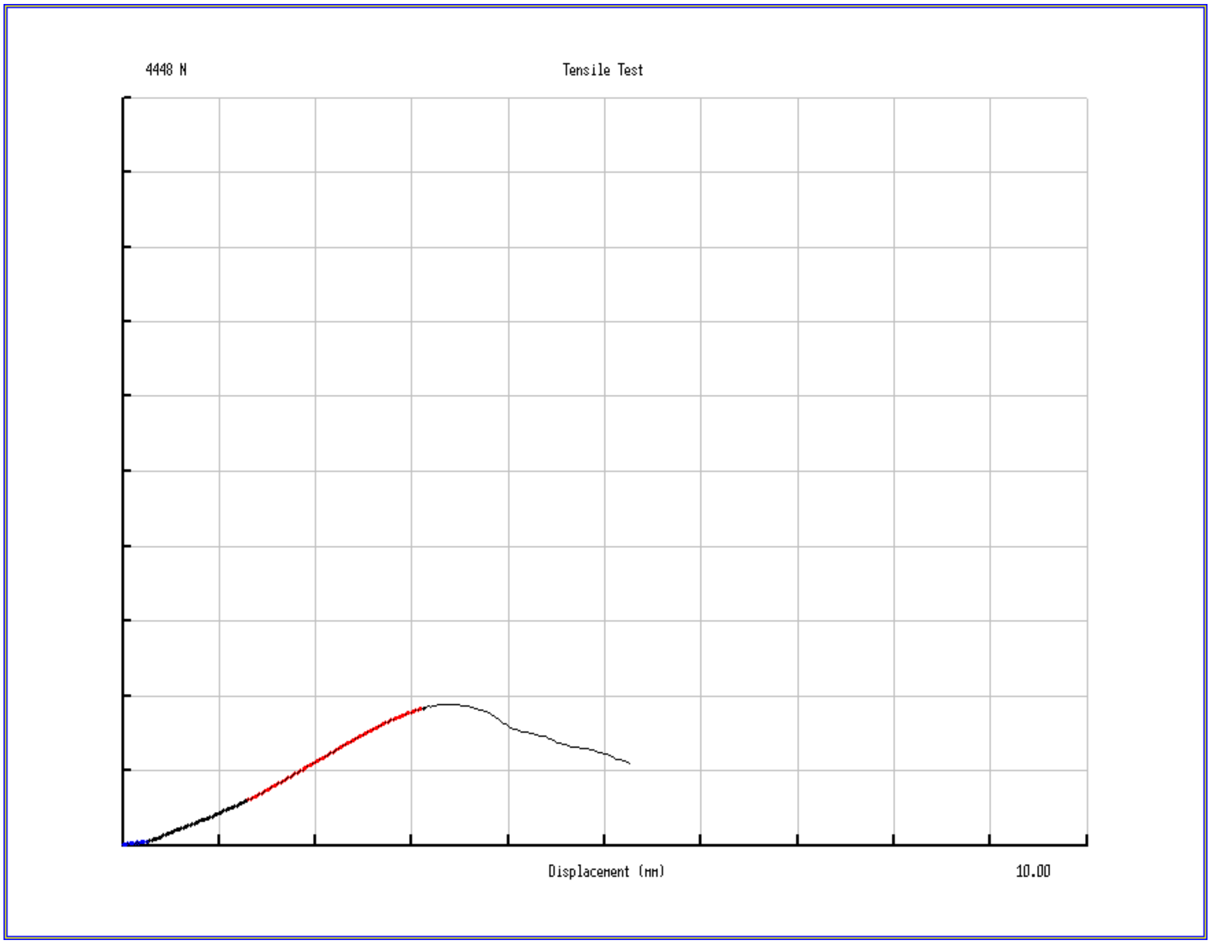

PETG
S2m
S2m



PETG-S-3

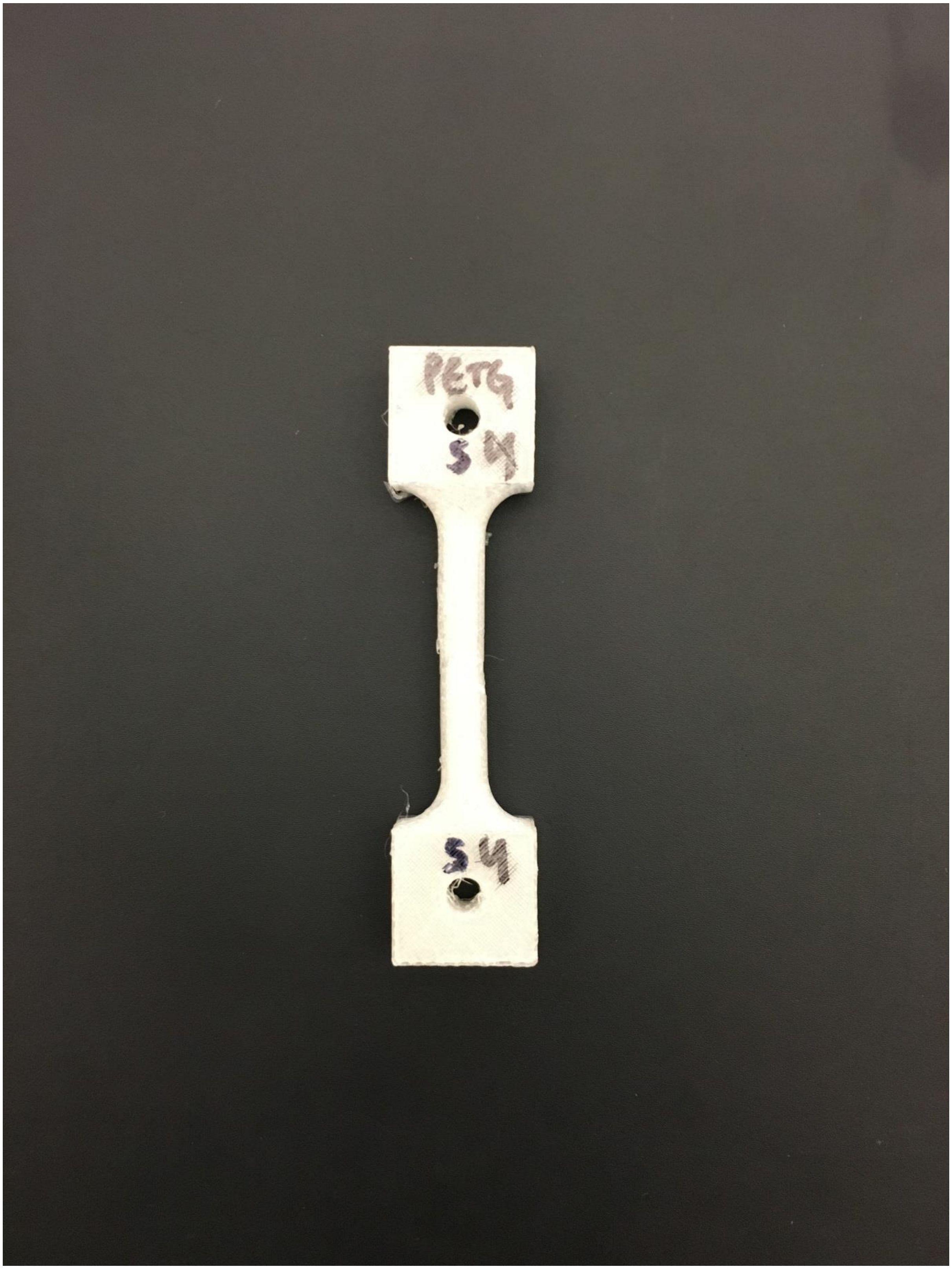
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	2.95	809.81	6.24	25.85	369.29

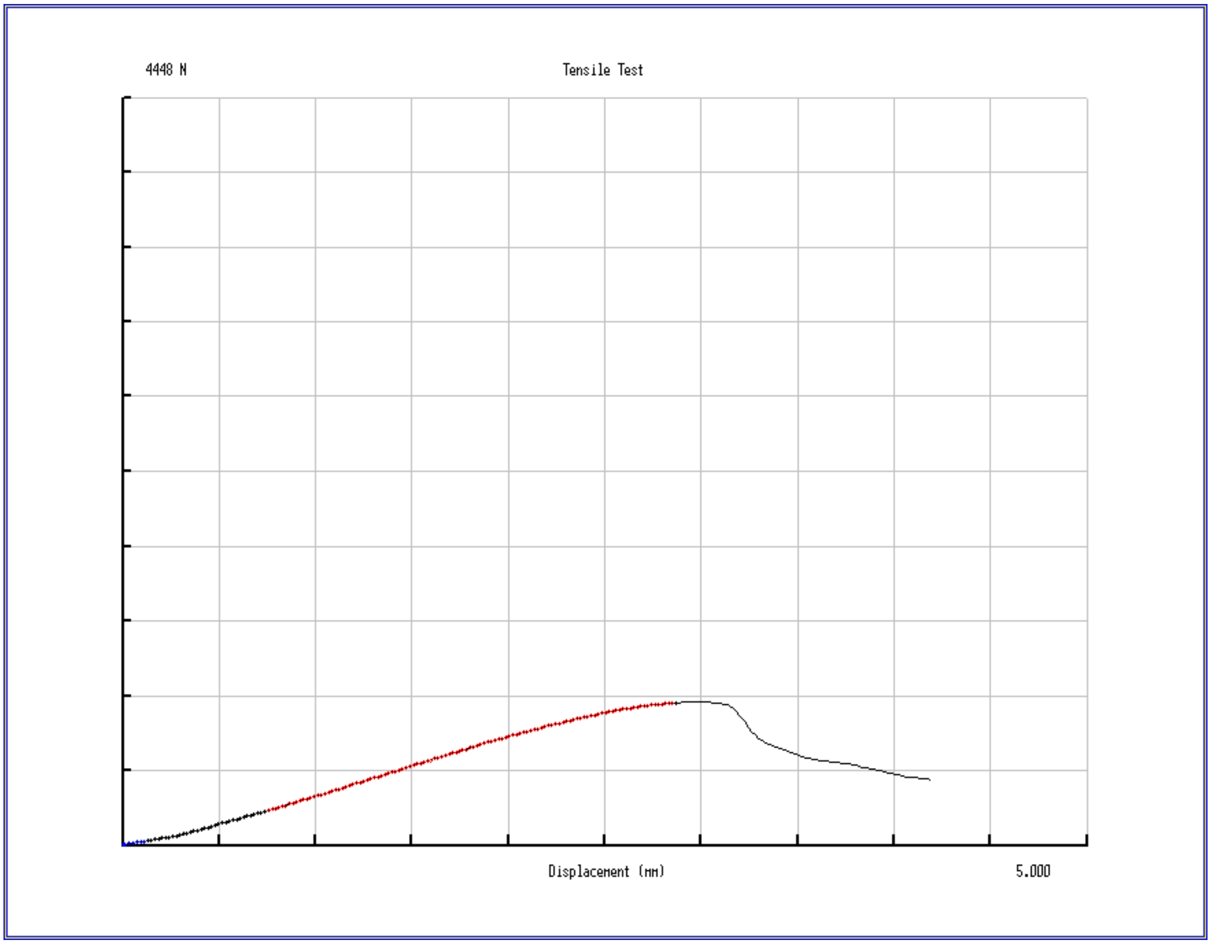

PETG
S3
S3



PETG-S-4

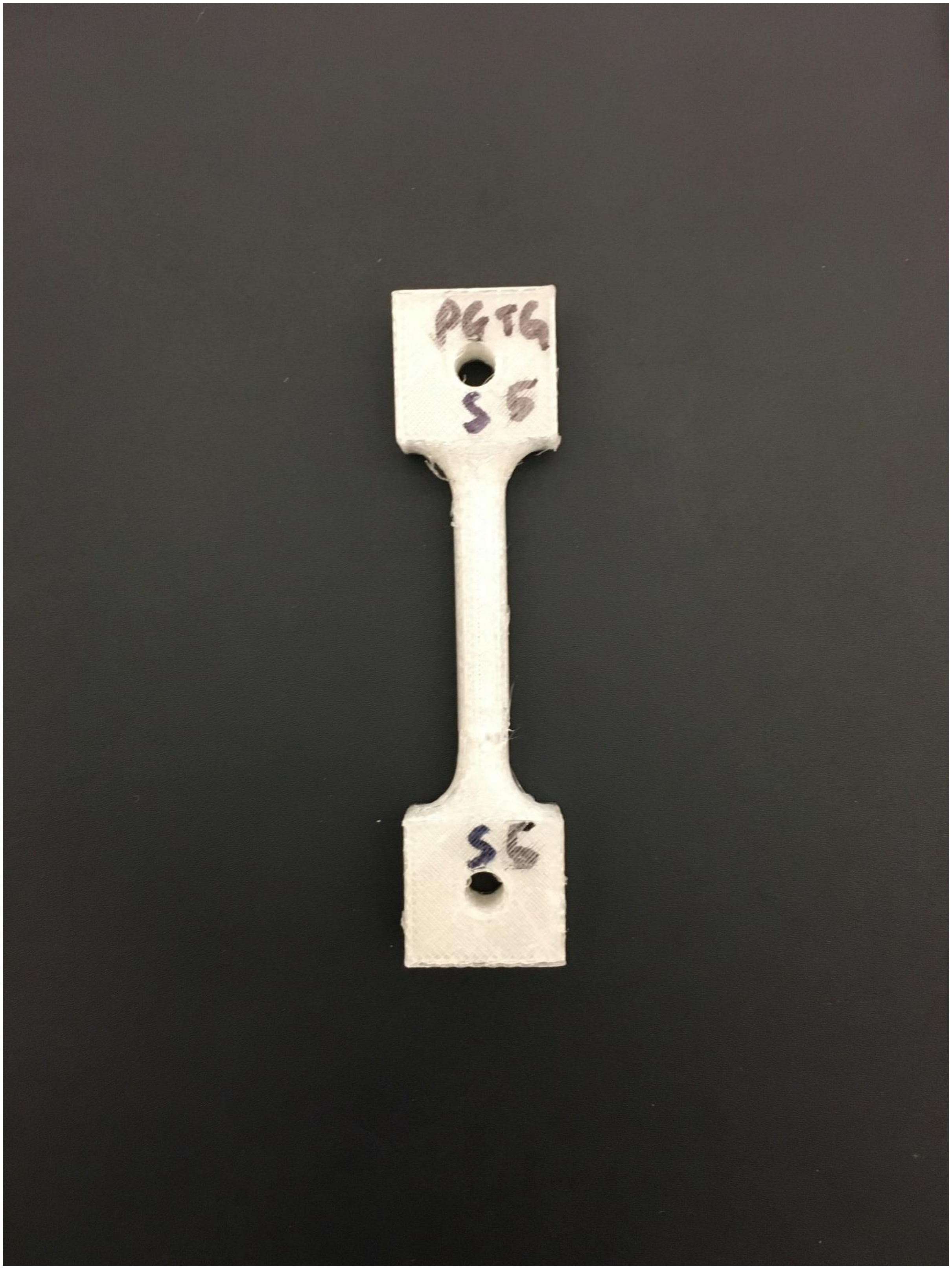
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed on Side	3.39	838.26	6.22	26.01	650.31

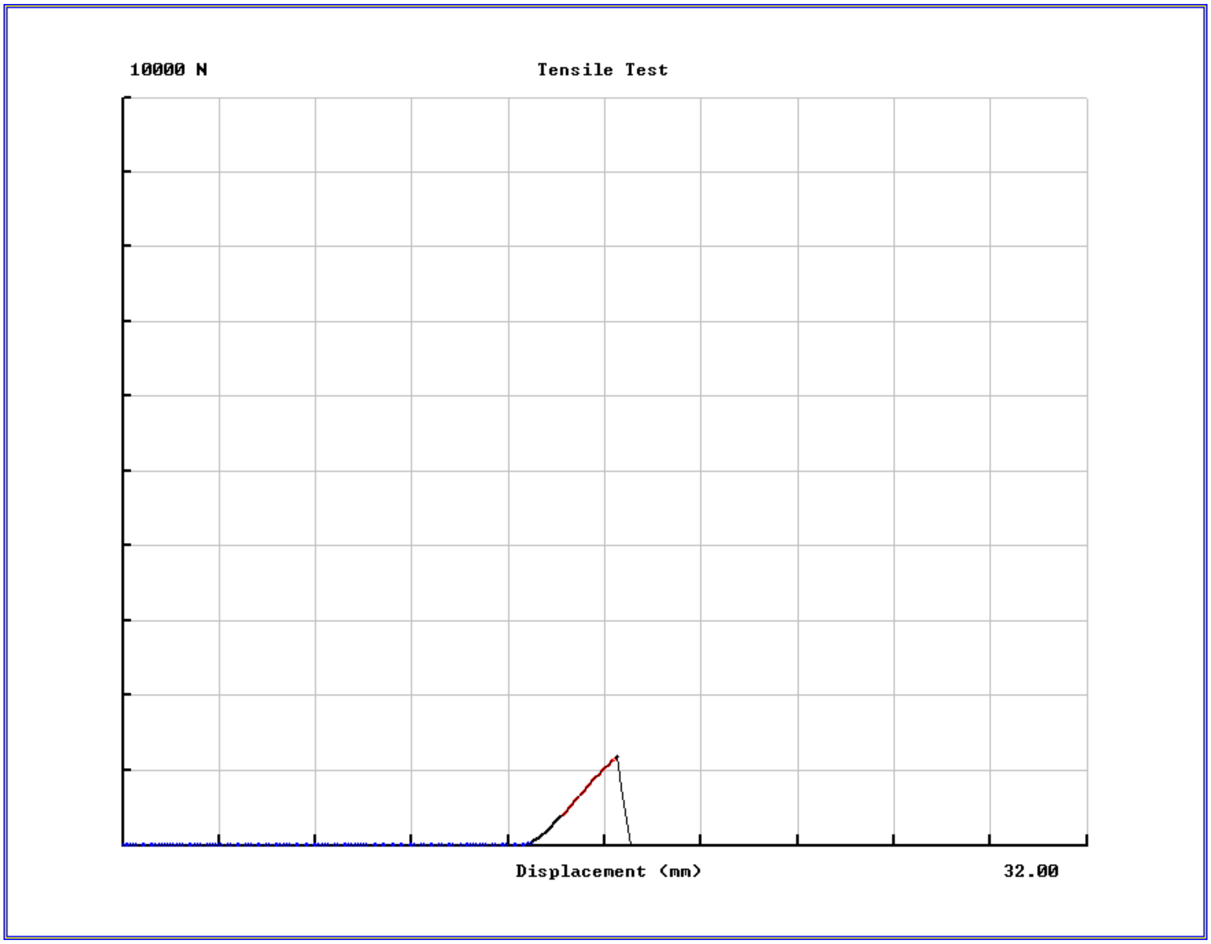

PETG
S 4
S 4



PETG-S-5

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	3	854.29	6.17	28.78	394.27

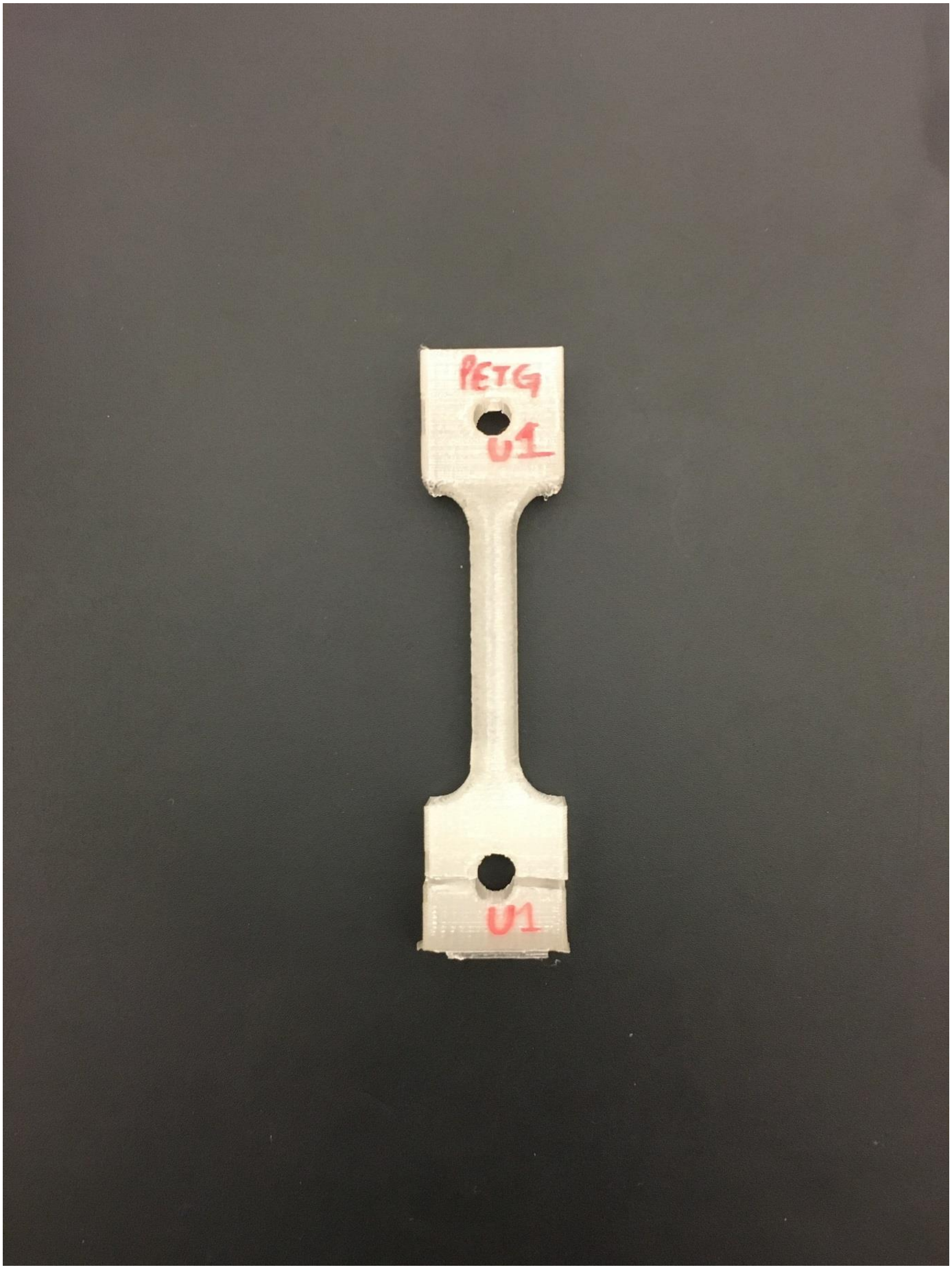

PGTG
S5
S6

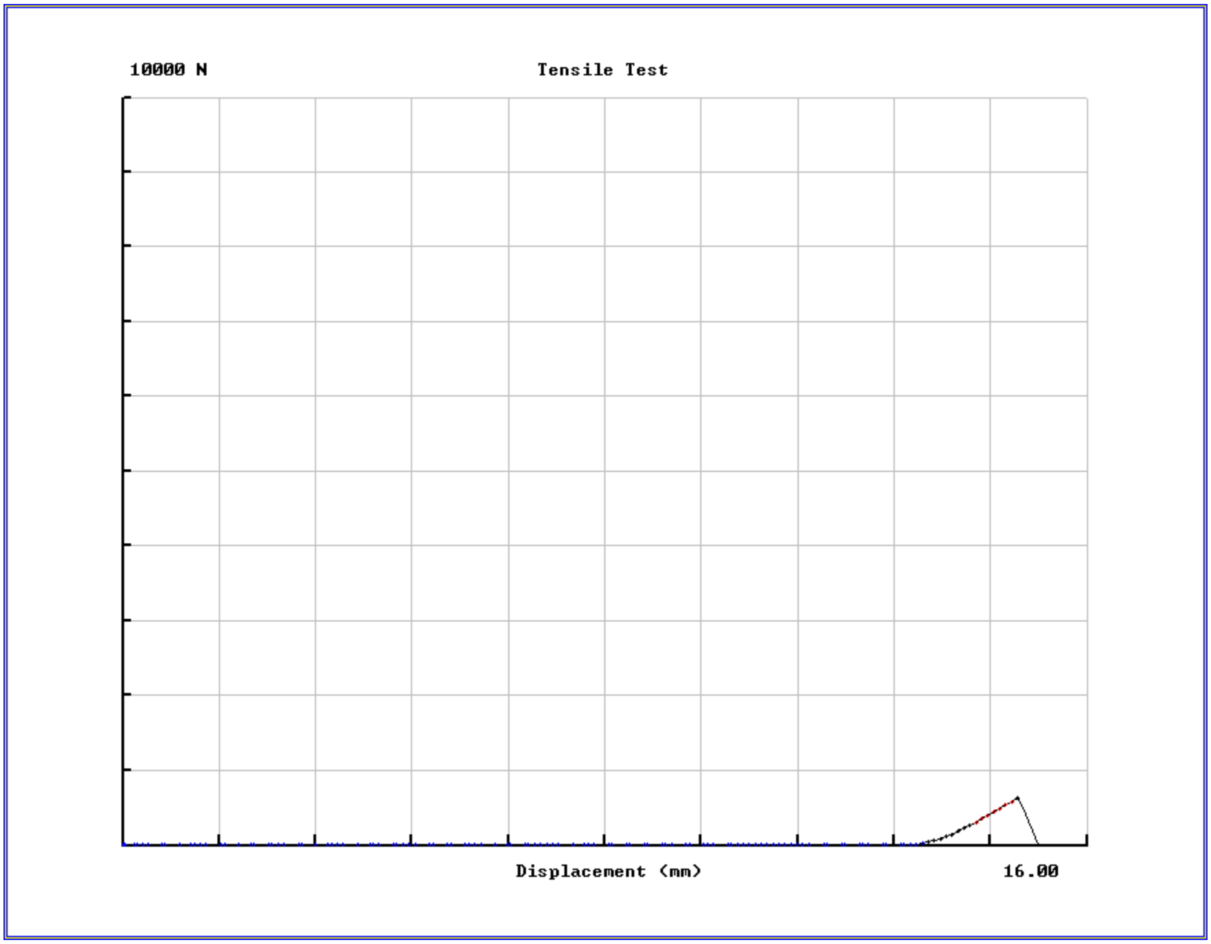


PETG-U-1

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	**16.41**	**1180.72**	**6.31**	**36.8**	**1082.35**

- **Invalid result due to wrong failure (see picture)**

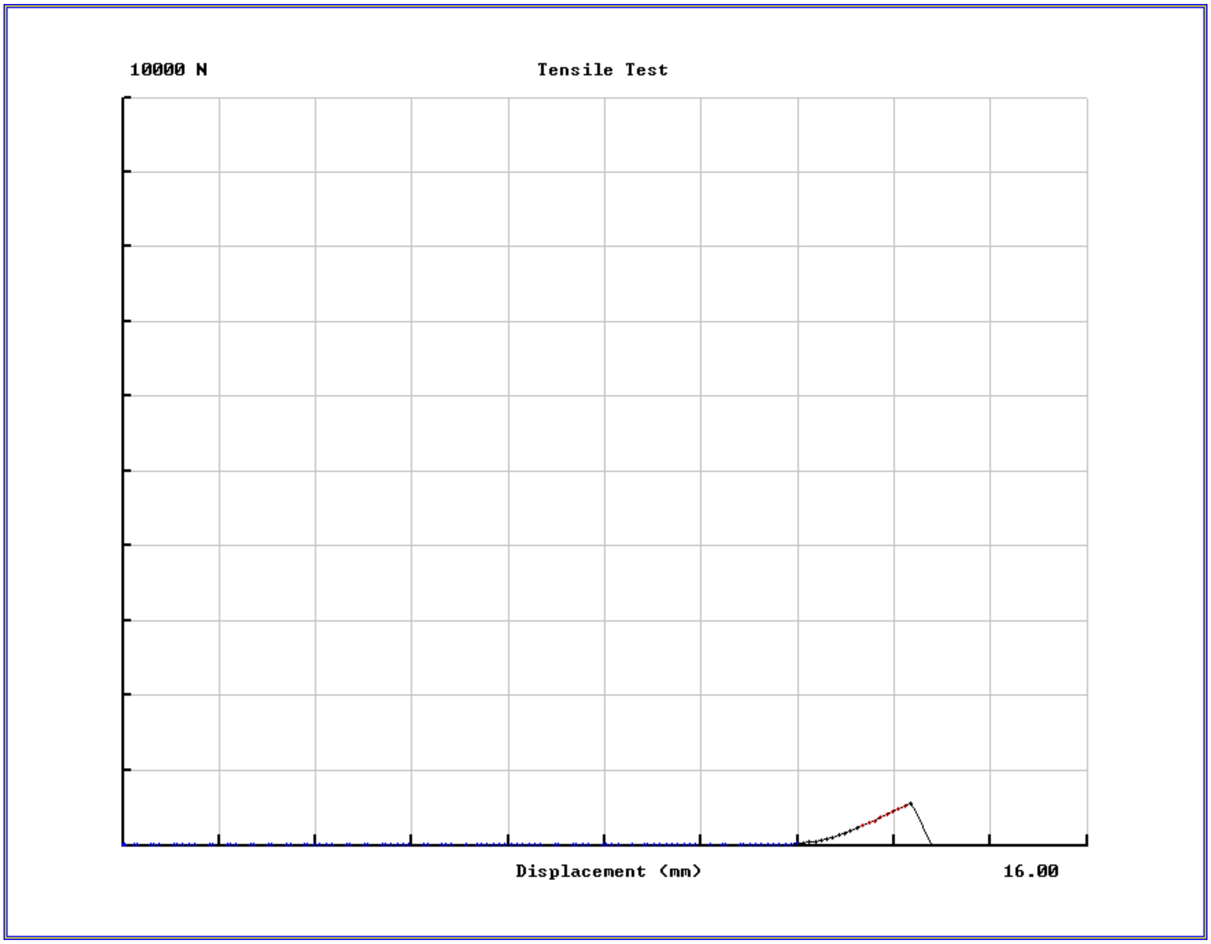

PETG
U1
U1



PETG-U-2

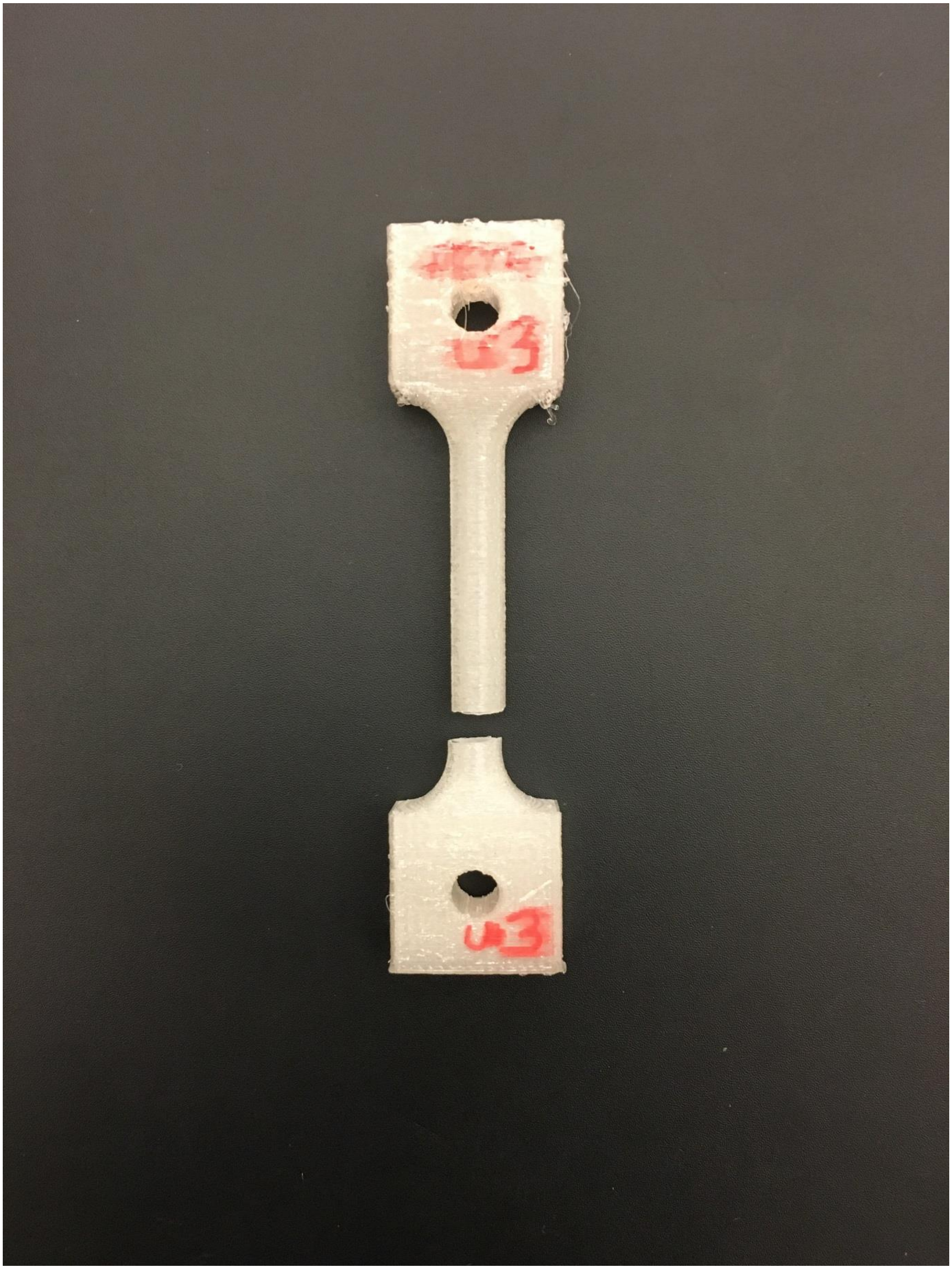
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	14.85	632.27	6.14	21.12	1408.13

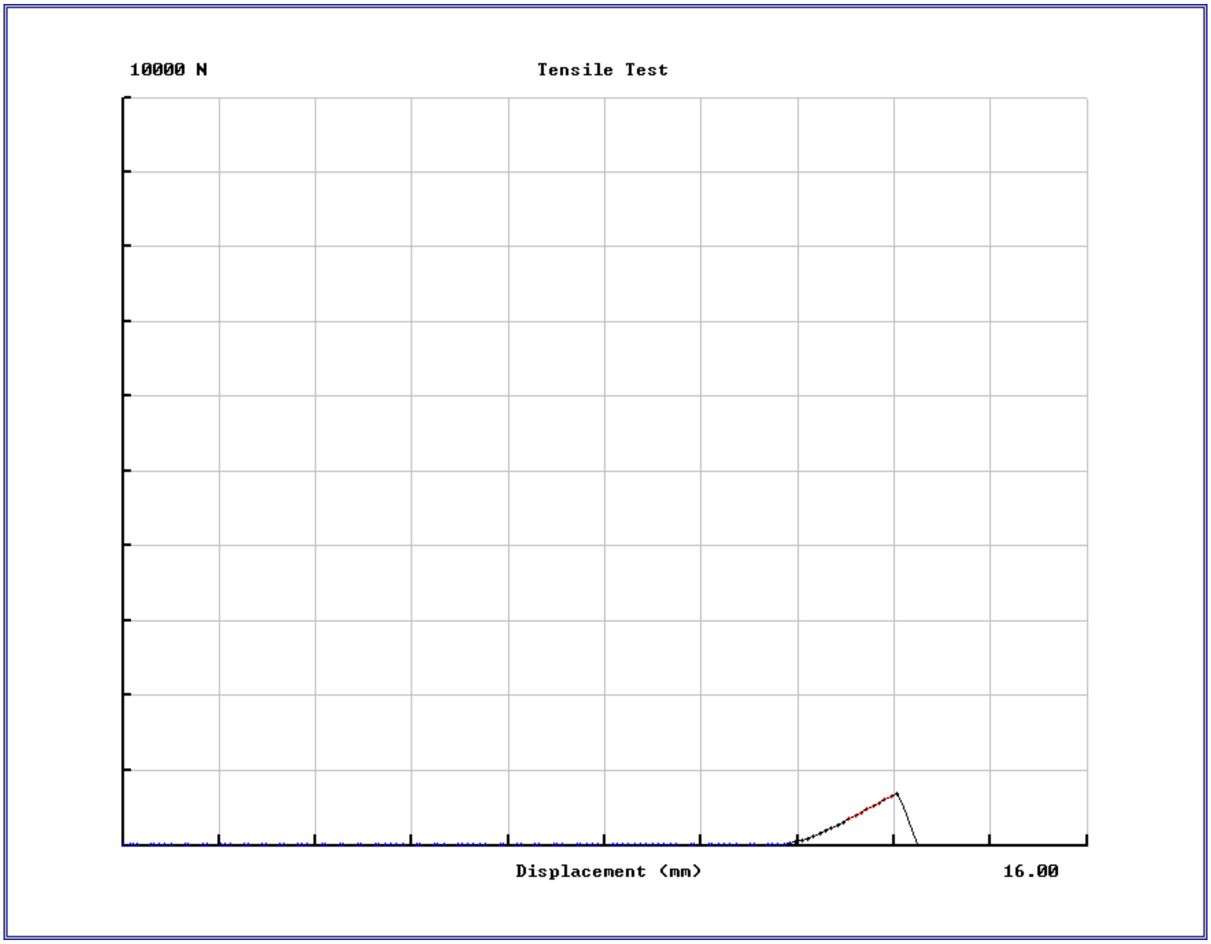

PETG
42



PETG-U-3

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	**13.07**	**565.82**	**6.14**	**19.60**	**753.84**

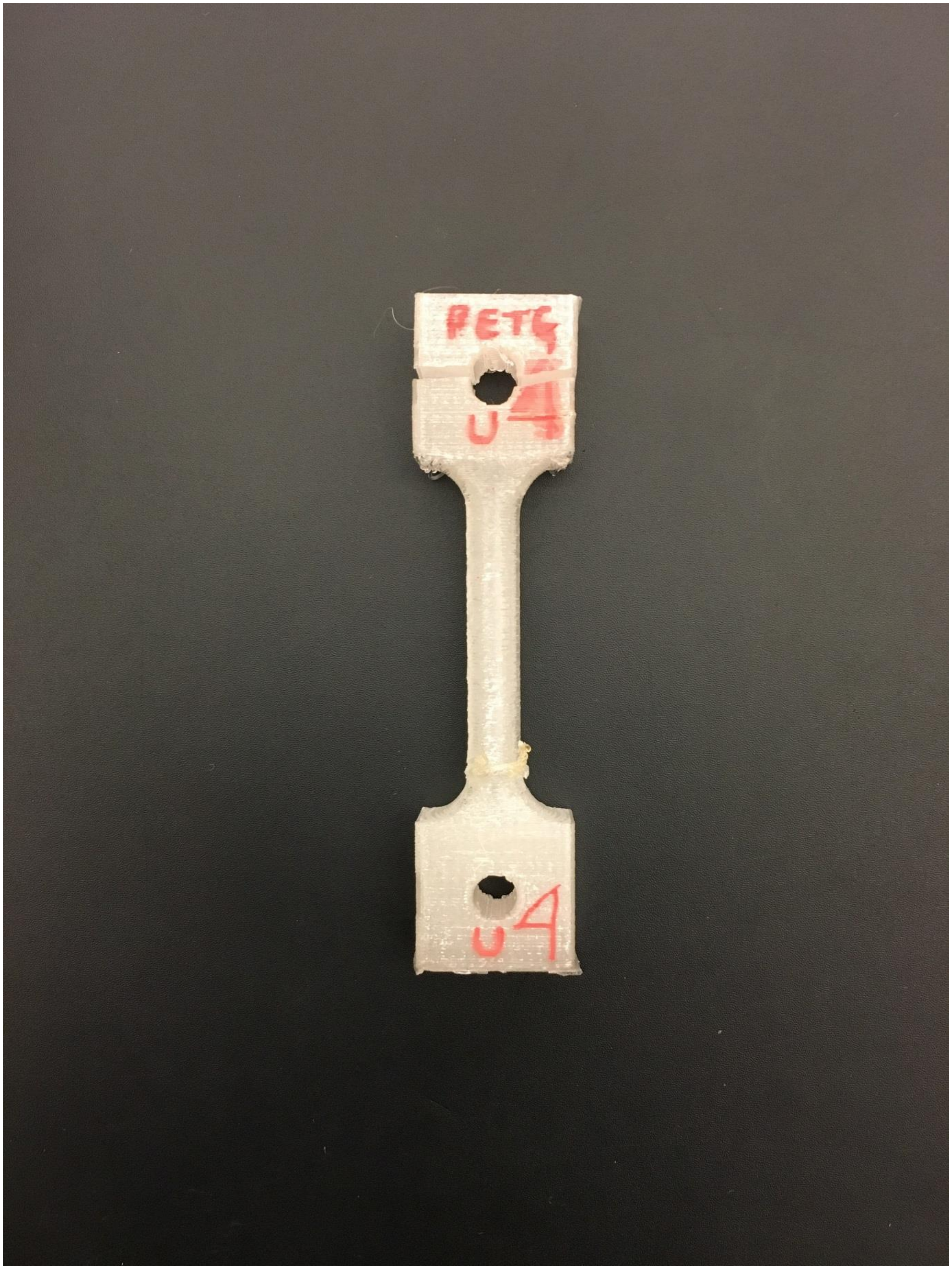

U3
U3



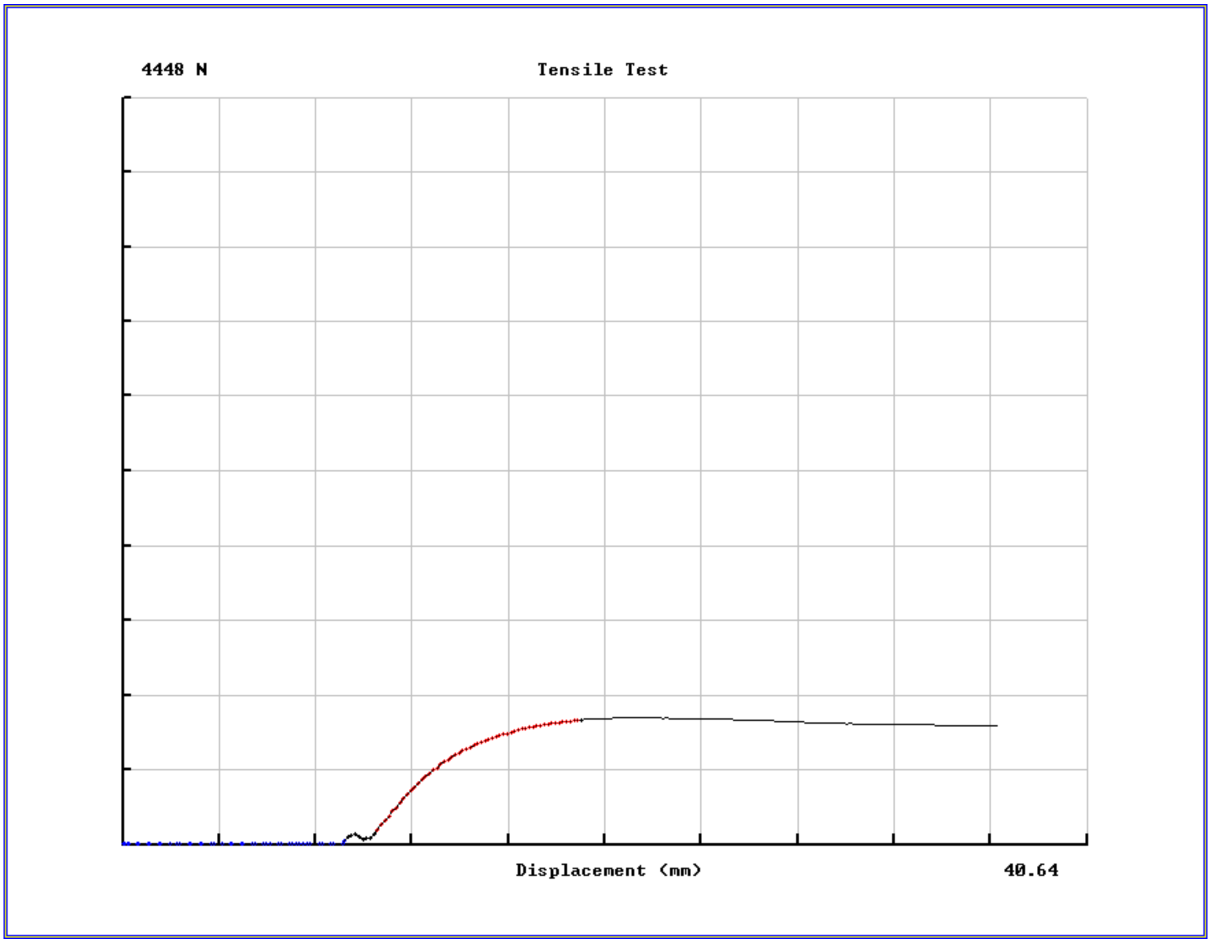
PETG-U-4

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	**12.84**	**696.29**	**6.41**	**21.70**	**834.82**

- **Invalid result due to wrong failure (see picture)**


PETG
U4
U4

A3. Nylon

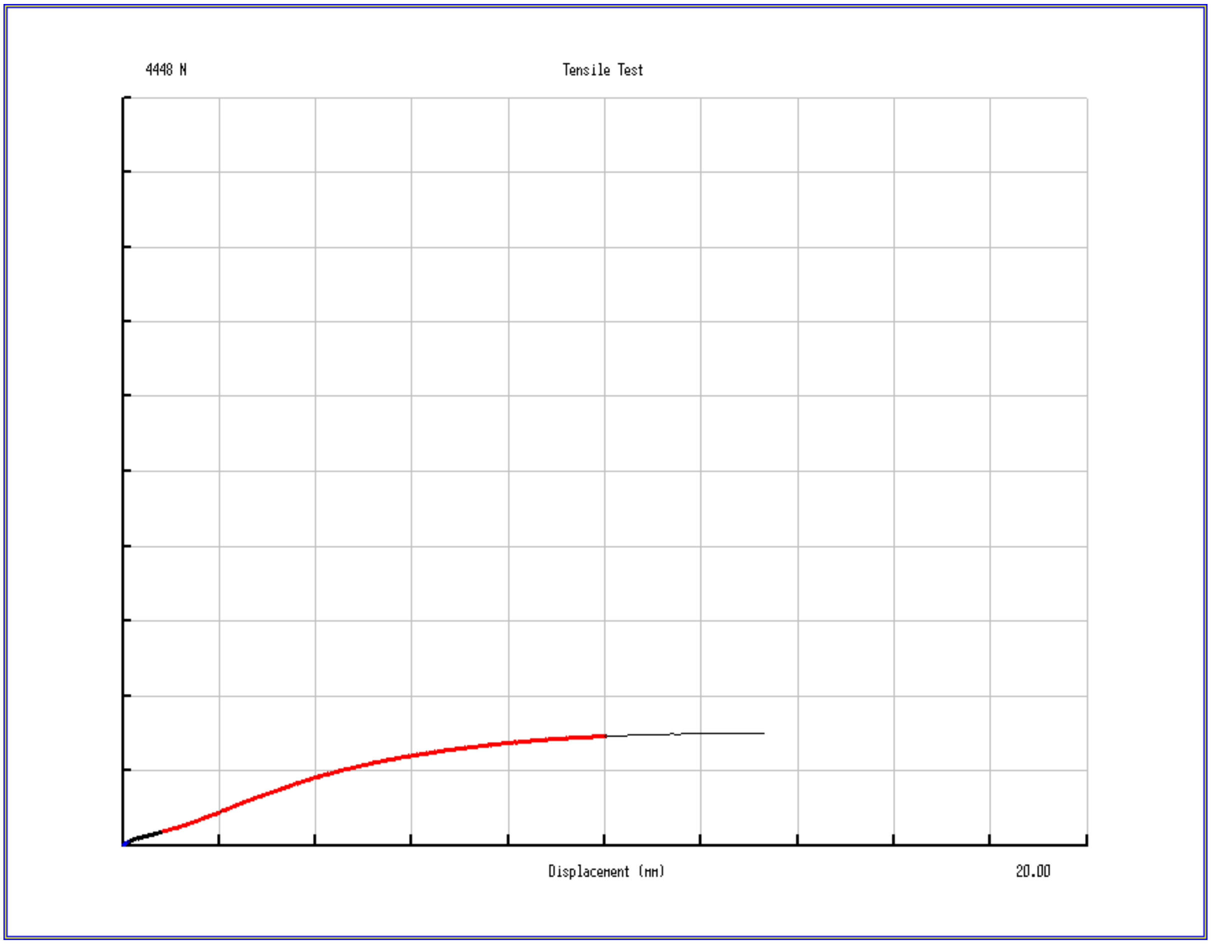


NY-S-1

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	**22.47**	**753.19**	**6.28**	**24.23**	**201.93**

- **Invalid test (see picture)**

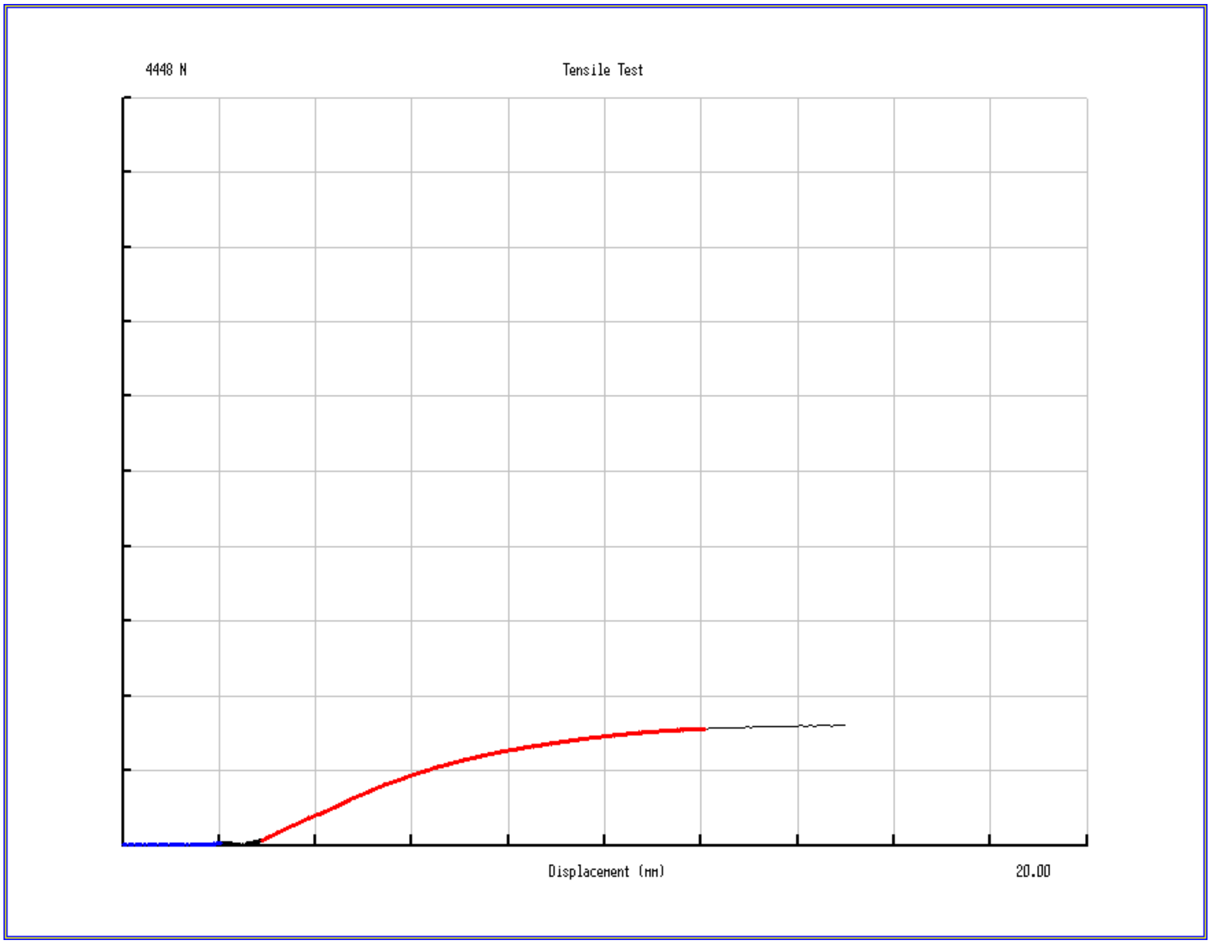

NY
S1
NY
S1



NY-S-2

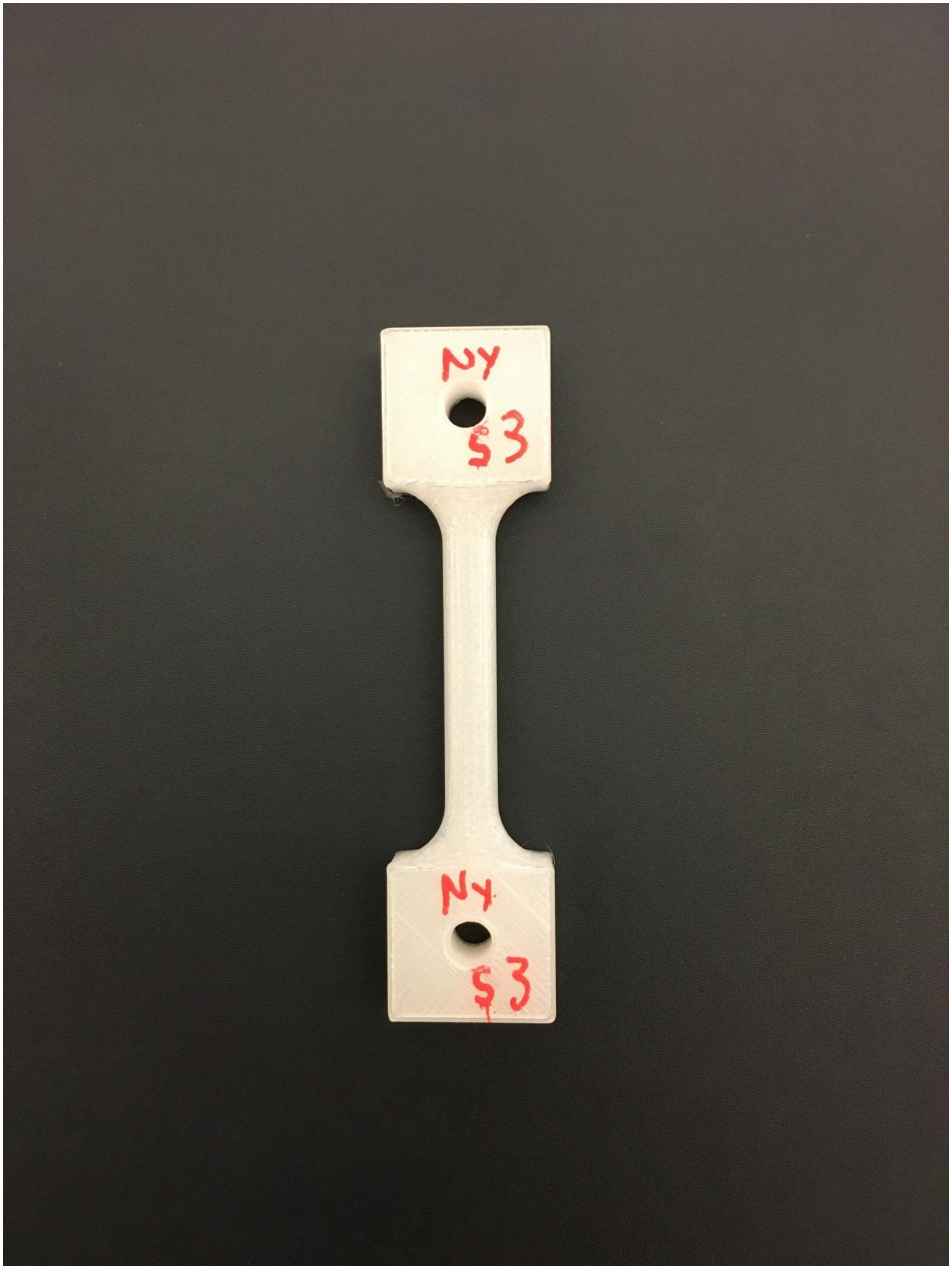
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	13.09	669.15	6.22	22.06	183.84

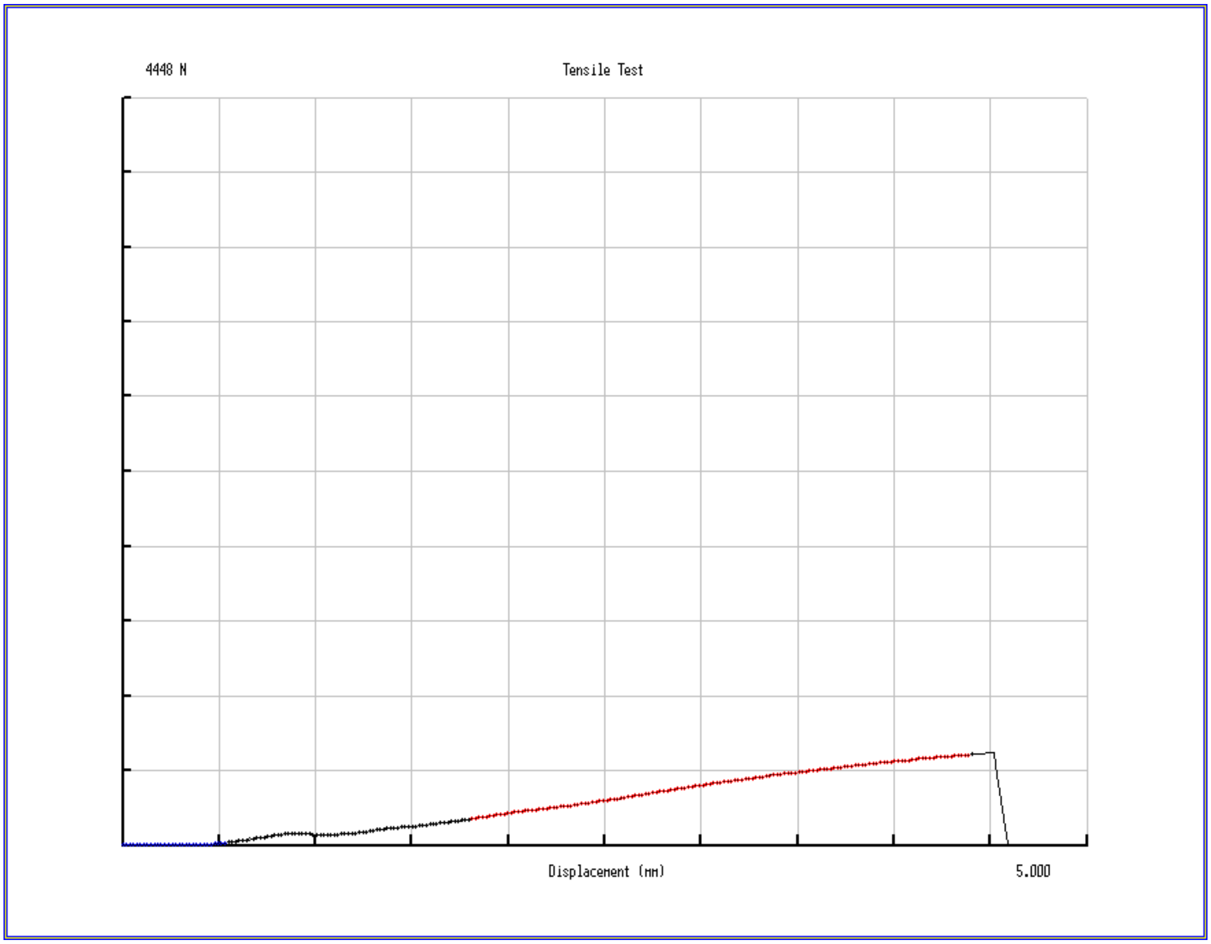

NY
S
2
NY
S
2



NY-S-3

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed on Side	15.01	712.95	6.24	23.23	185.84

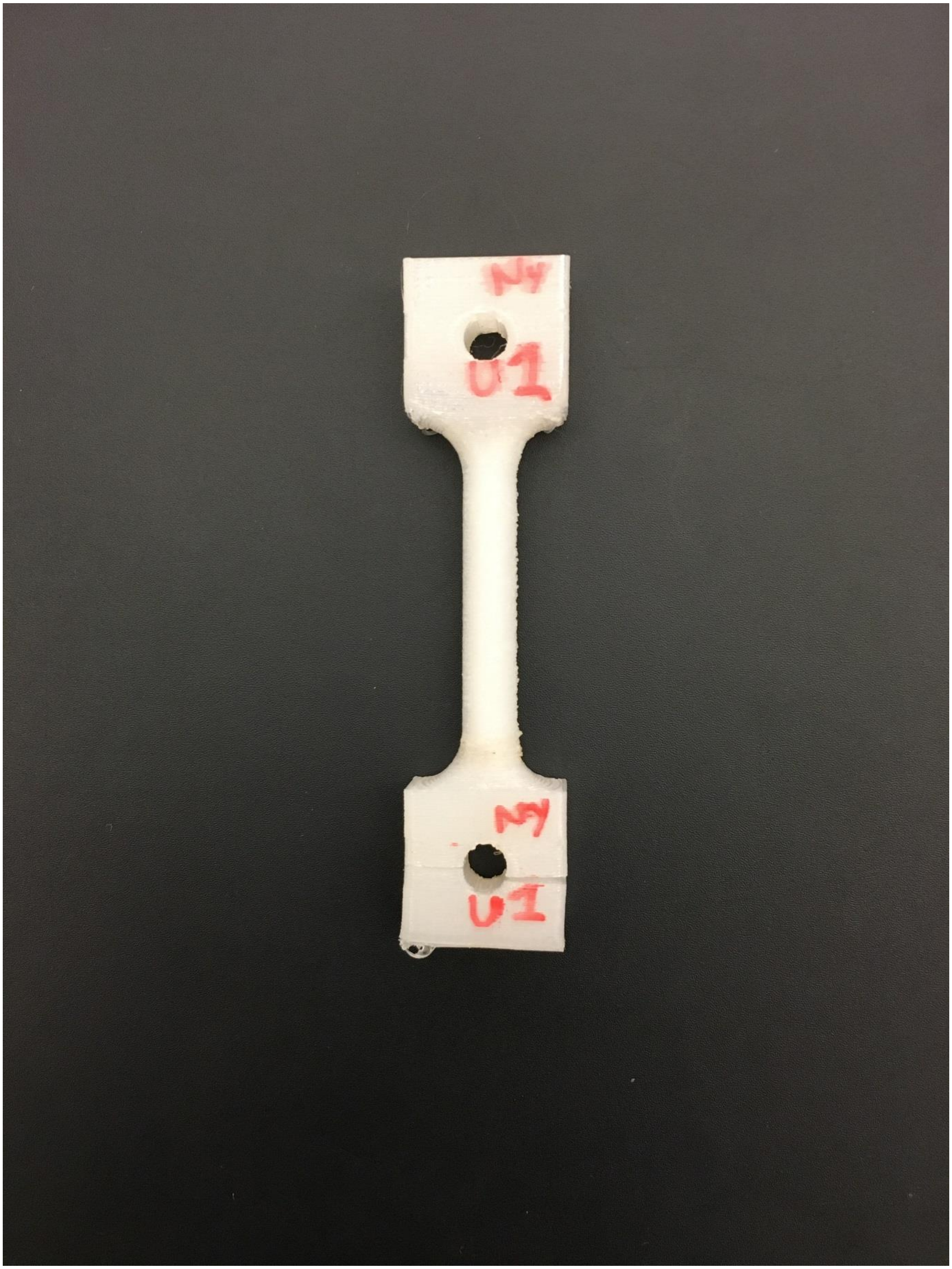

NY
S3
NY
S3

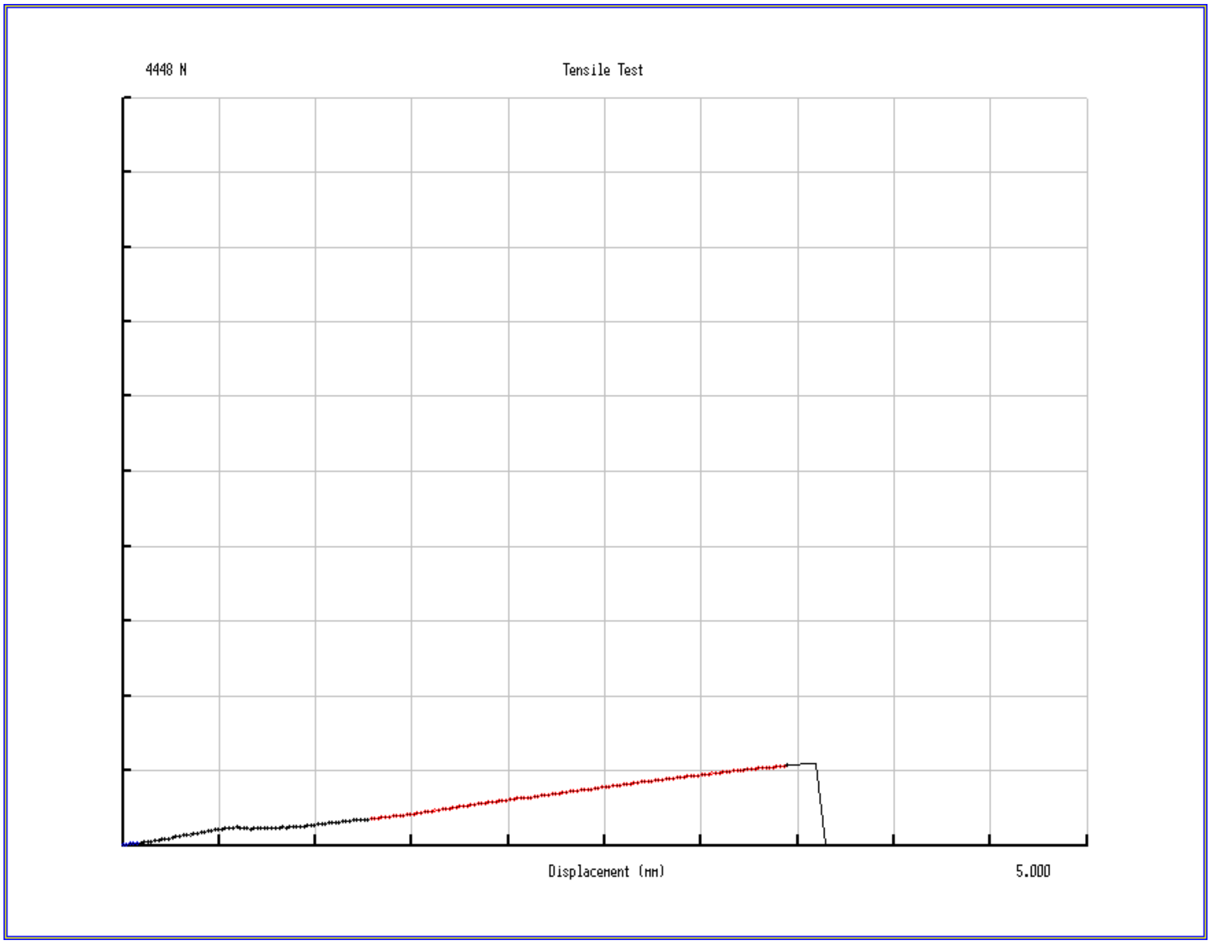


NY-U-1

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	4.51	550.57	6.33	17.32	361.02

- **Invalid result due to wrong failure (see picture)**


Ny
U1
Ny
U1

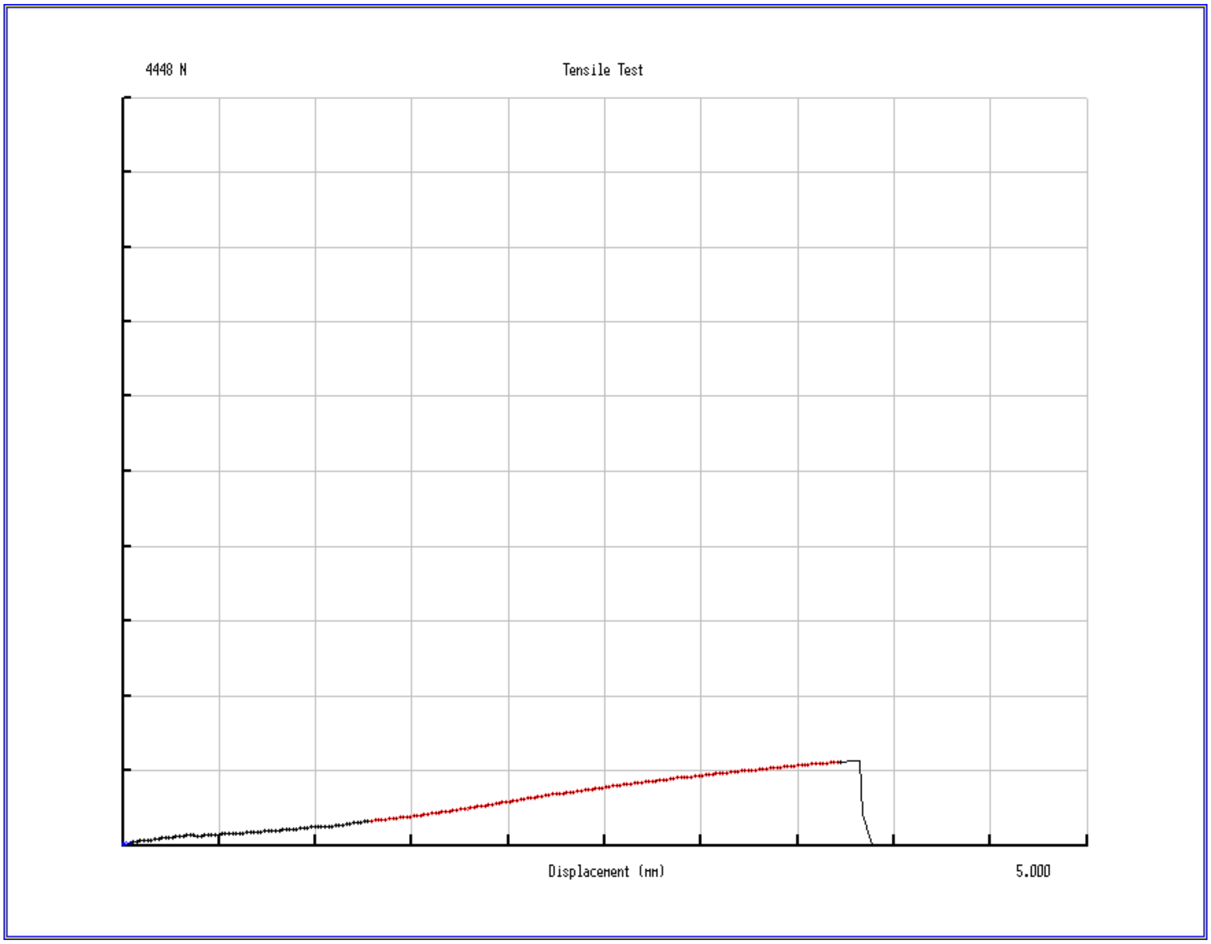


NY-U-2

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	3.59	489.18	6.42	15.45	359.44

- **Invalid result due to wrong failure (see picture)**


U2
U2



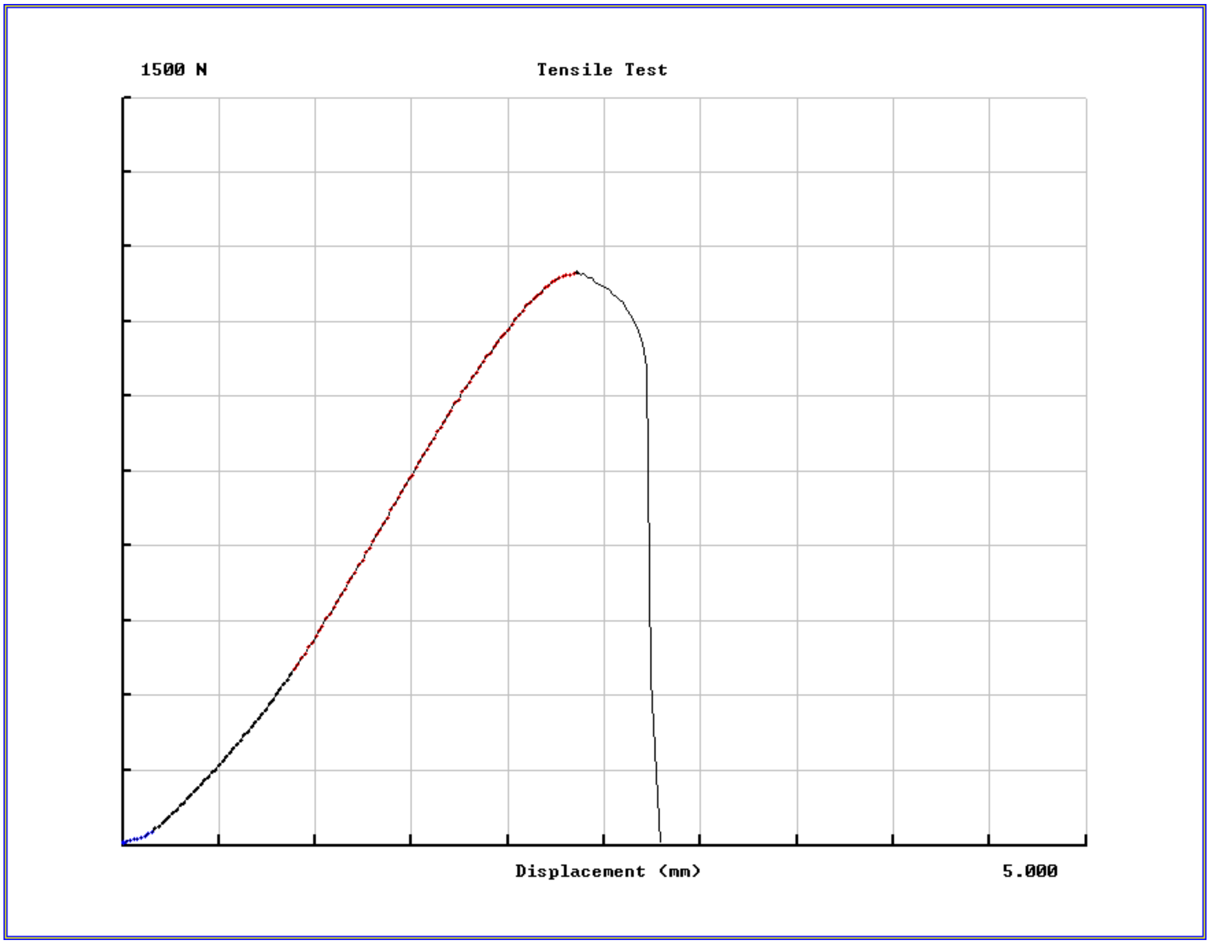
NY-U-3

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	3.81	505.81	6.29	16.10	335.41

- **Invalid result due to wrong failure (see picture)**


U3
U3

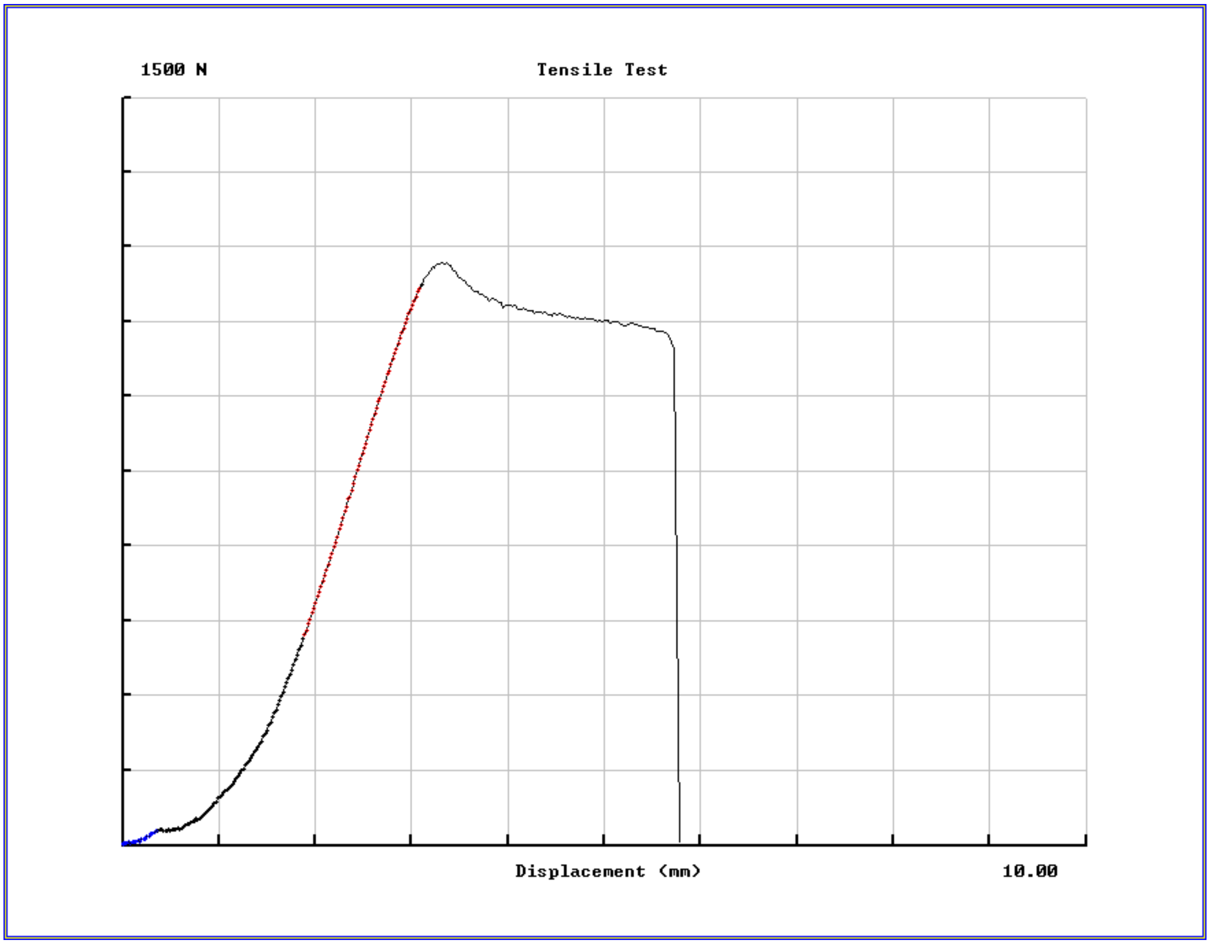
A4. ABS



ABS-S-1

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	**2.34**	**1146.8**	**6.78**	**31.87**	**910.57**

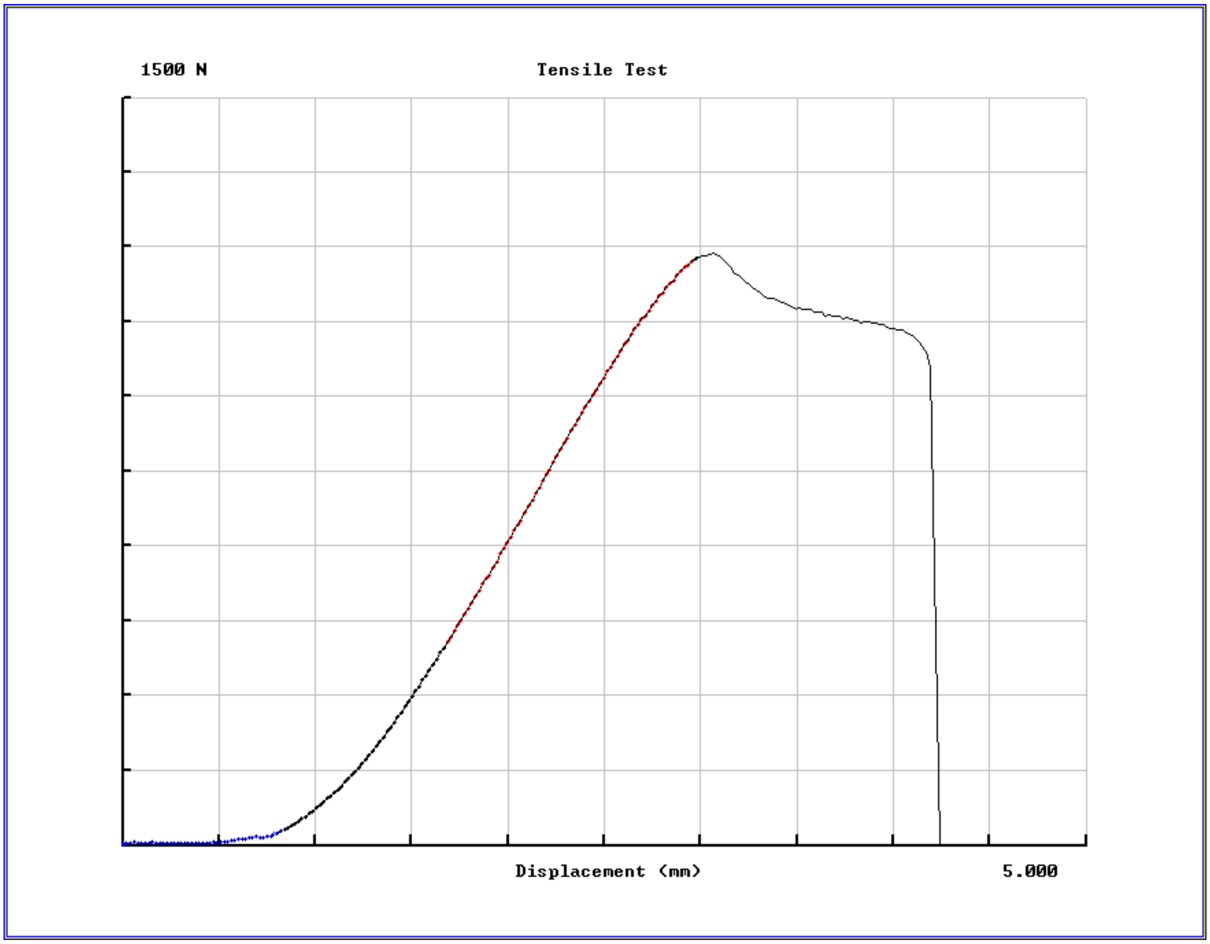

ABS
S1
ABS
S1



ABS-S-2

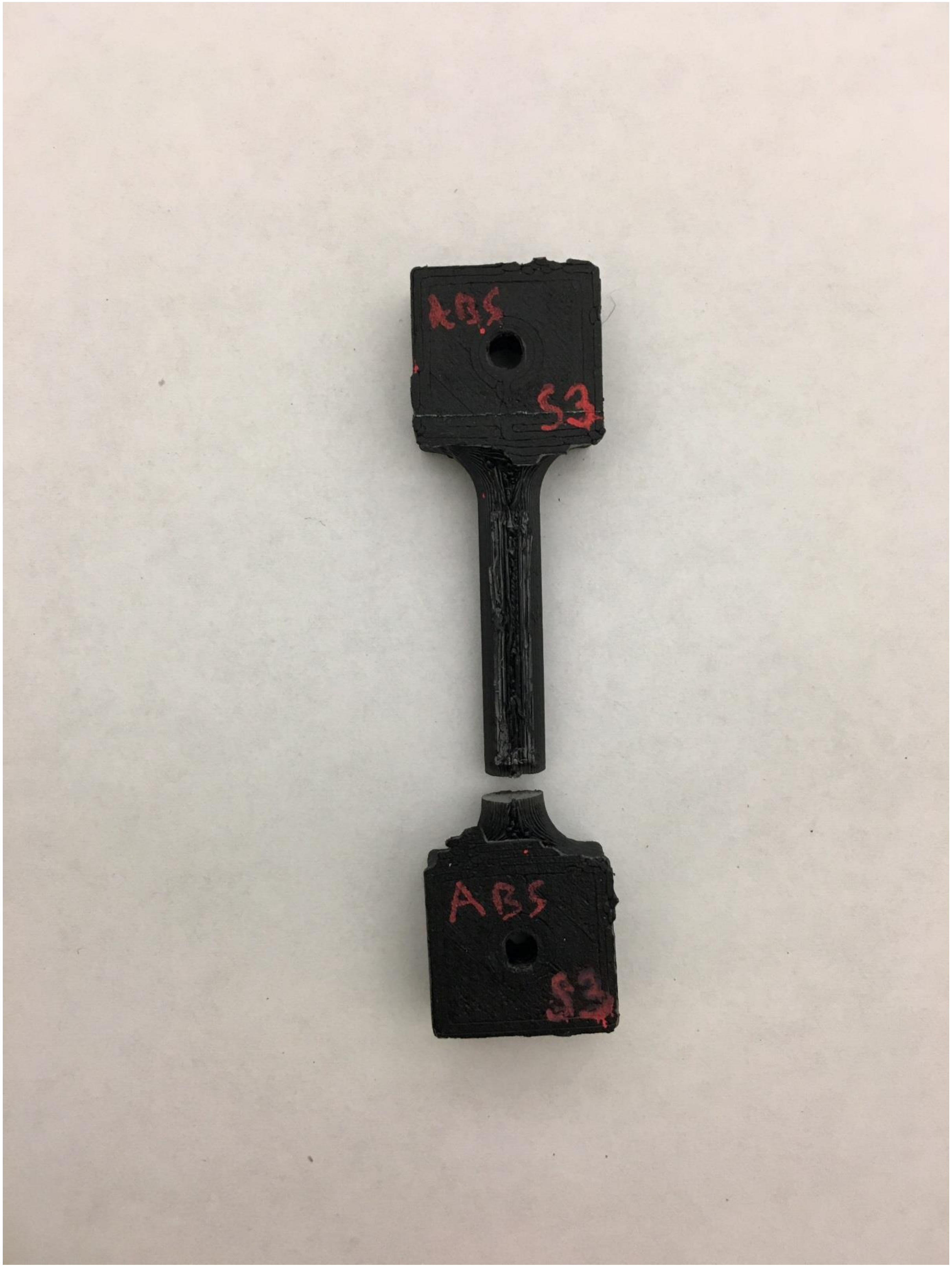
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed on Side	**3.31**	**1169.09**	**6.7**	**32.28**	**1241.83**

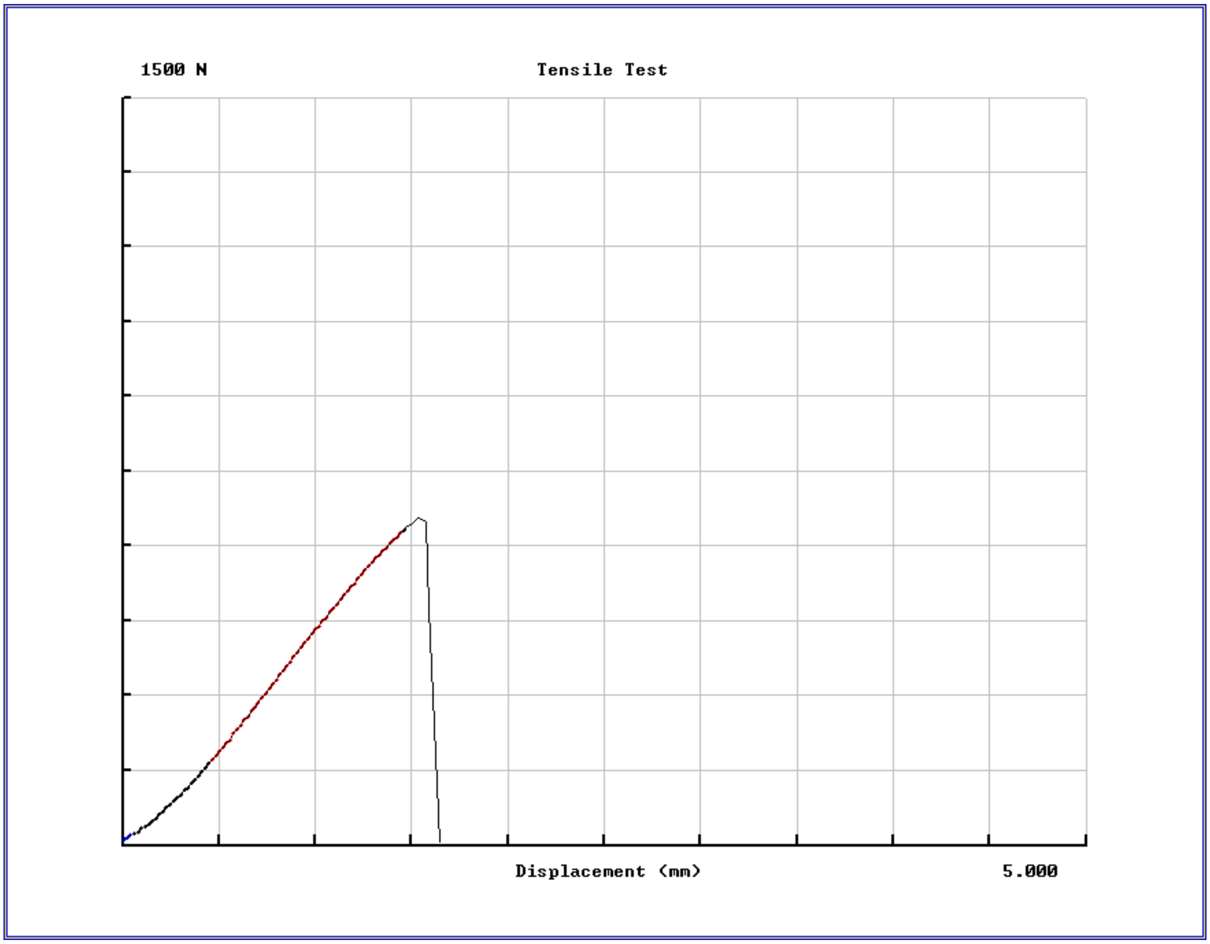

ABS
S2
ABS
S2



ABS-S-3

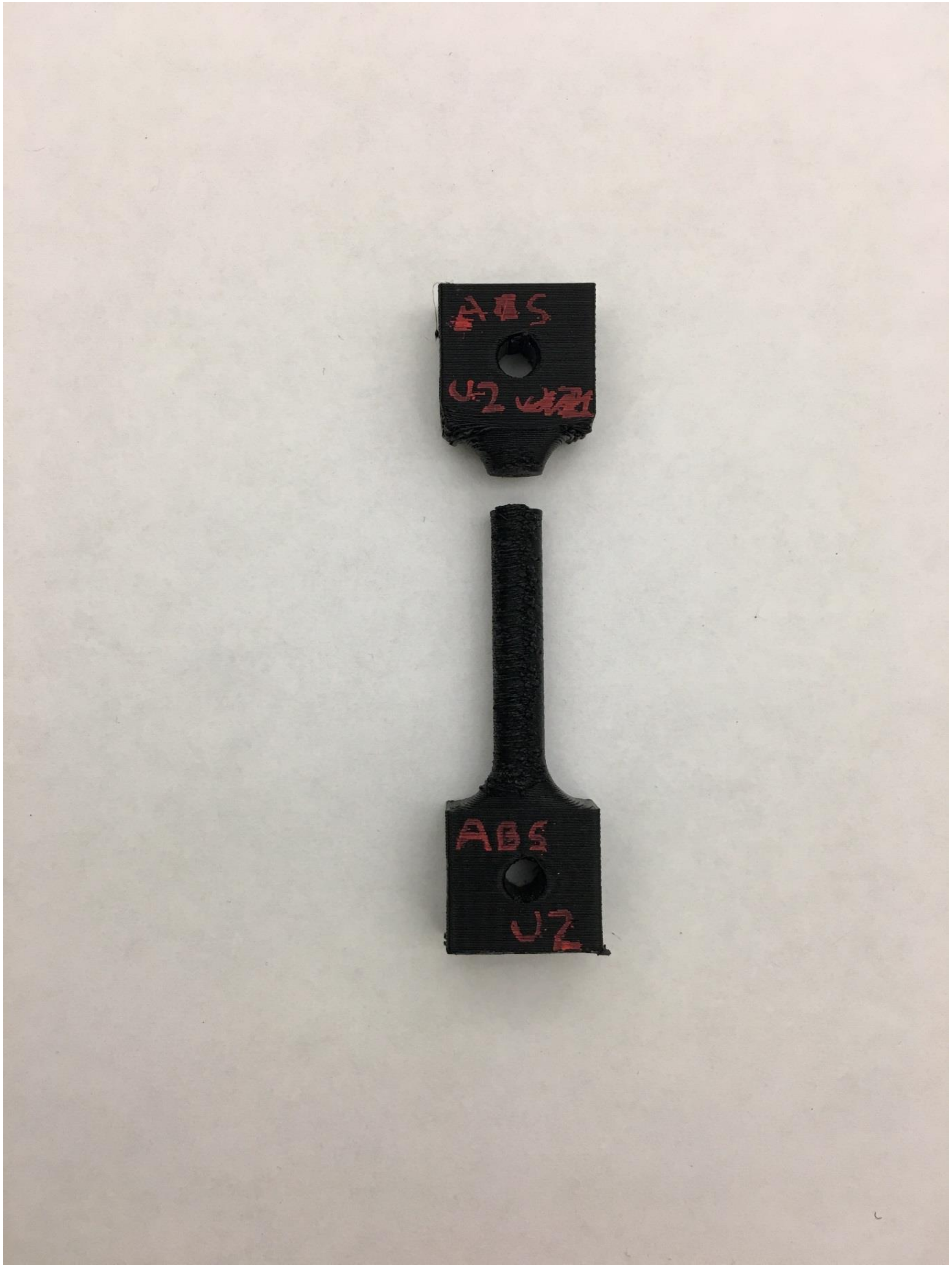
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed on Side	3.06	1186.39	6.72	35.44	720.75

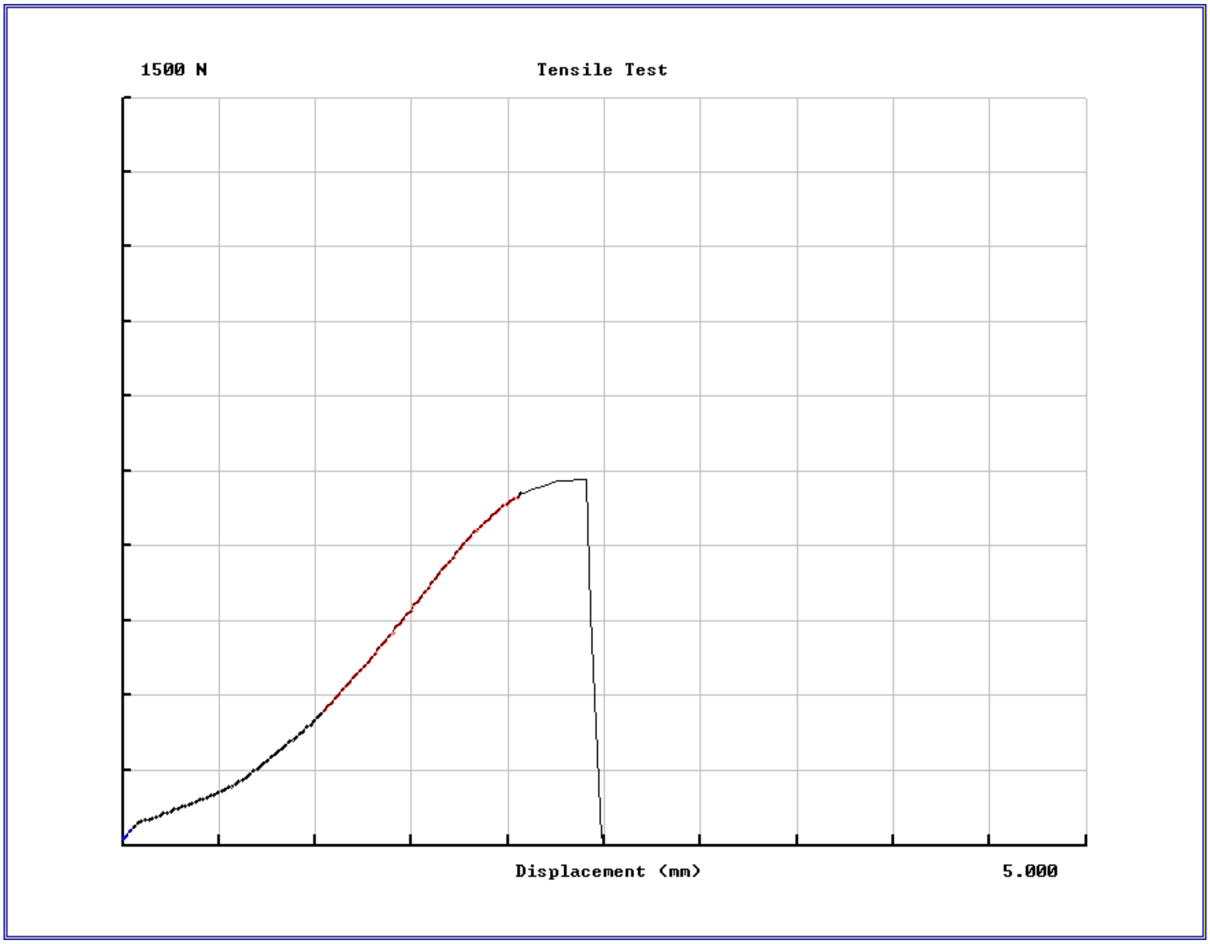

ABS
S3
ABS
S3



ABS-U-2

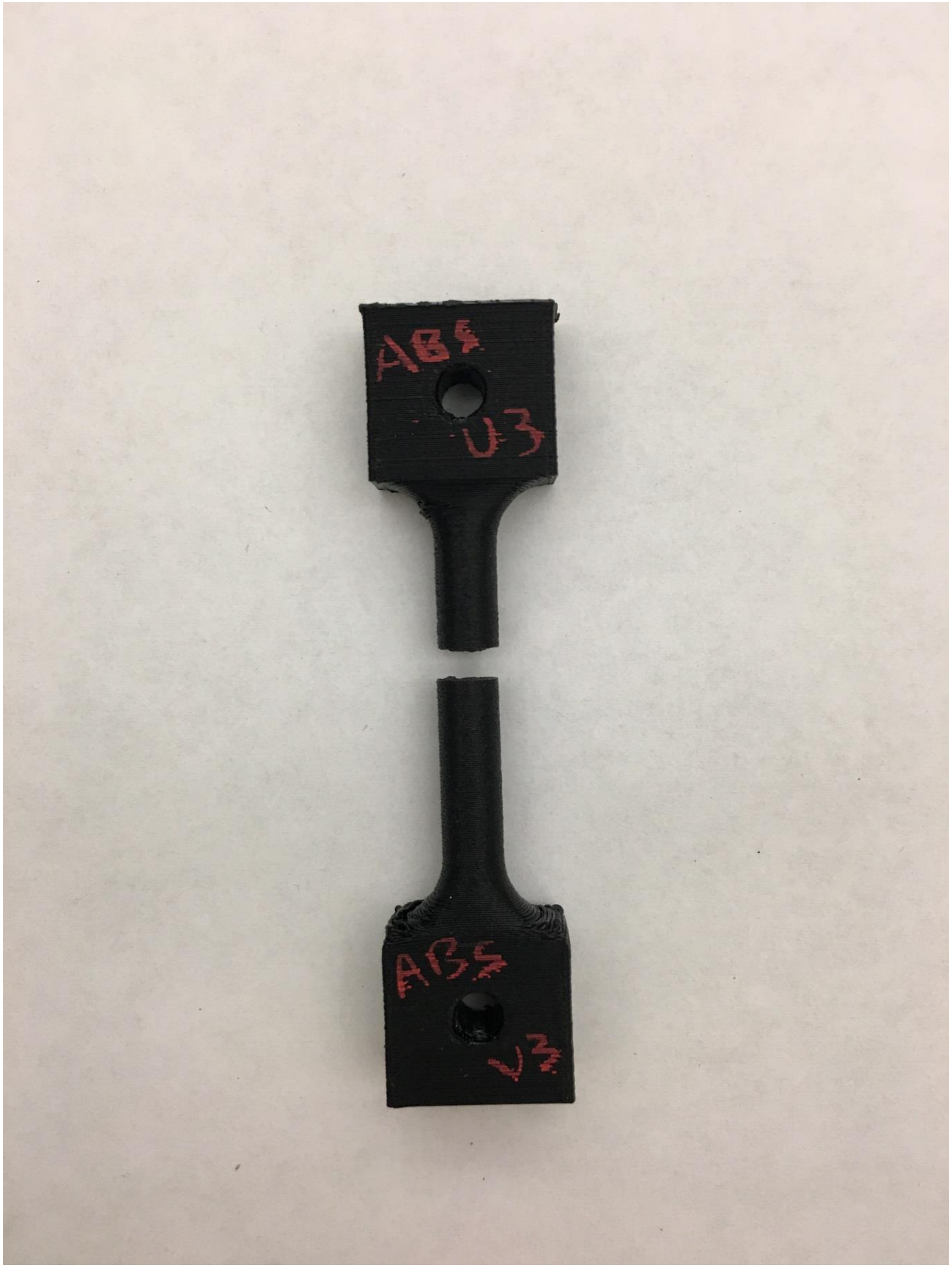
Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm²)	Young's Modulus (N/mm²)
Printed Upright	1.53	656.53	6.52	19.47	778.8


ABS
U2
ABS
U2



ABS-U-3

Print Orientation	Displacement (mm)	Rupture Force (N)	Sample Diameter (mm)	Ultimate Stress (N/mm^2)	Young's Modulus (N/mm^2)
Printed Upright	2.39	734.08	6.5	21.10	781.48


ABS
V3
ABS
V3