An Analysis of the Mechanical Properties of 3D Printable Plastics Recycled using MixFlow™ Extrusion Technology

October, 2021

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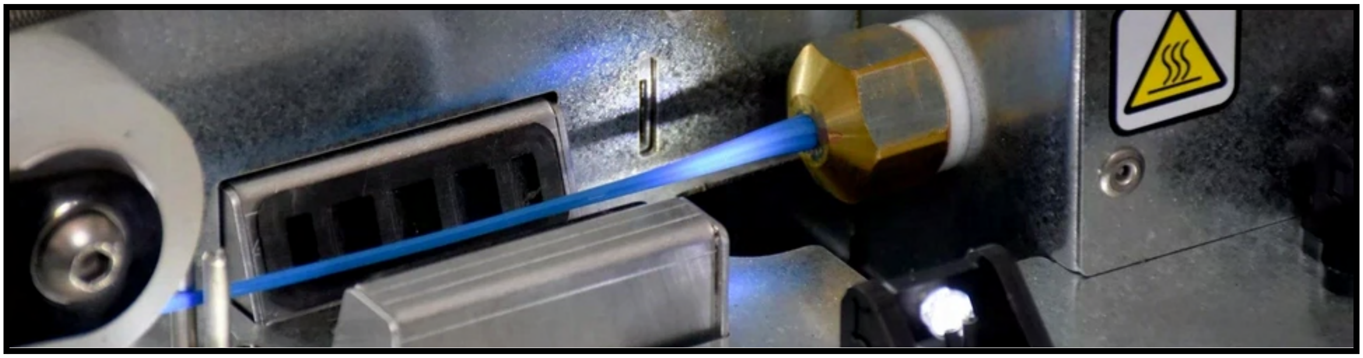
Executive Summary



A solution allowing for the recycling of common use plastics in an energy-efficient, ecological, and cost-effective manner has massive implications for plastics manufacturers, 3D printer users, and the global community. Allowing plastic to be recycled in a sustainable way can contribute meaningfully to the future of the ongoing use of plastics. However, a solution of this kind may only be realised if the material properties and workability of plastics are maintained throughout the recycling and reuse process.

This study examined the capability of ReDeTec's patented MixFlow™ extrusion technology to retain the mechanical integrity of four common 3D printer plastics: Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), High Impact Polystyrene (HIPS), and Polypropylene (PP) - each of which were tested throughout three recycling cycles. Specifically, MixFlow™ was tested as implemented in the ProtoCycler+, a filament Maker and mechanical polymer recycling machine. Plastic samples were 3D printed, mechanically tested, and then grinded and recycled back into filament using the ProtoCycler+ to be used and tested again in order to determine how the mechanical properties of the plastics changed throughout the recycling process. PLA, ABS , HIPS, and PP were recycled at 75%, 50%,100%, and 75% respectively, when referring to the weight percentage of recycled plastic vs. virgin plastic in each new batch. A total of four testing rounds were completed in this study (round 1 = virgin plastic, round 2 = recycled once, etc.).

The average ultimate tensile strength (UTS) and elastic modulus (E) for each plastic followed a largely flat trend over four rounds of testing, with the exception of the E of PP. In regard to the UTS: a cumulative drop of 2.5%, 3.6%, and 1.3% was observed after four rounds of testing for PLA, ABS, and HIPS respectively, corresponding to an equivalent 0.7%, 1.2% and 0.2% average drop after each round of recycling, whereas PP saw a cumulative increase in of 9.0% after four rounds, corresponding to an equivalent 2.4% average rise in UTS each round of recycling. In regard to the E: a cumulative drop of 0.8%, and 9.6% was observed after four rounds of testing for PLA and PP, corresponding to an equivalent 0.5% and 3.7% average decline after each round of recycling. Finally, ABS and HIPS each saw a cumulative increase of 1.0%, and 2.7% after four rounds, corresponding to an equivalent 0.6%, and 0.8% average rise in E after each round of recycling.

These results suggest that after 3 recycling cycles the UTS and E of PLA, ABS, PP and HIPS remain relatively unchanged when recycled using the MixFlow™ technology an extremely promising result for the feasibility of MixFlow™ technology to play a major role in the future of sustainable plastics use in plastics industries including and beyond 3D printing.

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Glossary

Terms

Desiccant Packaging	Small packets filled with hygroscopic substances, used for drying.
Feedstock	Raw material consisting of either virgin plastic pellets or plastic regrind used to create new plastic.
Hygroscopic	Tendency to absorb moisture from the air.
Mechanical Test	A test aimed to determine the mechanical properties of a given material.
MixFlow™	ReDeTec's patented plastic extrusion technology that sits at the core of the ProtoCycler+.
Post-Consumer	Referring to plastic that has been left over or made as waste from consumer products and services.
Post-Industrial	Referring to plastic that has been left over or has been made as waste from an industrial process.
Regrind	Plastic particles that have been created from grinding and/or shredding manufactured plastic parts, with no chemical or otherwise non-mechanical forms of processing.

Acronyms

E	**Elastic Modulus** Or Young's modulus when referring to tensile stresses, refers to the ratio of an object's elongation or deformation along an axis when a tensile force acts along said axis. Commonly stated in stress units such as MPa (N/mm^2).
HFN	**High Flow Nozzle** One of the possible nozzle configurations for a ProtoCycler+ that provides lower flow resistance and allows for higher throughput extrusion.
SFN	**Standard Flow Nozzle** The standard nozzle configuration for a ProtoCycler+, facilitating normal levels of extrusion throughput.
UTS	**Ultimate Tensile Strength** Refers to the maximum stress that a material can withstand before breaking. Commonly stated in stress units such as MPa (N/mm^2).

1.0 Introduction

1.1 Plastics Recycling in Canada and Abroad

Plastic continues to play an increasing role in the everyday lives of individuals around the world, thanks to its lightweight, affordable and versatile nature. Worldwide plastics production from 1950 to 2015 increased nearly 200 times, and the current levels around 360-380 millions tonnes/year is expected to double by 2050 [1][2][3]. However, as a direct result of increased plastics use, plastic pollution continues to grow as a large-scale domestic and global issue; with only an estimated 9% of plastics in Canada and around the world being recycled [4][5][6], and only a total of 13% of plastics (recycling and incineration) in Canada being diverted from landfills and unmanaged dumps/leaks [4].

Some of the largest inhibiting factors towards plastics recycling and landfill diversion in Canada have been identified as improper and/or insignificant plastics collection and sorting mechanisms across consumer, industrial, commercial and institutional sectors; high recycled plastics costs when compared to virgin plastics; and a small market for recycled plastics [5]. Thus, the ability to insert a solution allowing for the recycling of common use plastics in an energy-efficient, ecological, and cost-effective manner higher up in the recycling processing chain facilitating landfill diversion may have massive implications for plastics industries and plastics consumers around the world contributing to the future of the sustainable use of plastics.

1.2 Purpose of this Study

The realization of the implications stated in section 1.1 are largely dependent on the properties and workability of recaptured plastics being maintained throughout the recycling and reuse process. This study will seek to validate the capability of ReDeTec's patented MixFlow™ extrusion technology to retain the mechanical integrity of the plastics it recycles. MixFlow™ technology will be examined in a low risk, high impact scale product; the ProtoCycler+, a 3D printer filament maker and recycler; in preparation for the full commercialization of MixFlow™ technology in the broader plastics extrusion and injection molding industries.

1.3 Testing Details

In order to assess the MixFlow™ technology a series of mechanical tests were conducted using four common plastics: Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), High Impact Polystyrene (HIPS), and Polypropylene (PP). Plastic samples were 3D printed, mechanically tested, grinded and recycled back into filament using the ProtoCycler+ , and tested again in order to determine how the mechanical properties of the plastics had changed. Preliminary studies began in June 2021, focusing on optimizing testing sample geometries, plastic grinding procedures, mechanical testing parameters, and recycled filament composition percentages (% recycled plastics vs. % virgin plastic per batch). A full description of the testing process can be found in *section 2.0* of this report.

1.4 Scope and Limitations of this Study

This study was conducted entirely in-house in ReDeTec's development and production facility beginning in early August 2021, and is the first stage in an ongoing analysis of MixFlow™ technology's ability to maintain the mechanical integrity of recycled plastics.

At this stage in the analysis four rounds of testing and three full recycling cycles have been completed coinciding with the release of this initial report, however conclusions presented in this report may be updated in the future as testing continues. It should be noted that the testing facility had limited access to consistent humidity and temperature controls, which may have introduced environmental errors into the testing results . Additionally, due to the nature of the physical testing environment and reuse of grinding and recycling equipment between trials, there was a risk of cross-contamination between plastics throughout the experimental procedure. These considerations, and techniques used to mitigate environmental errors and the risk of cross contamination are explained further throughout *section 2.0*.

2.0 Testing and Processing

2.1 Equipment

In order to conduct this analysis the following equipment was used:

Table 2.1: *Testing Equipment*

Equipment Name	Specifications	Use	
ProtoCycler+ (PC+)	120V Model HFN and SFN Firmware Ver. 1.04 PCC Ver. 3.2.7	Making recycled filament. Grinding 3D printed parts. Sorting grinded plastic.	[7]
Artillery SideWinder X1 (ASX1) x2	0.6mm Nozzle. Bed (depending on plastic): ● PEI Sheet ● Blue Painters Tape ● Clear Packing Tape	3D printing.	[8]
Fuzion VIBE EQ Series scale	100g maximum capacity. 0.01g resolution.	Weighing dogbone samples.	[9]
Black and Decker Convection Oven	1500W. Model TO4314SSD.	Drying grinded plastic.	[10]
Bolaide BLD-1028 Tension Testing Machine	200 kg Maximum capacity. 0.001N resolution. 100Hz sampling freq.	Testing tensile properties of dogbone samples	[*Appendix A*]
Fine Mesh Strainer		Sorting grinded plastic.	

2.2 Methodology

The general procedure of this analysis is shown below:

1. Make filament out of dry virgin plastic pellets using a PC+ .
2. Use filament to print dogbone samples with an ASX1 printer.
3. Measure and record dogbone sample weights using a VIBE EQ Series scale.
4. Mechanically test dogbone samples using a BLD-1028 Tension Testing Machine.
5. Collect and store testing data for future analysis.
6. Grind and sort dogbone sample remains using a PC+ into what is known as plastic “regrind”.
7. Dry regrind using a 1500W convection oven.
8. Make recycled filament out of regrind and virgin plastic pellets mixture using a PC+ .
9. Repeat steps 2-8, for further testing cycles.

2.3 MixFlow™ and Making Filament

Figure 2.3: *The ProtoCycler+ Filament Maker and Recycler [7]*

MixFlow™ is a novel reprocessing technology that allows plastics to be recycled at lower energy exposures and for significantly shorter processing times, permitting upwards of 60% total energy savings when compared to recycling industry standards. MixFlow technology is also capable of processing plastics at up to 100% regrind rates, meaning that all of the plastic being processed in a given batch can be post-consumer and/or post-industrial plastic. The PC+ filament maker is ReDeTec’s first commercial implementation of MixFlow™ technology.

The PC+ system consists of a feed throat that guides plastic feedstock into a thermally isolated auger and MixFlow™ extrusion system, which then extrudes plastic into filament cooling and spooling subsystems, controlled by a dual optical diameter feedback system. PC+ also includes a light duty grinder for grinding 3D printer waste into usable chunks, for re-use with the MixFlow™ extrusion system. However, the grinder included with ProtoCycler+ is not always able to produce uniform sized ground material, making it more difficult to achieve consistent hopper loading without incorporating a certain percentage of virgin material. Because the PC+ is designed for nano-scale throughput on a desktop level, this variation in ground input material dimensions has an outsized effect on the feedthroat’s ability to intake plastic at a consistent rate (i.e. since only ~10 pellets are taken in at a time, variation in size is not able to average out across the input stream). Therefore, depending on the plastic, a specific percentage of virgin plastic pellets was used in the feedstock in order to maintain consistent pressures to avoid such disruptions. This is purely a limitation of ProtoCycler+ itself, and the underlying MixFlow™ technology within the PC+ is otherwise able to process plastic at 100% regrind rates, as mentioned above.

Both virgin and recycled filaments were created for this analysis using a PC+. In the case of the former, a mix of dry virgin plastic pellets and OMNICOLOR™colourant [11] was fed into the PC+ (mix ratio: 11g colourant/500g pellets), where as recycled filament was created from a predetermined mix of dry recycled regrind plastic and dry virgin plastic pellets.

Table 2.3: *Recycled filament composition percentages for each plastic.*

Material	PLA	ABS	HIPS	PP
Filament composition	75wt.% Rec.	50wt.% Rec.	100wt.% Rec.	75wt.% Rec.

Optimal extrusion parameters and recycled filament composition percentages were determined during preliminary studies known as Allowable Recycled Filament (ARF) tests, which are explained further in Appendix B. The optimized PC+ extrusion parameters that were used for the study can be found in *Appendix C*.

Filament was created consistently to be of 1.75mm diameter and extrusion parameters were sometimes manually altered (e.g. melt temperature, pressure limit, cooling) during PC+ operation in order to improve filament diameter consistency in response to large variations in filament diameter most commonly caused by disruptions in drive section pressures as discussed above.

2.4 Materials and 3D Printing

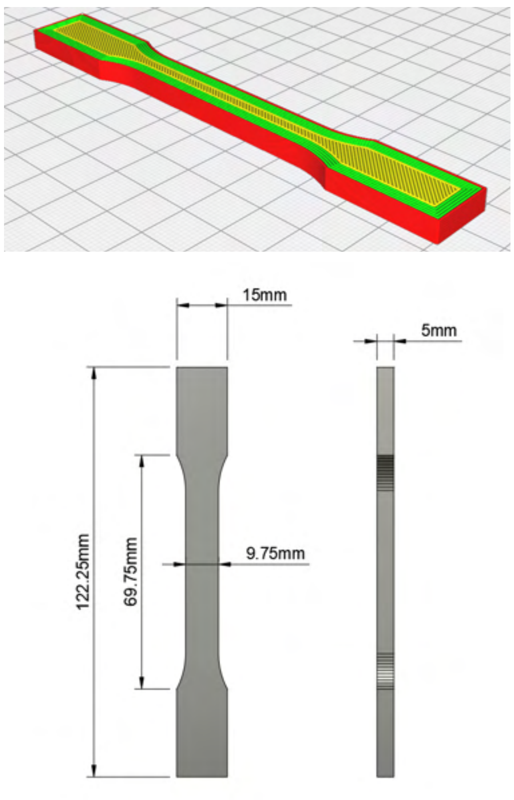
Material testing samples were printed on an ASX1 3D printer with the parameters found below in *Table 2.4.1*. When printing ABS and HIPS, a PEI sheet was used to cover the printer build plate. Blue masking tape and clear packing tape were used to cover the printer build plate when printing PLA and PP samples respectively.

Table 2.4.1: *3D Printing Parameters.*

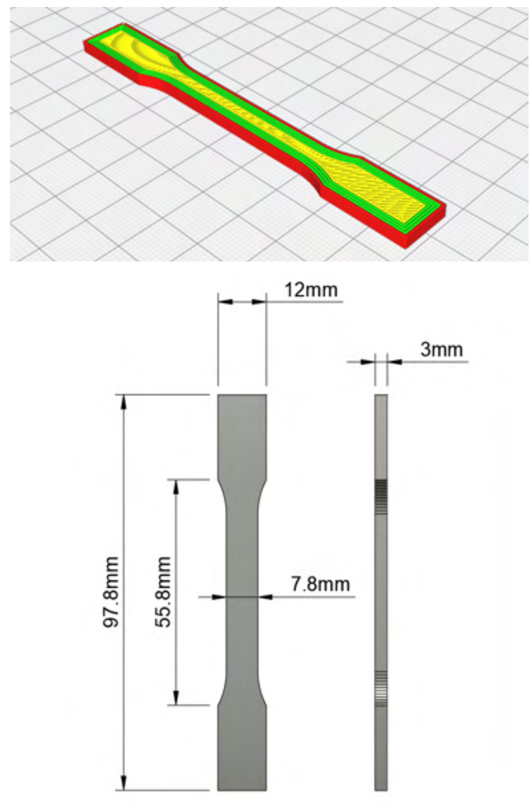
	Printing Temp. (ºC)	Bed Temp. (ºC)	Top/Bottom Layers.	Infill. (%)	Print Speed. (mm/s)	Layer height. (mm)	Layer width. (mm)	Wall count.	Flow Multiplier (%)
PLA	200	60	10	100	60	0.3	0.66	5	105*
ABS	240	115	10	100	50	0.3	0.66	5	105
HIPS	240	120	10	100	50	0.3	0.66	5	105
PP	220	130	10	100	60	0.3	0.66	4	105

**The flow multiplier for PLA samples varied from 105-130% in to adjust for high variance in sample weights through rounds 3 and 4 of PLA testing as a result of under extruded filament (see section 3.2).*

A “Dogbone” form (*Figure 2.4*) was used for the 3D printed testing samples in order to ensure material fracture would consistently take place in the middle of any given sample when pulled apart during tensile testing. The dogbone samples were designed to be a single solid component, consisting of only top/bottom layers with an effective infill percentage of 100%. PLA, ABS, and HIPS samples were printed using dogbone configuration #1, while PP samples were printed in configuration #2 (*Figure 2.4*). A smaller geometry was used for PP due to the excessively contracting nature of PP plastic when printed that led to significant warpage when printing dogbones of configuration #1.



Dogbone Configuration #1
Volume: 7.519cm^3, Original Length: 69.75mm,
Cross Sectional Area at Center: 48.75mm^2



Dogbone Configuration #2
Volume: 2.88cm^3, Original Length: 55.80mm
Cross Sectional Area at Center: 23.40mm^2

Figure 2.4: *3D Printed dogbone configurations. All samples printed as shown relative to ASX1 build plate, with print direction in line with tensile loading direction.*

A smaller geometry was not as prone to warping and was used to ensure more consistent PP prints throughout testing rounds. It was decided to continue using configuration #1 for PLA, ABS, and HIPS as opposed to printing all plastics with configuration #2, as larger samples were predicted to yield more consistent testing results due to a smaller percent error compared to absolute error in regards to sample weight and ultimate force measurements. At least 8 dogbone samples were printed for each testing round, however the sample size was often much higher and depended on how much filament could be created for a given round. Any excess filament was used to print small 10mmx10mmx3mm tiles (using the parameters from *Table 2.4.1*) in order to increase the amount of plastic available for grinding and testing in future rounds.

Table 2.4.2: *Theoretical Dogbone sample weights.*
Volume values from Figure 2.4, density values from vendor specifications.

	Density (g/cm^3)	Dogbone Configuration	Theoretical Weight (g)
PLA	1.24	1	9.32
ABS	1.05	1	7.89
HIPS	1.04	1	7.82
PP	0.90	2	2.60

After printing, samples were weighed using the Fuzion VIBE EQ Series scale. Sample weights were compared to the theoretical weights (*Table 2.4.2*), and later referenced for results calculations.

2.5 Tensile Testing Procedure

Mechanical testing was conducted using the Bolaide BLD-1028 Tension Testing Machine, and companion software. A simple tension test was performed for each trial wherein a sample was stretched at a constant speed of 100mm/min for approximately 15mm while displacement and tension force data were recorded. An image of the test parameters from the testing machine companion software is shown in *figure 2.5.1*.

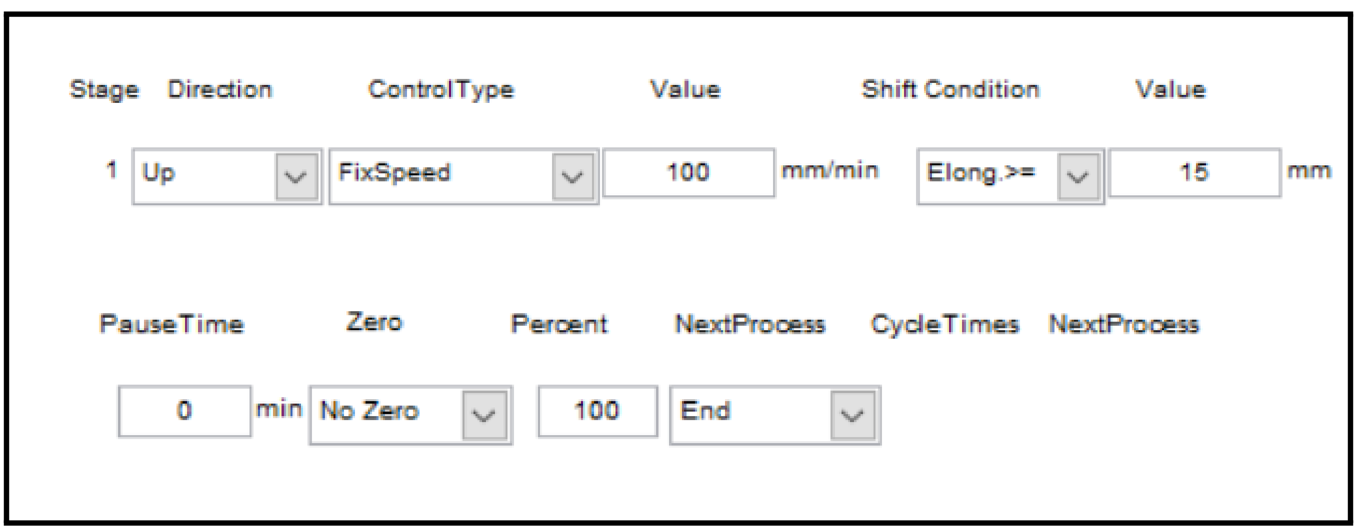
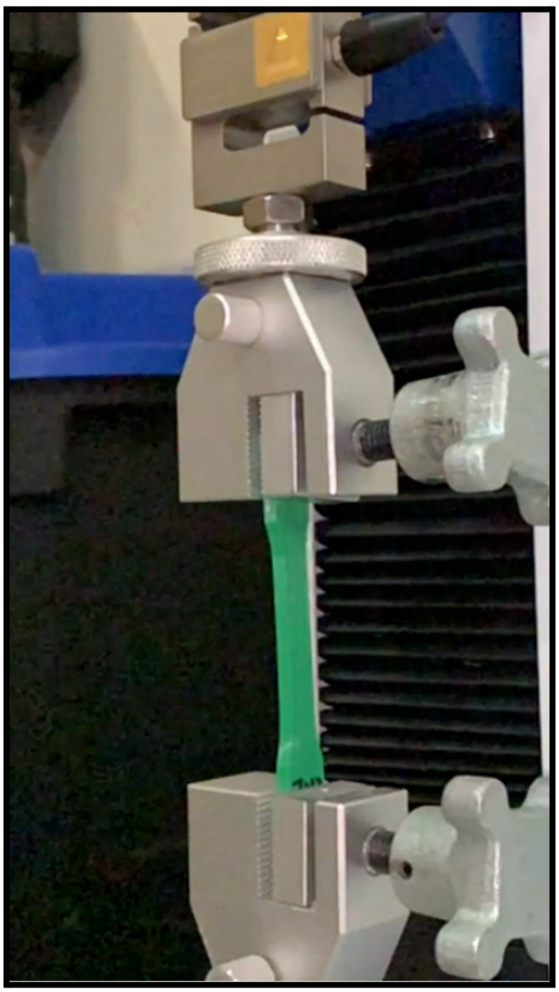


Figure 2.5.1: *Tension Testing parameters*

A trial would begin by zeroing the force sensor (positioned directly above the upper clamp, *figure 2.5.2*) and displacement sensors with no dogbone samples present in the machine. Samples were then manually placed and aligned in between the tension testing machines upper and lower clamps. The clamps were then tightened sufficiently by hand using a small wrench. The test would then begin and the dogbone samples would be pulled apart from either end until a 15mm displacement was achieved, while displacement and force data were recorded. The broken samples would then be removed from the machine, the clamps would be moved back to their original positions and sensors re-zeroed for another trial.



Figures 2.5.2 and 2.5.3: *A fully clamped PLA Dogbone sample prior to testing(left), and PLA samples after testing (right).*

2.6 Grinding Procedure

The grinding of tested dogbone samples and extra plastic tiles into small pellet sized chunks was achieved using the PC+ built in grinder [7]. Pieces of 3D printed plastic were run through the grinder two times, and then sorted using the PC+ sorting bin. Small enough plastic chunks were then collected, while larger chunks were sent through the grinder another two times. Once all plastic was small enough to pass through the sorting bin, a fine mesh strainer was used to sift out small amounts of plastic powder residue created during the grinding process. After grinding PLA, ABS, and HIPS regrind was then dried in a Black and Decker Convection Oven at 85°C for 4 hours.

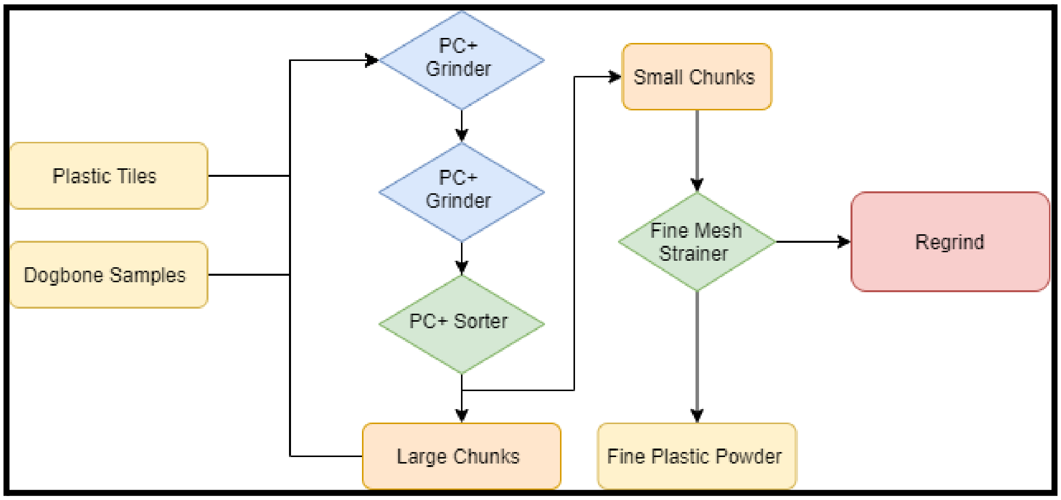


Figure 2.6: *The grinding process.*

2.7 Material Storage and Cleaning Procedure

PLA, ABS, and HIPS are considered to be hygroscopic plastics, and are at risk of having their mechanical properties altered if left exposed to humid environments for prolonged periods. Due to the lack of consistent environmental humidity and temperature control in the testing facility as mentioned in *section 1.4*, PLA, ABS, and HIPS plastic in all forms (filament, 3D printed components, and regrind) was constantly (excluding during testing, 3D printing and grinding processes) stored in air-tight containers with desiccant packaging throughout the analysis to ensure that significant amounts of moisture were not absorbed by the plastic samples introducing environmental error. PP is not considered to be hygroscopic and so humidity control measures were not used for its storage.

Throughout the analysis one PC+ and two ASX1 printers were available to conduct the testing. The cleaning of these devices between rounds of testing while changing between different plastics was paramount in minimizing the risk of cross-contamination amongst plastic samples. Regarding the PC+, when changing between two plastics the grinder was partly disassembled, and cleaned thoroughly with compressed air. The PC+ extruder was cleaned using virgin plastic pellets following an established material purge procedure, “disco purging”, as outlined in the ProtoCycler+ User Manual. The ASX1 print beds were cleaned with microfiber cloths and isopropyl alcohol, and print heads were purged of old filament when switching between materials. Additionally storage containers were cleaned using compressed air and then wiped with microfiber cloths and isopropyl alcohol.

3.0 Results

3.1 Data Handling

Manually recorded sample weights and force/displacement data from the tensile tests was saved to a local hard drive and internal cloud database. Python scripts written for this analysis were then used to read this data and calculate the results seen throughout *section 3.0.*

3.2 Raw Data

The average sample weights and maximum force recorded throughout each trial are shown below in *table 3.2* and *figure 3.2.* Note that samples which "shattered" or failed along a fracture line parallel to the direction of loading were excluded from the data set. Data filtering will be explained further in section 3.3.

Table 3.2: *Weight and Max. Tensile Strengths Averages for each round, SD refers to standard deviation.*

Round		Population Size	Weight (g)		Maximum Tensile Strength (KgF)	
			Mean	SD	Mean	SD
PLA	1	9	8.18	0.28	257.90	2.84
	2	9	8.04	0.14	255.02	2.90
	3	7	8.14	0.14	257.62	4.53
	4	9	8.47	0.20	258.38	6.26
ABS	1	8	7.72	0.11	257.51	1.18
	2	13	7.78	0.08	255.94	2.25
	3	14	7.77	0.09	252.93	2.83
	4	17	7.53	0.10	242.69	3.94
HIPS	1	8	7.49	0.12	151.58	2.55
	2	11	7.78	0.07	153.82	2.98
	3	12	8.02	0.15	162.16	6.80
	4	14	7.80	0.06	156.32	1.66
PP	1	11	2.91	0.08	91.45	2.05
	2	17	2.46	0.13	85.23	3.71
	3	12	2.47	0.13	83.50	4.45
	4	18	2.23	0.09	76.27	3.23

As seen above in Table 3.2 and below in figure 3.2, there was small but significant variance in the average weights across the testing rounds for each plastic, with the exception of ABS samples which were fairly consistent in weight across the testing rounds. Considering that all samples were printed using the same configurations and print parameters across all rounds of testing, this variance in weight can be attributed to variance in the filament diameter used to 3D print the samples. Furthermore, the variance in the filament diameter can be attributed to the variations in pressure within the PC+ drive section as discussed in *section 2.3.* In certain trials such as in rounds 3 and 4 of PLA testing, dogbone samples were printed with increased flow multipliers in order to compensate for smaller diameter filament that was causing underweight dogbone samples prone to “shattering”. Additionally, it is not suspected that the density of the plastics changed throughout the recycling process causing variations in the 3D printed sample weights. Pictures of the samples after testing can be found in *appendix D*.

Figure 3.2: *Weight and Max. Tensile Strength Averages for each round. Error bars represent +/-1 SD. (axis ranges are equally sized with a 4g weight range and a 80kgF strength range, and have been offset to center the data).*

3.3 Data Filtering

Samples which “shattered” or failed along a fracture line parallel to the direction of loading were excluded from the data set as they were not representative of the recycled material properties. Samples that failed in this manner commonly had a large degree of horizontal layer separation when printed as well as significant areas of under extrusion. When tested these samples were considerably weaker than their average trial populations, as they were more prone to break apart at these regions of under extrusion or layer separation before reaching the true material stress threshold. Visual examples of the different kinds of failure modes seen in the dogbone samples can be seen in *figures 3.3.1 and 3.3.2.*

Figure 3.3.1: *Examples of desired failure.*
(clean fracture perpendicular to loading axis and within tapered region of dogbone)

Figure 3.3.2: *Examples of undesired failure.*
("messy" fracture(s) parallel to the loading axis and outside tapered region of dogbone).

Additionally, some trials were excluded from the data set due to incorrect zeroing, and/or errors involving mechanical testing such as measurements stopping after sample break and not the designated displacement. Additionally, wherever possible, data for certain trials was "stacked" in order to improve visual inspection as well as Young Modulus identification. The stacking process involved graphically aligning all data sets in a trial horizontally along the x-axis (elongation) using the x-axis intercept. Graphs representing the Force vs. Elongation response of each dogbone sample can be found in *appendix E*.

3.4 UTS Calculations

In order to calculate the true ultimate tensile strength (UTS) of each sample, the maximum force experienced by the sample before failure was divided by the cross sectional area of the dogbone. However, as discussed in *sections 2.3 and 2.4* and seen in *section 3.2* the weight of the samples varied significantly from round to round, and as demonstrated by *figure 3.2* there is a strong correlation between maximum tensile strength and sample weight. Furthermore, upon inspection it was found that lighter samples tended to have larger areas of under extrusion (air gaps) along their central cross-sectional area as seen in *figure 3.4.1*.

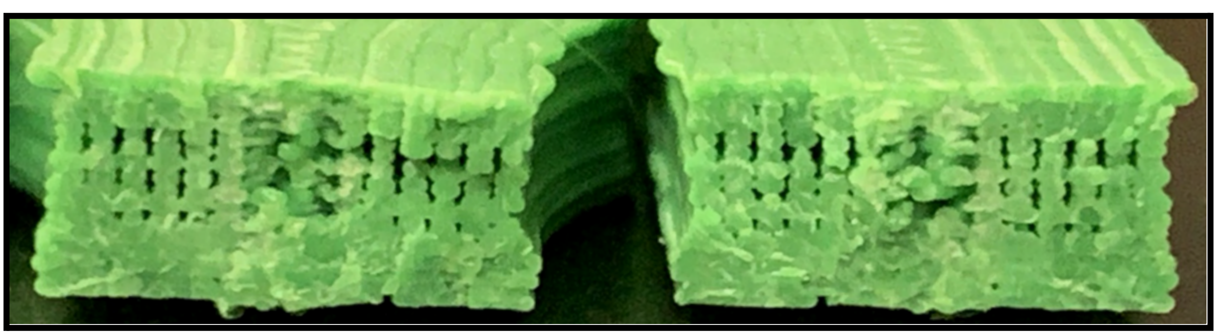


Figure 3.4.1: *Under extrusion, resulting in decreased cross-sectional area of a dogbone sample.*

In order to accommodate the relationship between over/under-extrusion and cross sectional area, a volume fraction factor was established under the assumption that throughout all rounds of testing and recycling the density of the plastic remained constant.

Table 3.4: *UTS averages for each round, SD refers to standard deviation.*

Round		Population Size	UTS (Mpa)	
			Mean	SD
PLA	1	9	59.2	1.48
	2	9	59.5	0.72
	3	7	59.3	1.32
	4	9	57.7	1.16
ABS	1	8	53.0	0.71
	2	13	52.2	0.37
	3	14	51.7	0.38
	4	17	51.1	0.77
HIPS	1	8	31.9	0.26
	2	11	31.1	0.54
	3	12	31.8	0.97
	4	14	31.5	0.29
PP	1	11	34.3	0.80
	2	17	37.7	0.59
	3	12	36.8	0.89
	4	18	37.4	0.62

Additionally, taking the assumption that the length of the dog bones remained constant regardless of extrusion variability and that the sample length is negligible when considering cross sectional area, then the ratio of the weight of a given dogbone sample compared with its relative theoretical weight identified in *table 2.4.2*, can be considered directly proportional to the ratio of the actual cross sectional area of a dogbone sample compared to the theoretical cross sectional area (identified in *figure 2.4*). Taking this volume fraction into account an approximate cross sectional area could be identified for each dogbone sample and the UTS could be calculated. Results of these calculations are summarised in *Table 3.4* and *Figure 3.4.2*.

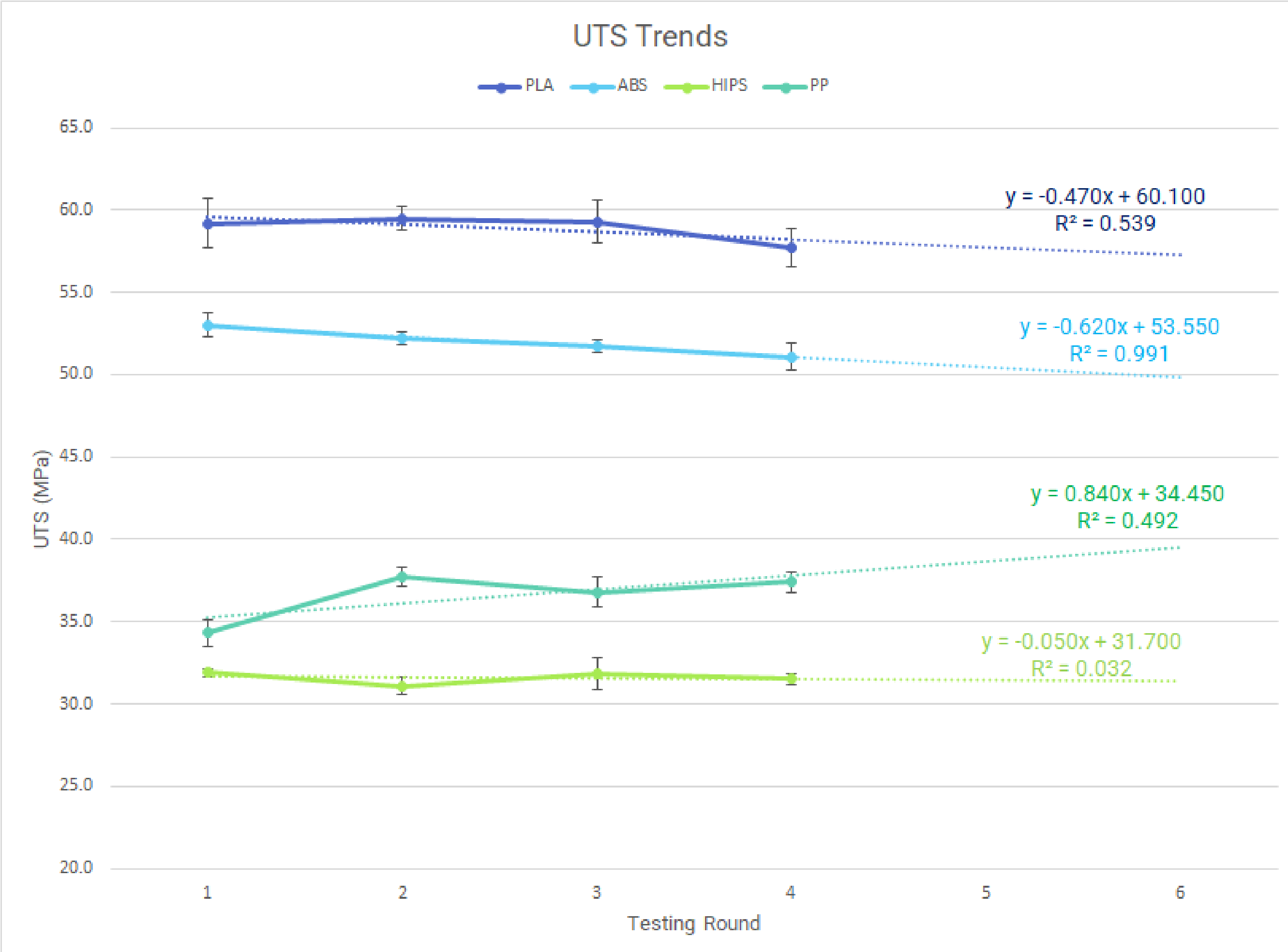


Figure 3.4.2: *UTS averages for each round. Error bars represent +/-1 SD.*

3.5 Elastic Modulus Analysis

In order to identify the elastic modulus of each trial, a linear region was identified from a stress-strain curve and a least squares regression line was fitted to the trial data for that region (*figure 3.5.1*), the slope of which represented the Elastic Modulus (E). Raw force data in kgF was equated to stress values in MPa using the same volume fraction calculations as explained in section 3.4. Strain values were identified by dividing the sample elongation by the original sample length taken between the beginnings of tapered regions on the top and bottom of each sample as shown in *figure 2.4.* The linear region for each round of testing for each plastic was visually determined with a resolution of 0.01 strain. The results of the regression fitting for each trial are summarized below in *table 3.5* and *figure 3.5.2.* Additional graphs displaying the linear fitting for each trial similar to *figure 3.5.1* can be found in *appendix F.*

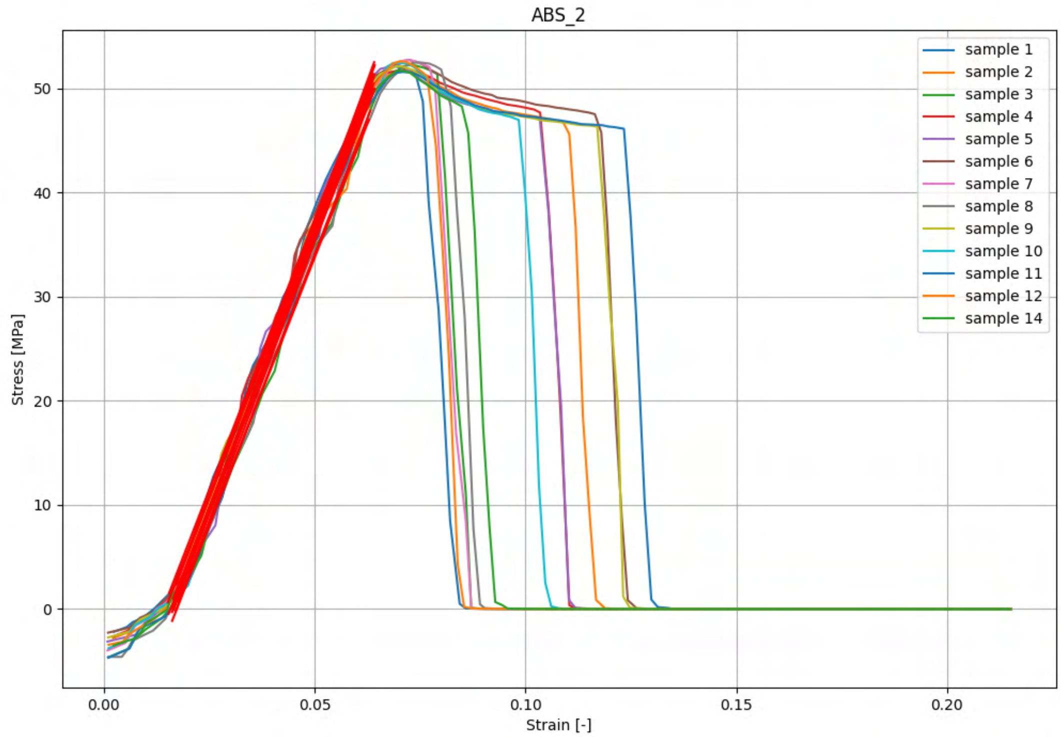


***Figure 3.5.1**: Regression lines of ABS round 2 trial data highlighted in red.*

***Table: 3.5:** E averages for each round, SD refers to standard deviation.*

Round		Population Size	Modulus of Elasticity (E) (Mpa)	
			Mean	SD
PLA	1	9	1300	26.2
	2	9	1320	36.2
	3	7	1290	17.9
	4	9	1290	70.0
ABS	1	8	1030	12.0
	2	13	1050	20.7
	3	14	1080	41.8
	4	17	1040	19.0
HIPS	1	8	941	28.4
	2	11	931	62.4
	3	12	927	30.8
	4	14	966	65.2
PP	1	11	853	39.1
	2	17	870	36.9
	3	12	797	38.6
	4	18	771	35.3

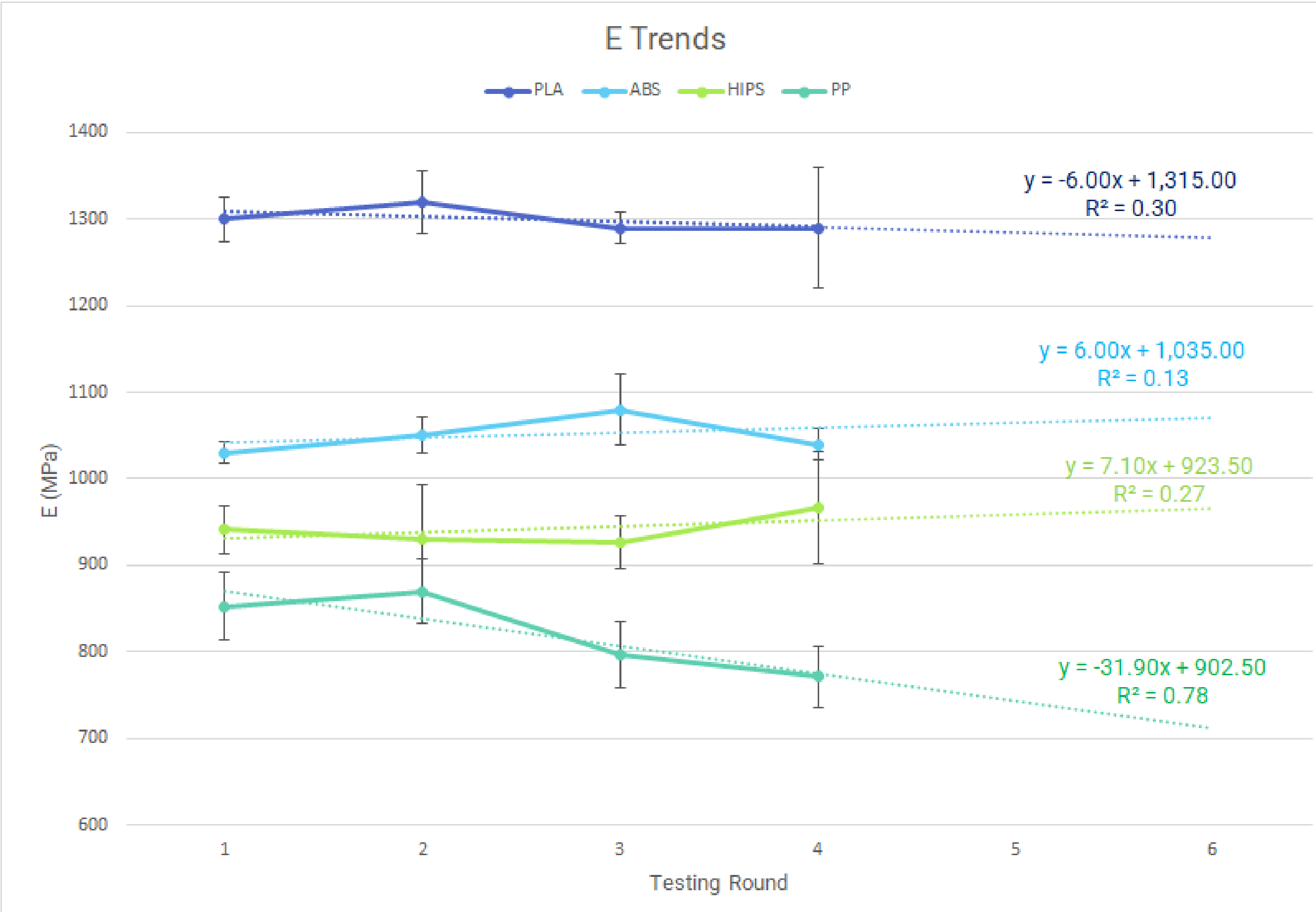


Figure 3.5.2: *E averages for each round. Error bars represent +/-1 SD.*

3.6 Discussion

In regard to the accuracy of these results, the limited precision of the Fuzion VIBE EQ scale meant that UTS and E calculations were limited to 3 significant digits in their accuracy. Weight measurements were required for use of the volume fraction equivalency discussed in *section 3.4,* and so this form of measurement error, as well as theoretical error introduced with the assumptions made for the equivalency, were unavoidable in this analysis. However, the results remain significant as the maximum potential error in accuracy seen in the UTS and E values is only ~0.3% and ~1.0% respectively, with 3 significant digits.

PLA

Table 3.6.2: *Recycled PLA results* (% of round 1 avg.).

Rec. Filament Comp.	Cumulative change in UTS	UTS equivalent Trend	Cumulative change in E	E equivalent Trend
75%	-1.5 Mpa (~2.5%)	-0.470 Mpa (~0.7%)	-10 Mpa(~0.8%)	-6.00 Mpa (~0.5%)

The recycled PLA plastic demonstrated a cumulative drop of 2.5% UTS and 0.8% E after 4 rounds of testing (3 recycling cycles) corresponding with a small declining trend of 0.7% and 0.5% for UTS and E each time the plastic was recycled. There was relatively minimal variance in all trials as seen in the small standard deviations in UTS and E calculations and the homogenous stress-strain curves seen in *appendix E and F*, with the exception of trial 4 in which the identification of an average E across all samples had significant variance with a standard deviation of 70 MPa centered around a mean of 1290 MPa, a deviation of ~5.4%. Overall, these relatively precise results suggest strong evidence that after 3 recycling cycles the UTS and E of PLA plastic remains relatively unchanged when recycled using MixFlow™ extrusion technology implemented in the ProtoCycler+.

When compared to the literature, the recycled PLA plastic performed better than expected in retaining UTS, with previous trials of 100% recycled 3D printed PLA samples exhibiting a ~2.4% [12] and 10.9% [13] drop in UTS after a single recycling round. The literature also found a ~0.4% [12] and ~0.0%[13] drop in E for the same samples, slightly less than seen in this study. However, the differences in the recycled filament composition (75% vs. 100%) makes these results difficult to compare.

ABS

Table 3.6.3: *Recycled ABS results* (% of round 1 avg.).

Rec. Filament Comp.	Cumulative change in UTS after 4 rounds.	UTS equivalent Trend (% of round 1 avg.)	Cumulative change in E after 4 rounds.	E equivalent Trend (% of round 1 avg.)
50%	-1.9 Mpa (~3.6%)	-0.620 Mpa (~1.2%)	+10 Mpa(~1.0%)	+6.00 Mpa (~0.6%)

The recycled ABS plastic demonstrated a cumulative drop of 3.6% UTS and increase of 1.0% E after 4 rounds of testing corresponding with a small declining trend of 1.2% and inclining trend of 0.6% for UTS and E each time the plastic was recycled. ABS trial data was exceptionally precise with negligible variance across all trials and calculations, with the exception of E line fitting in trial 3 which had some small variance. Overall, these results present strong evidence that after 3 recycling cycles the UTS and E of ABS plastic remains relatively unchanged when recycled using MixFlow™ extrusion technology implemented in the ProtoCycler+.

These results are in disagreement with the literature on the mechanical properties of 3D printed recycled ABS samples. Previous studies using virgin ABS powder to create filament and then proceeding to print and recycle dogbone samples in a very similar manner to this study, have shown that until the 5th recycling cycle the UTS and E of 100wt.% recycled ABS actually increased (in good agreement with additional literature), citing the alignment of amorphous polymer chains (as facilitated by the extrusion and 3D printing process) for this increase in mechanical properties [14]. The study mentioned above saw increases of 20% and 15% in UTS and E in ABS that had been recycled 5 times, when compared to virgin ABS properties. However, these increases began to disappear after the 6th recycling process as the ABS plastic began to deteriorate due to thermomechanical cycling [14]. Again, the differences in the recycled filament composition (50% vs. 100%) makes these results difficult to compare, however this stark difference in results warrants further investigation.

<u>HIPS</u>

Table 3.6.4: *Recycled HIPS results* (% of round 1 avg.).

Rec. Filament Comp.	Cumulative change in UTS	UTS equivalent Trend	Cumulative change in E	E equivalent Trend
100%	-0.4 Mpa (~1.3%)	-0.050 Mpa (~0.2%)	+25 Mpa(~2.7%)	+7.10 Mpa (~0.8%)

The recycled HIPS plastic demonstrated a cumulative drop of 1.3% UTS and increase of 2.7% E after 4 rounds of testing corresponding with a small declining trend of 1.3% and inclining trend of 2.7% for UTS and E each time the plastic was recycled. Variations in HIPS UTS results were consistently small, however the HIPS E results for all trials were somewhat significant, particularly trials 2 and 4 both having a standard deviation of approximately 6.7% of their respective means. Overall, these results suggest evidence that after 3 recycling cycles the UTS and E of ABS plastic remains relatively unchanged when recycled using MixFlow™ extrusion technology implemented in the ProtoCycler+.

When compared to the literature, the recycled HIPS plastic performed very well, with previous mechanical tests of one time, 100% recycled, compression molded HIPS samples showed a 2.8-5.6% lower UTS and 5.2-9.8% lower E in samples when compared to virgin HIPS samples of the same form [15].

<u>PP</u>

Table 3.6.5: *Recycled PP results* (% of round 1 avg.).

Rec. Filament Comp.	Cumulative change in UTS	UTS equivalent Trend	Cumulative change in E	E equivalent Trend
75%	+3.1 Mpa (~9.0%)	+0.840 Mpa (~2.4%)	-82 Mpa(~9.6%)	-31.9 Mpa (~3.7%)

The recycled PP plastic demonstrated a cumulative rise of 9.0% UTS and drop of 9.6% E after 4 rounds of testing corresponding with an increasing trend of 2.4% and declining trend of 3.7% for UTS and E each time the plastic was recycled. PP trial data was considerably more scattered than the other plastics tested and had considerable E variance across all trials. This relative increase in variance is expected to have been caused from the lighter PP samples yielding larger percent errors compared to absolute error and effectively amplifying experimental errors. Additionally, as seen in *appendix F* the PP samples exhibited only a small linear region before beginning to plastically deform in all trials, making line fitting less accurate as regression analysis had to take place of a smaller range of data points. Overall, these results present evidence that after 3 recycling cycles the UTS of PP plastic remains relatively unchanged, while the E steadily decreases when recycled using MixFlow™ extrusion technology implemented in the ProtoCycler+.

A literature review of over 33 papers on the mechanical properties of recycled polypropylene found that the mean tensile strength of recycled PP samples was 15% lower while on average the E dropped 3% (maximum drop of 41%) once recycled compared to the minimum values found in studies of virgin PP [16]. The PP UTS results of this study are in disagreement with the literature as they demonstrated an increase in UTS of recycled PP. However, the 3.7% drop in E determined in this analysis is in agreement with the 3% drop found in the literature, as the maximum potential error in accuracy seen in the E values is ~1.0% respectively as mentioned previously.

4.0 Conclusion

In this study PLA, ABS, HIPS, and PP plastic was mechanically tested and recycled at a recycled filament composition of 75%, 50%, 100%, and 75% for 4 rounds of testing consisting of 3 recycling cycles. Results showed that for all plastics and their parameters except for the E of PP the overall change shown was negligible, demonstrating the ability of MixFlow™ extrusion technology to maintain the mechanical integrity of the plastics it recycles, an extremely promising finding for the feasibility of this technology to play a major role in the future of sustainable plastics use, promoting both plastics recycling and waste reduction with ecological and economical advantages over industry standards.

The results of this study are somewhat in agreement with current literature, suggesting great potential for MixFlow™ extrusion technology or highlighting the influence of errors on this study. There were several potential sources of error at play, namely the risk of cross contaminating plastics, the lack of temperature and humidity control during testing, and the variance in sample weights requiring a volume fraction equivalency calculation outlined in section 3.4. Many steps were taken to mitigate these potential sources of error, and their effect is considered to be insignificant on the findings.

As mentioned in *section 1.4* this study is only the first step in an ongoing analysis of the MixFlow™ extrusion technology's ability to maintain the mechanical integrity of plastics when recycling. In the future this analysis will expand to continue further rounds of testing and to include the study of additional commonly used 3D printer plastics, namely Polyethylene terephthalate glycol (PETg), High Density Polyethylene (HDPE), Polyamide(PA)6, Polyamide(PA)12 and Polycarbonate (PC). Additionally, further analysis into PC+ parameters and improved filament grinding processes may allow for increased recycled filament composition percentages to be used for PLA, ABS, and PP while maintaining output filament diameter consistency. Lastly, the feasibility of a temperature and humidity controlled testing environment in order to mediate the effects of temperature and humidity on the testing samples, and isolated grinding and PC+ extruders to eliminate the risk of cross contamination amongst materials will be investigated.

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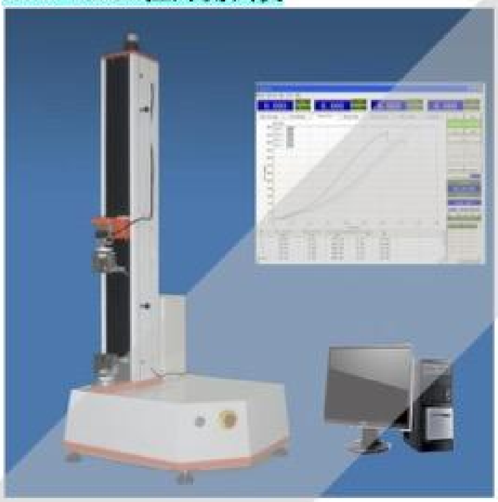
Appendix A: BLD-1028 Specifications

BLD-1028A拉力测试仪



BLD-1028A

I. Application

1. Professional testing of mobile phone film stickiness 2. Professional testing of medical products stickiness 3. Electronic components pull-off, peel-off, welding strength. Small deformation. 4. Testing of non-label stickiness 5. Protective film stickiness test, release glue, adhesive paper stickiness test. 5. Peeling Test of Printed Circuit Board 6. Spring Test

2. **Introduction of the index and system function of the tension testing machine:**

The software system is a computer-based measurement and control system. It can control and display test data, curve, speed, material specifications and other functions individually and conveniently. It can print test results combined with micro-printer. It also has the function of auto-return to the origin. The software also has the function of connecting a PC through USB interface and R232 serial port, and can transmit two-way data. Functions such as computer software control, data analysis, curve drawing, etc.

Power: High-precision actuator and motor. Achieve more accurate control of speed, position and so on. Combine with German precision clearance-free.
Ball screw and high resolution data acquisition system to achieve the accuracy of force, position and speed results.
Tensile (tension), compression (compression), bending, shearing, tearing and peeling tests can be carried out. PC and interface board are used to collect, save, process and print data. It can calculate the maximum force, yield force, average peeling force, maximum deformation, yield point, modulus of elasticity

and other parameters. It can process curves, multi-sensor support, graphical interface, flexible data processing, MS-ACCESS database support, which makes the system more powerful.

Equipment Composition: 1. Like Sensor 2. Ball Screw 3. Braid Control Software 4. AC Motor 5. Synchronization Wheel 6. Electrostatic Spraying Paint 7. Column Aluminum Profile 9. Computer

V. Standards:

The tension testing machine should meet the requirements of JB 706-77 "Technical Conditions for Mechanical Tension Testing Machines" for the identification of the testing machine.
Tension testing machine should be equipped with automatic recording stripping
The product is designed and manufactured according to the relevant specifications of GB17200, and its performance indexes conform to GB/T 2790 (adhesive 180 degree peeling strength test), GB/T 2791 (adhesive T peeling strength test), GB2792 (pressure sensitive adhesive tape 180 degree peeling strength test), GB4 (low speed unwinding strength test), GB7754 (shear strength test), GB8808 (composite film peeling strength test), ZBY28004. (The requirements of test methods such as heat sealing strength determination, GB13022 (film tension test), GB7753 (pressure sensitive adhesive tape tension test) are suitable for peeling, shearing and breaking test of adhesive, adhesive tape, non-drying adhesive, composite film, artificial leather, woven bag, film, paper and other related products.

VI. IV: Specification parameters

Capacity: 2KG 5KG 10KG 20KG 50kg 100KG 200KG
2. Units of force: N, kN, kgf, gf, LBF
3. Strength units: Pa, kPa, MPa, kgf/cm2, lbf/in2
4. Load decomposition: 200000
5. Indicative error: +0.5%
6. Resolution: 0.001 N
7. Effective travel: 800 mm
8. Test speed: 0.5-500 mm/min (computer adjustment)
9. Power system: stepping motor or servo control
10. Driving mechanism: ball screw
11. Outward Size: (L *W *H) 300 *337 *930 mm
12. Weight: about 80 Kg

Connection Mode TCP/IP

Hardware Safety Protection Upper and Lower Limits, Emergency Stop Button Protection
Step-by-step control for power of machine
Precision reducer and ball guide screw can greatly reduce noise and transmission loss and increase transmission efficiency.
Features Sealing plate is anodized by aluminium alloy, and has dust-proof sleeve to protect screw, so as to increase service life and accuracy.
_Force sensor memory lock, can memorize all kinds of relevant parameters, change

different sensors will automatically change its parameters, no need to make other settings.
_Precision adjusting machine position with handwheel control
_Incremental rise and fall, easy to operate
Can cooperate with relevant testing, select and purchase appropriate fixtures, extension devices and other accessories.

_Data acquisition frequency can be set to 100 Hz
Operating mode: All the fixture positions can be adjusted by keyboard, mouse control and test, and also by the fast lifting key of the machine.
Operating Platform: Windows XP Operating System
Colour picture and multilingual display
_Operating screen can test data several times and display at the same time
Various changes in the public and British system of unit selection
Form flexibility, self-planning data location
The name of the data can be set by itself.
_Test screen can choose data display, graphic display or simultaneous display
Data Processing: Storable, Call, List, Compare, etc.
Graphic mode has power-elongation, strength-time, stress-strain,,,,,,,etc.
Testable tension, compression, bending, peeling, spring,,,,,, etc.
_The deformation of the machine can be corrected by itself so that the test data will not be erroneous due to the micro-deformation of the machine.
Software Protection: Overtravel, Overcapacity Protection, Overtime Shutdown

Appendix B: Allowable Recycled Filament Testing

Allowable Recycled Filament (ARF) testing investigated how much recycled filament could be recycled in a PC+ consistently for each material. The results of the ARF testing have a significant influence on the analysis as they dictate how much recycled plastic can be studied, and how much bias is introduced into the study due to the continued use of virgin plastic pellets in feedstock batches.

A series of pass/ failure criteria were established by the ReDeTec team that was used to quantify success during testing which related to filament diameter, extrusion flow rates, and pressure consistency. The failure of a test or a result of “inconsistent” would be the result of large variations in filament diameter that the PC+ was not able to stabilize, extremely low or high flow rates, and/or extremely low or high pressures seen within the PC+. Initially 10% recycled filament composition intervals were used but due to a lack of recyclable plastic material 25% intervals were ultimately used. Several extrusion trials were conducted at each interval in order to confirm the feasibility of extruding at a given interval. The results of the testing are shown below in *table B.1.* and *B.2.*

Table B.1: *ARF Testing results.*

	Wt.% recycled filament composition		
	50%	75%	100%
PLA	Pass	Pass	Inconsistent
HIPS	Pass	Pass	Pass
ABS	Pass	Inconsistent	Inconsistent
PP	Pass	Pass	Inconsistent

Table B.2: *Final composition percentages used for testing.*

Material	PLA	ABS	HIPS	PP
Filament composition	75% Rec.	50% Rec.	100% Rec.	75% Rec.

As mentioned in *section 2.3 the* recycled filament composition percentages were based on the ability of the PC+’s feed throat and auger (also known as the drive section) to compact and create consistent pressures with the often asymmetrical ground plastic particles before feeding into the MixFlow™ extrusion system. This is not a MixFlow™ limitation, but rather it is a limitation of the drive section and grinder system in ProtoCycler+ preventing the full potential use of MixFlow™ technology. Therefore this isn't a concern for larger units that utilize MixFlow™ technology beyond the ProtoCycler, as improvements in prospective future drive sections will have the capability to build and maintain pressure throughout the extrusion process, allowing for up to 100% recycled filament composition.

Appendix C: ProtoCycler+ Extrusion Profiles

Table C.1: *PC+ extrusion settings for PLA, ABS, HIPS, PP*

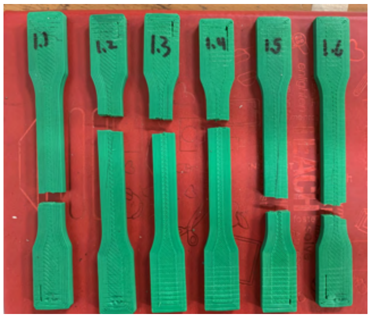
		PLA	ABS	HIPS	PP
Operation	-	Automatic	Automatic	Automatic	Manual
Nozzle	-	SFN	SFN / HFN	SFN / HFN	SFN / HFN
Melt Temp	(ºC)	181	220	250	235
Pressure	(P*)	93	93	93	93
Cooling	(C*)	80	48	100	100
Diameter	(mm)	1.75	1.75	1.75	1.65
Auger KP	-	5	4	4	5
Auger KI	-	0	0	0	0
Auger KD	-	1	1	1	1
Auger Imax	-	70	70	70	70
Diam KP	-	0.5	0.35	0.2	0.2
Diam KI	-	0	0	0	0
Diam KD	-	0.3	0.25	0.15	0.3
Diam Imax	-	0	0	0	0
Pre Pressure		38	38	38	38
Max Pressure		0	0	0	0
Min Pressure		0	0	0	0
Pre Pull	(C*)	30	40	20	30
Pre Cool	(C*)	20	35	50	20
Cool Function	-	10	1	1	10
Pre Heat	(ºC)	170	200	200	170
Max Heat	(ºC)	205	230	230	205
Min Heat	(ºC)	150	200	200	150
Flow Function Time Scale		255	250	250	255
Draw Down Time Scale		255	250	250	255
Flow Rate Time Scale		255	150	150	255
Pre Heat Time	(s)	60	60	60	60
Stabilization time	(s)	100	100	100	100
Flow Function Influence		0.4	0.1	0.1	0.4
Expected Flow		120	150	120	120
Smith Gamma		0.05	0.05	0.05	0.05
Smith Influence		0.4	0.4	0.4	0.4
Pressure Limit (PL)	(P*)	NA	NA	70	60

P* - A unitless numerical value ranging from 0-128 that represents the pressure created in the PC mix flow section, where 0 is off and 128 is maximum pressure.

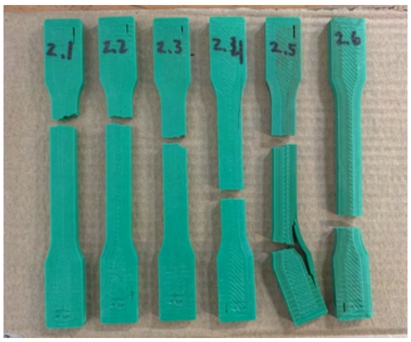
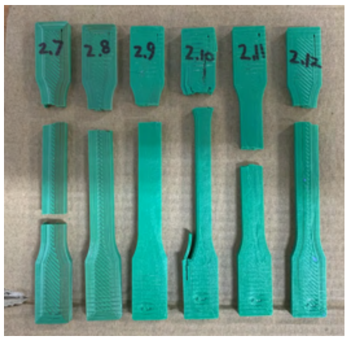
C* - A unitless numerical value ranging from 0-100 that corresponds to the PC+ filament cooling fan speed, where 0 is off and 100 is maximum speed.

Appendix D: Tensile Testing Sample Images

PLA Round 1



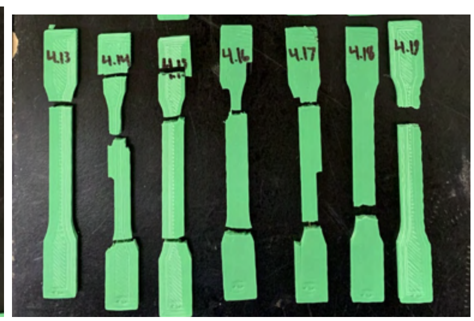

PLA Round 2

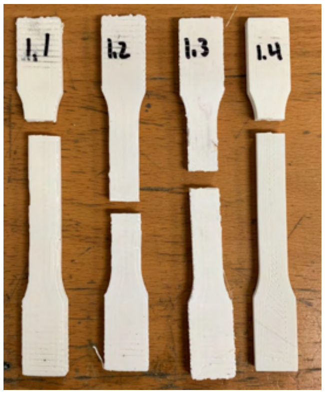
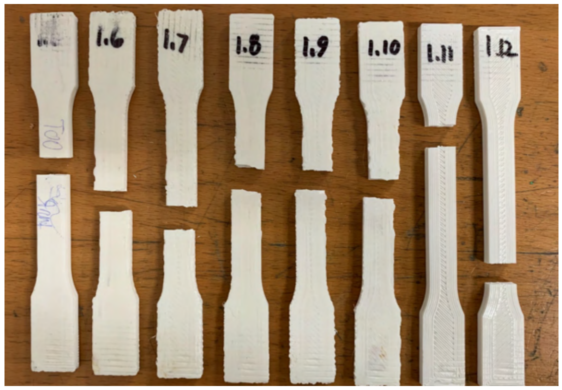
PLA Round 3

PLA Round 4



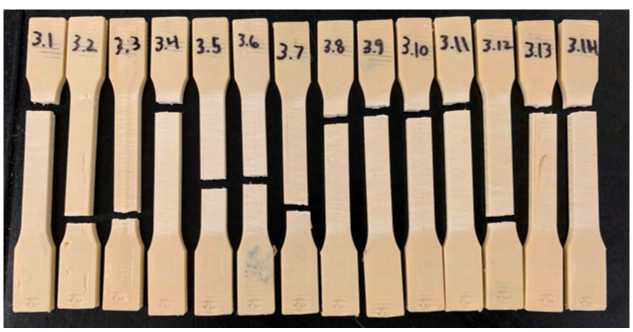


ABS Round 1

ABS Round 2


ABS Round 3

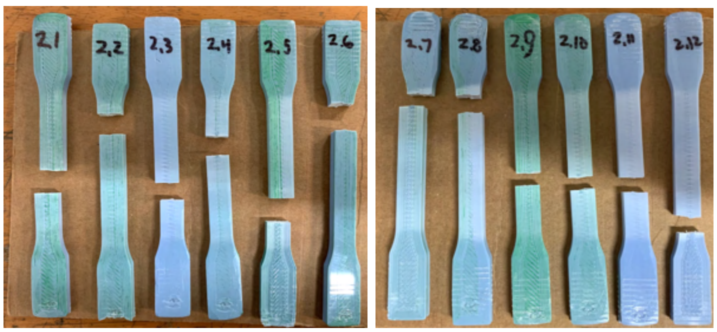


ABS Round 4



HIPS Round 1

HIPS Round 2

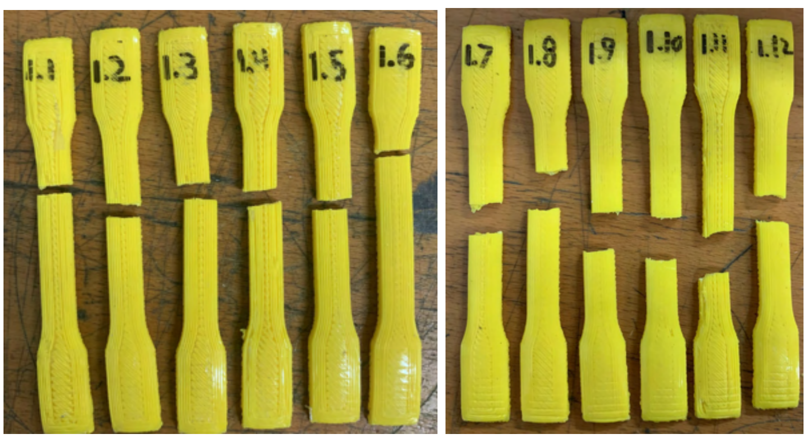


HIPS Round 3

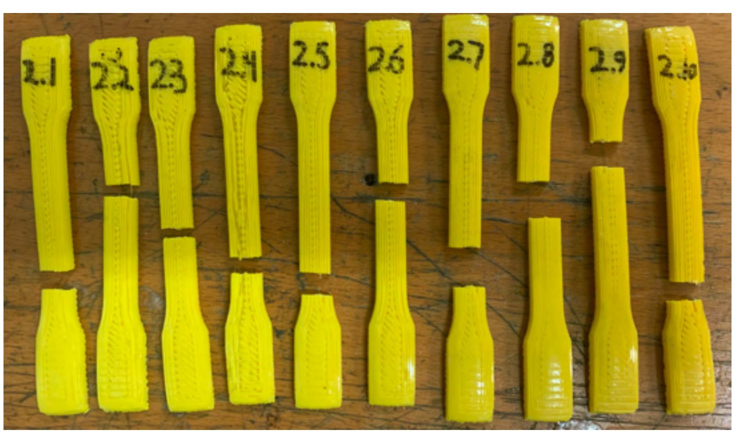
HIPS Round 4

A note on HIPS samples discolouration:
Early on in the analysis, the testing of HIPS round 1 needed to be redone due to a zeroing offset error with the tensile testing machine. In the remaking of the virgin plastic filament the colour white was used for the samples (the original samples had been blue). In the making of the regrind for HIPS round 2 only the broken dogbone samples from the original HIPS round 1 trial were used (blue), and so the blue colour is seen in HIPS rounds 2-4. The shade of blue appears to get lighter through trials 2-4, and this is suspected to be from plastic deformation causing discoloration in the samples (seen in pictures above) as well as due to the lighting of the photographs.

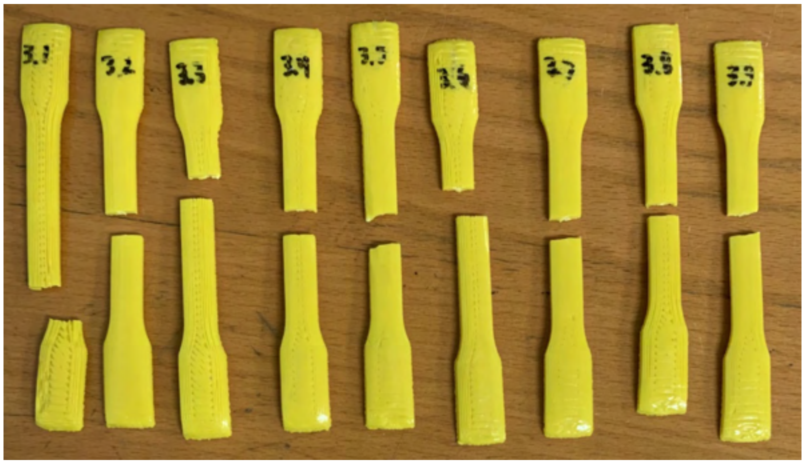
PP Round 1



PP Round 2



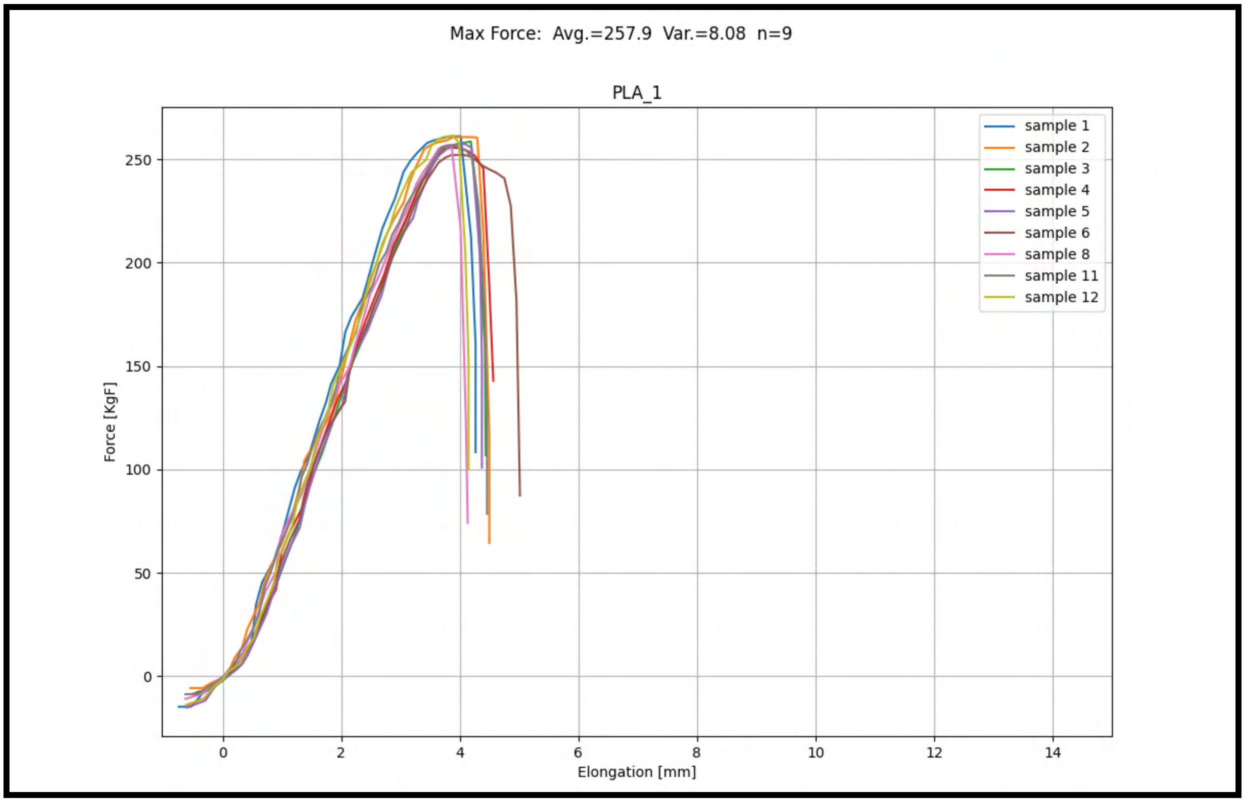
PP Round 3

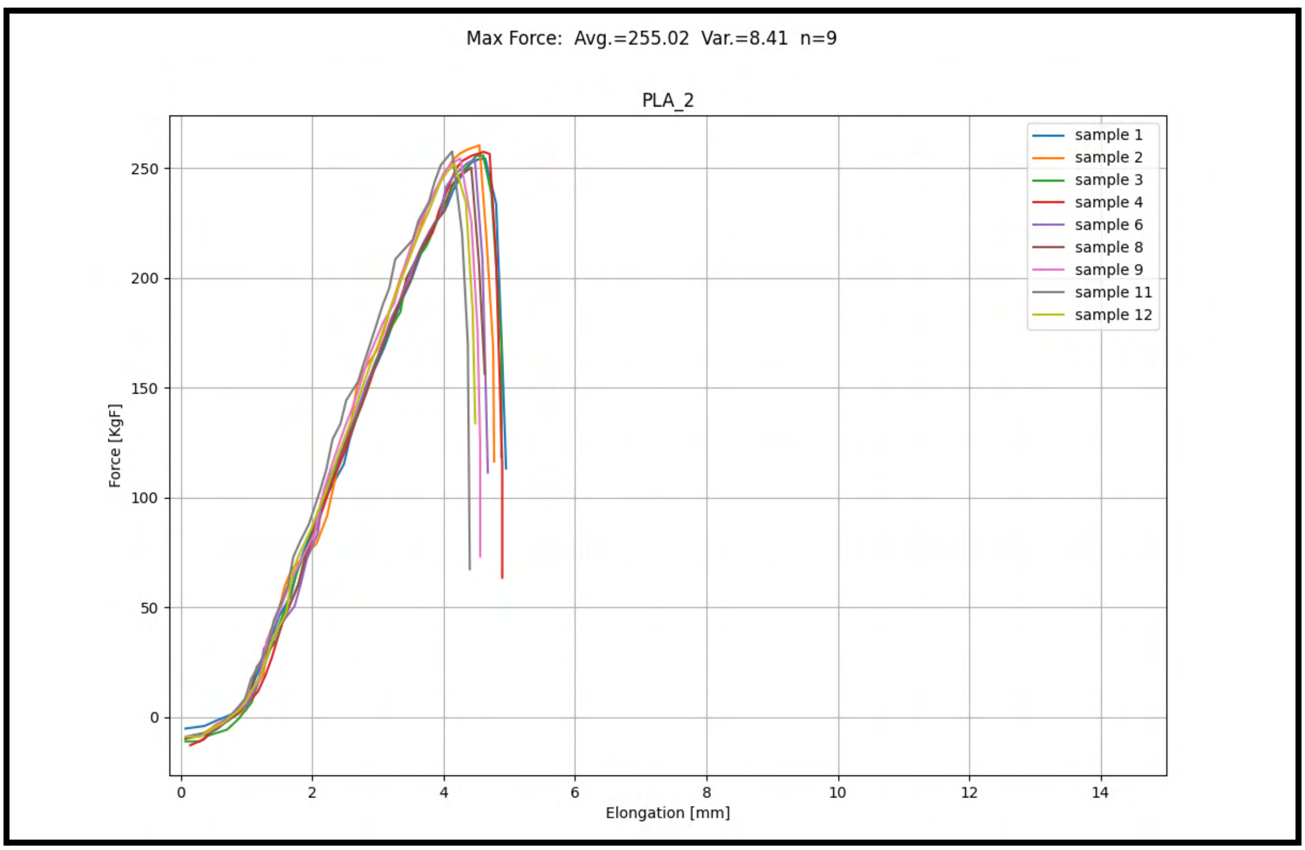


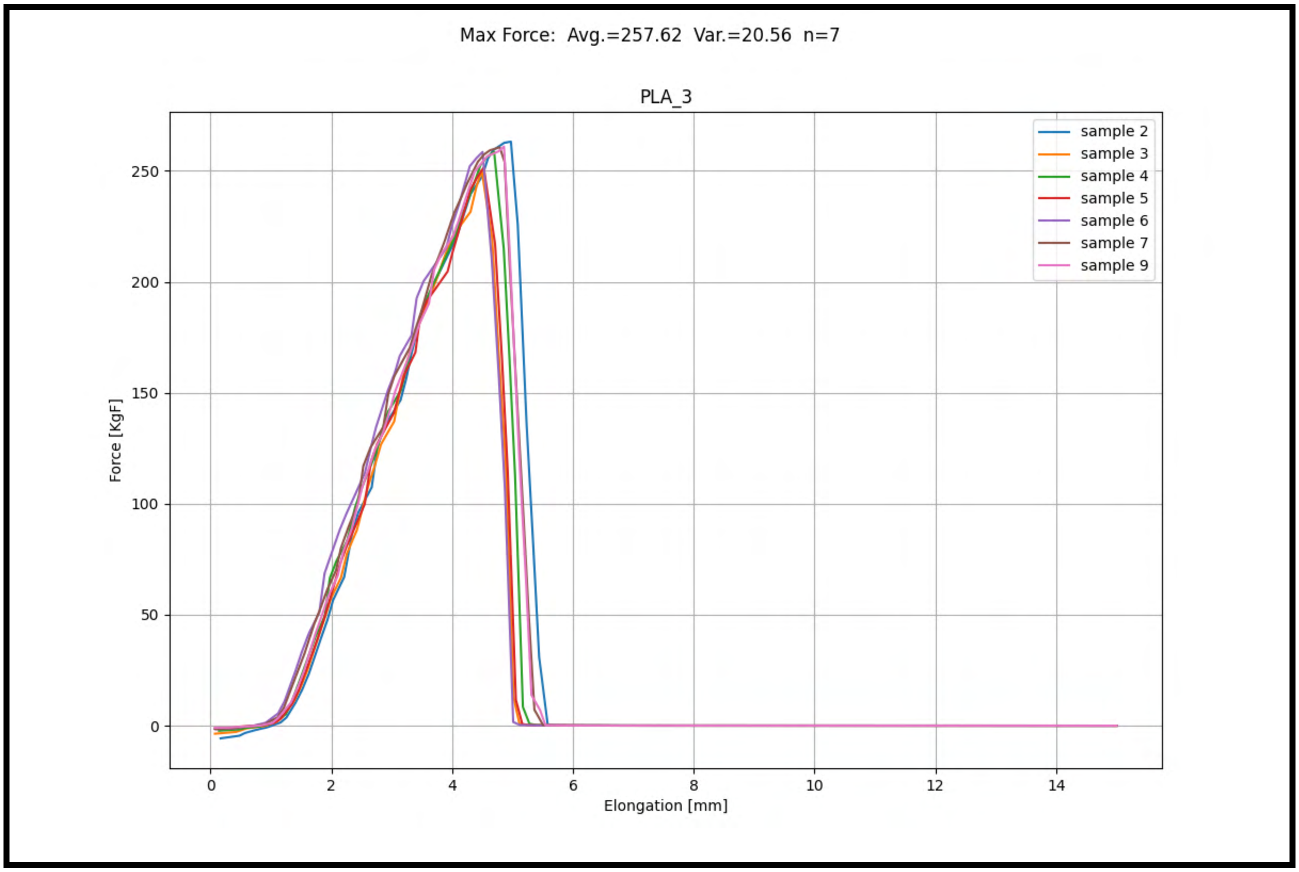
PP Round 4

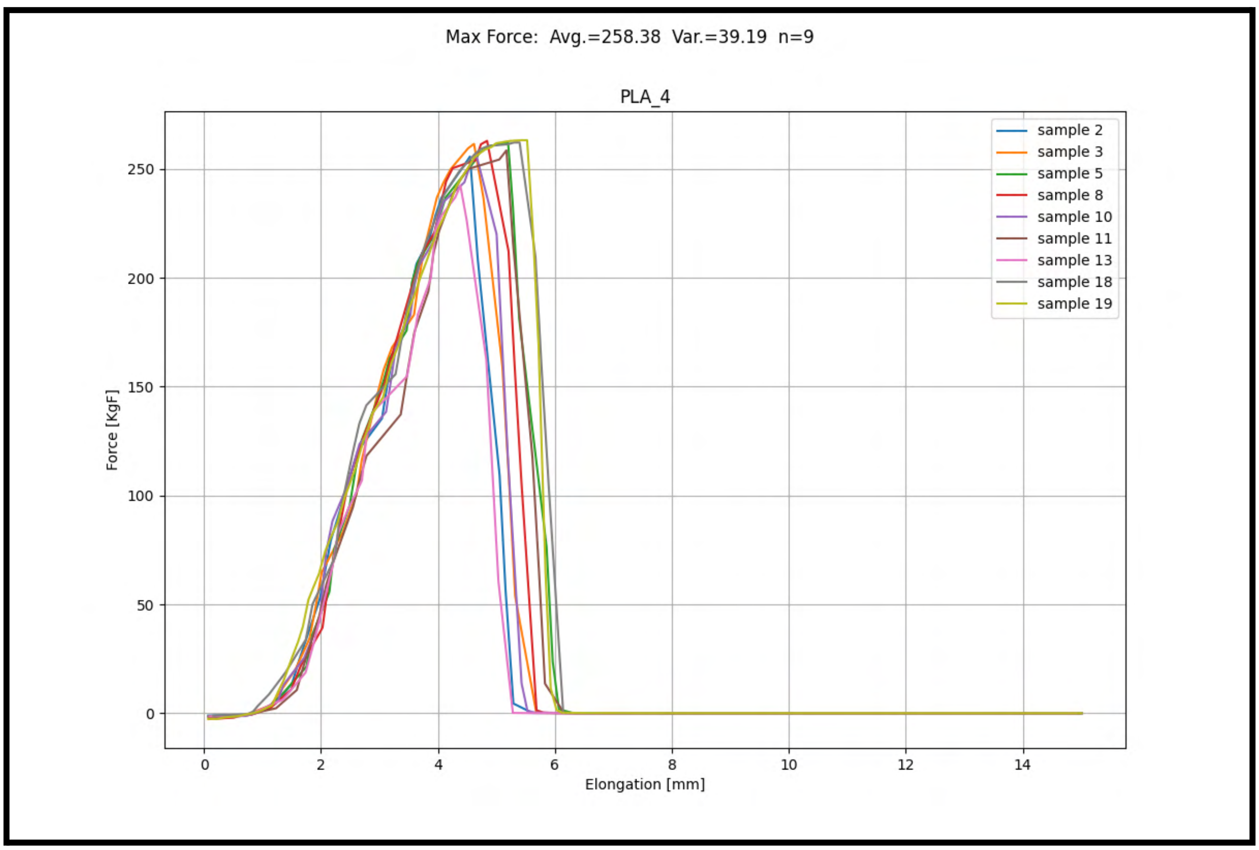
Appendix E: Tensile Testing Response Graphs

PLA

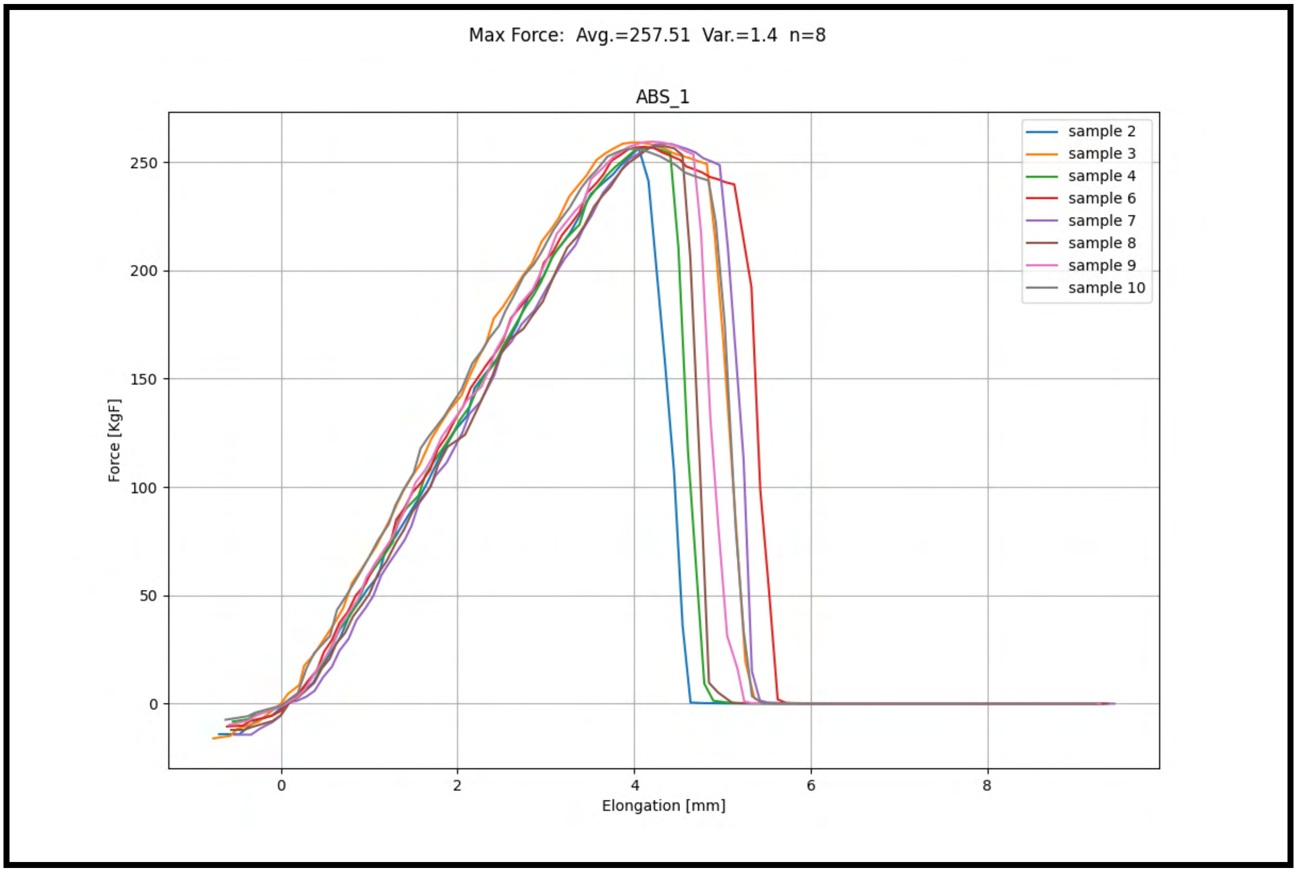


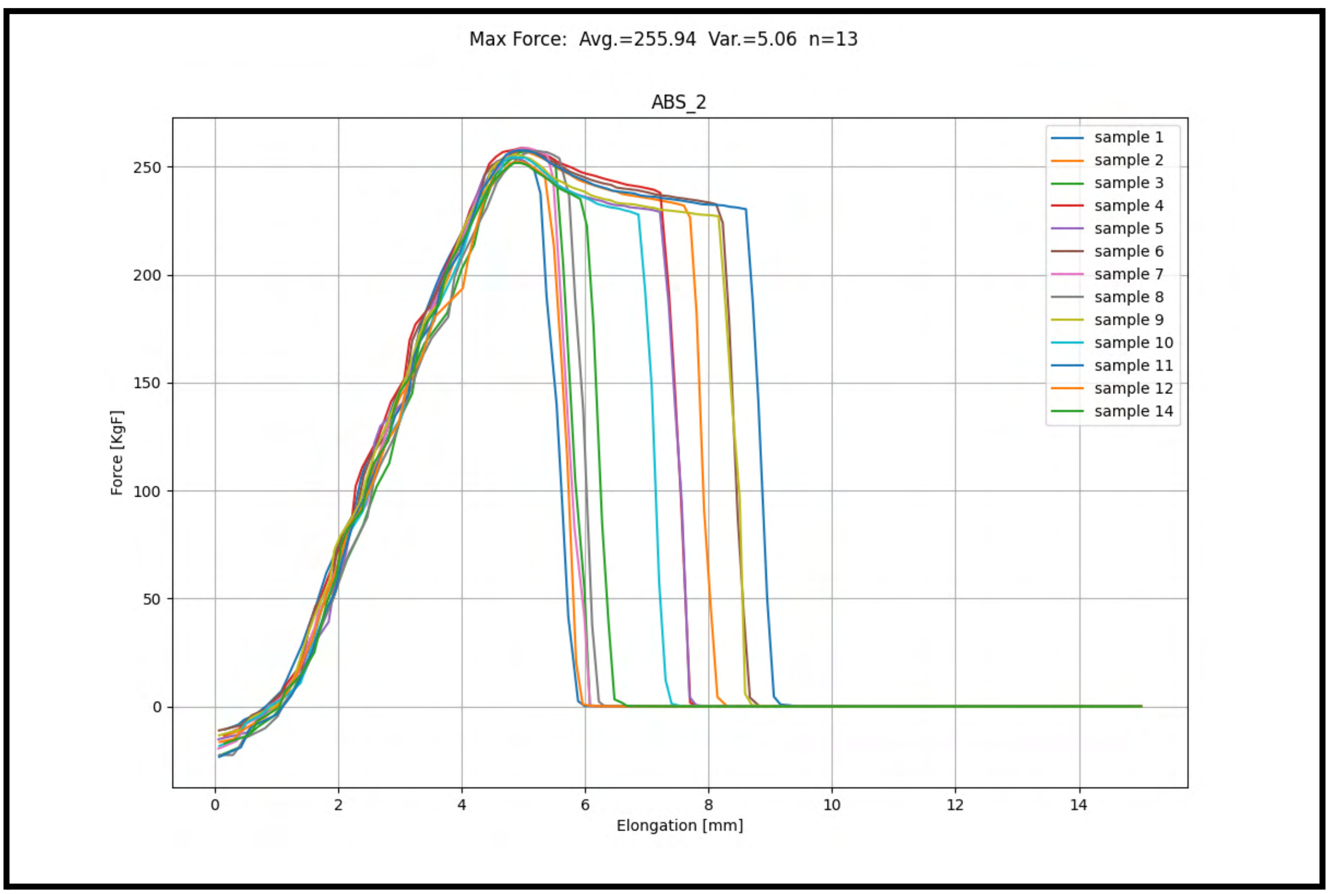


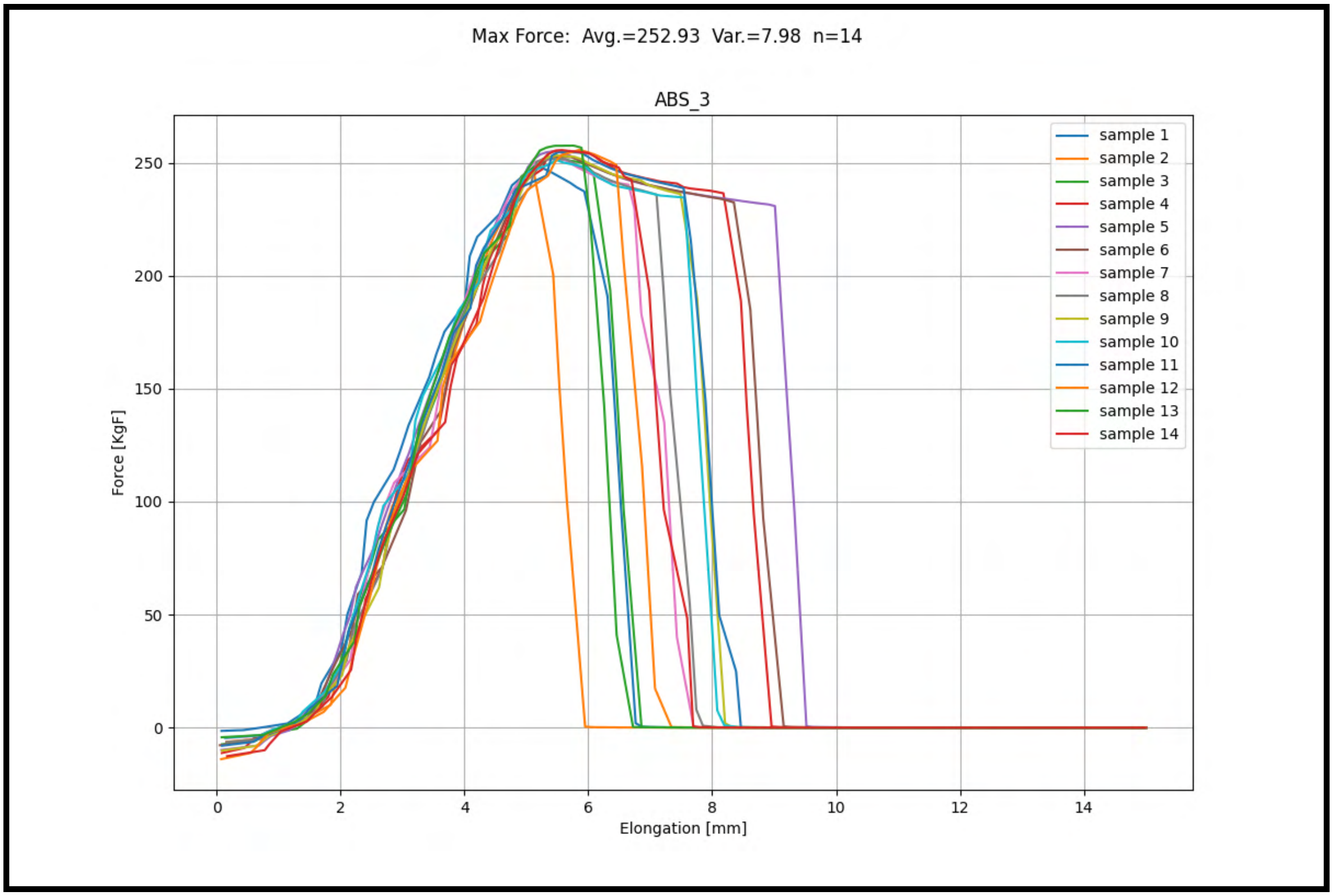

Max Force: Avg.=257.62 Var.=20.56 n=7
PLA_3
Force [KgF]
Elongation [mm]
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 9

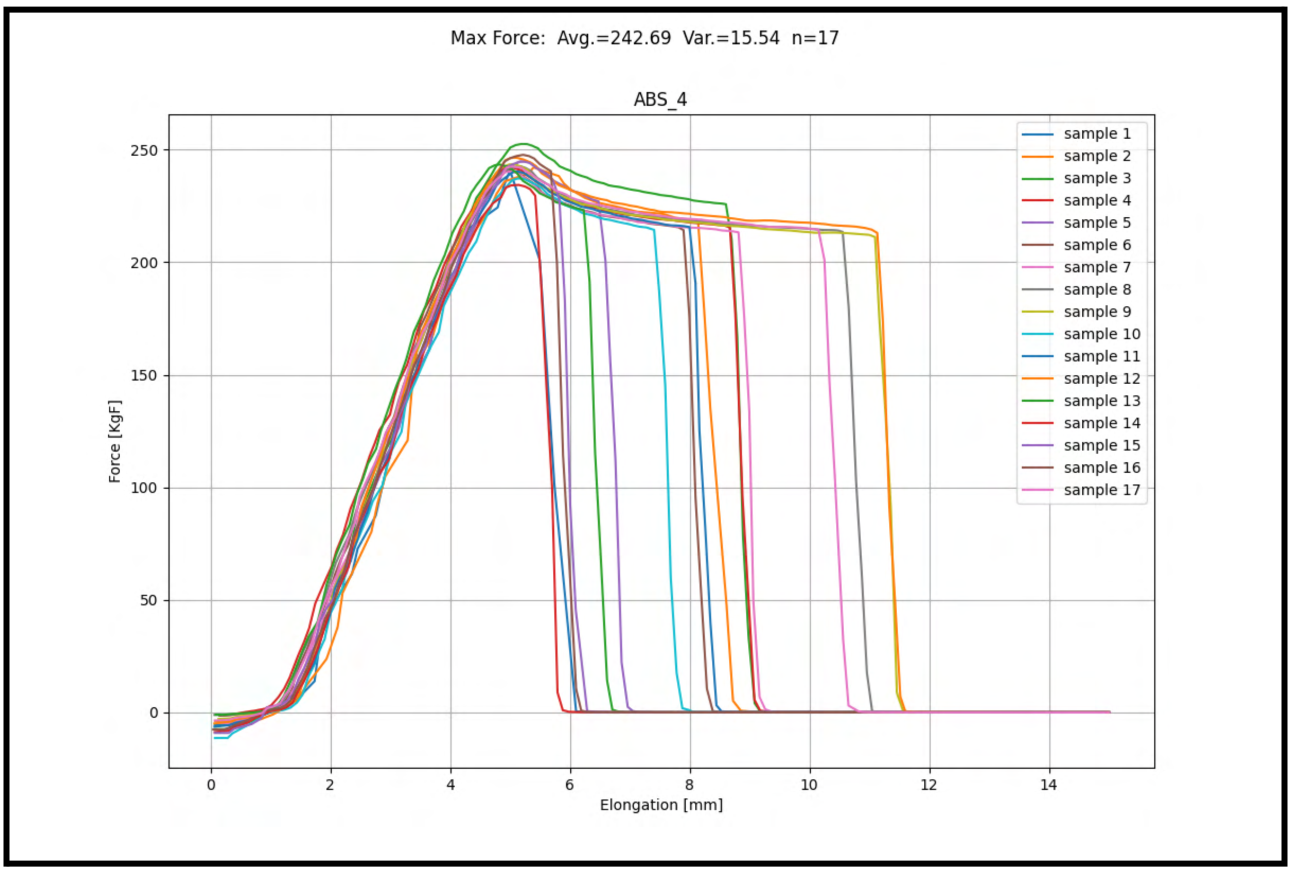

Max Force: Avg.=258.38 Var.=39.19 n=9
PLA_4
Force [KgF]
Elongation [mm]
sample 2
sample 3
sample 5
sample 8
sample 10
sample 11
sample 13
sample 18
sample 19

ABS

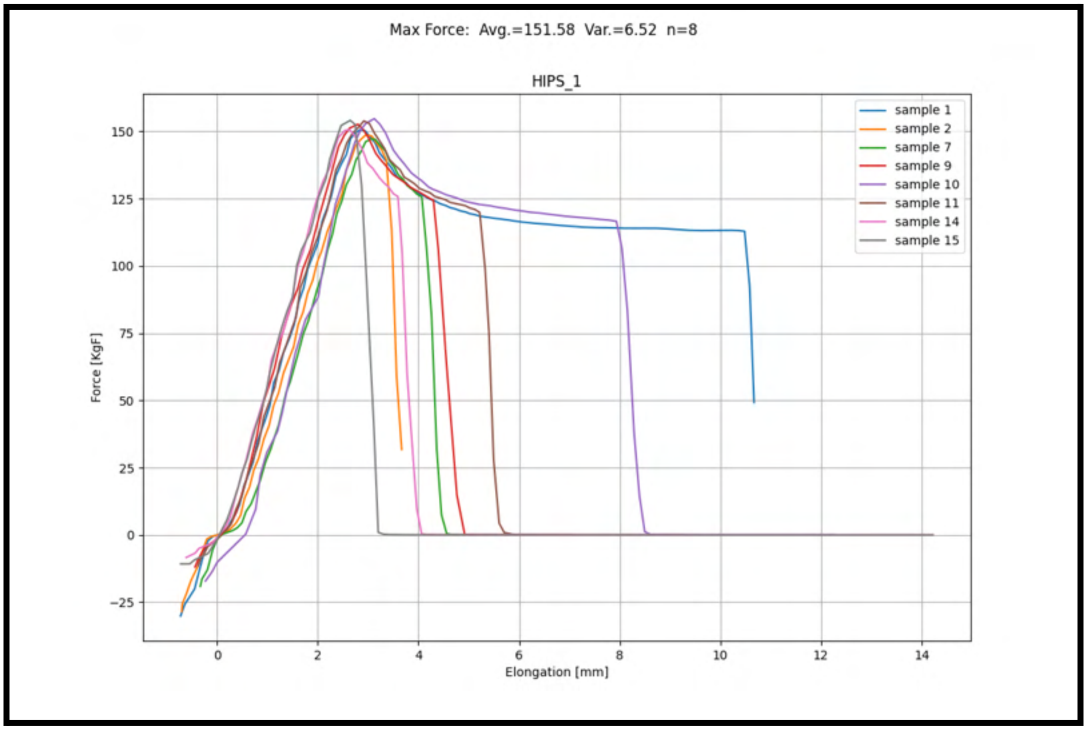

Max Force: Avg.=257.51 Var.=1.4 n=8
ABS_1
Force [KgF]
Elongation [mm]
sample 2
sample 3
sample 4
sample 6
sample 7
sample 8
sample 9
sample 10

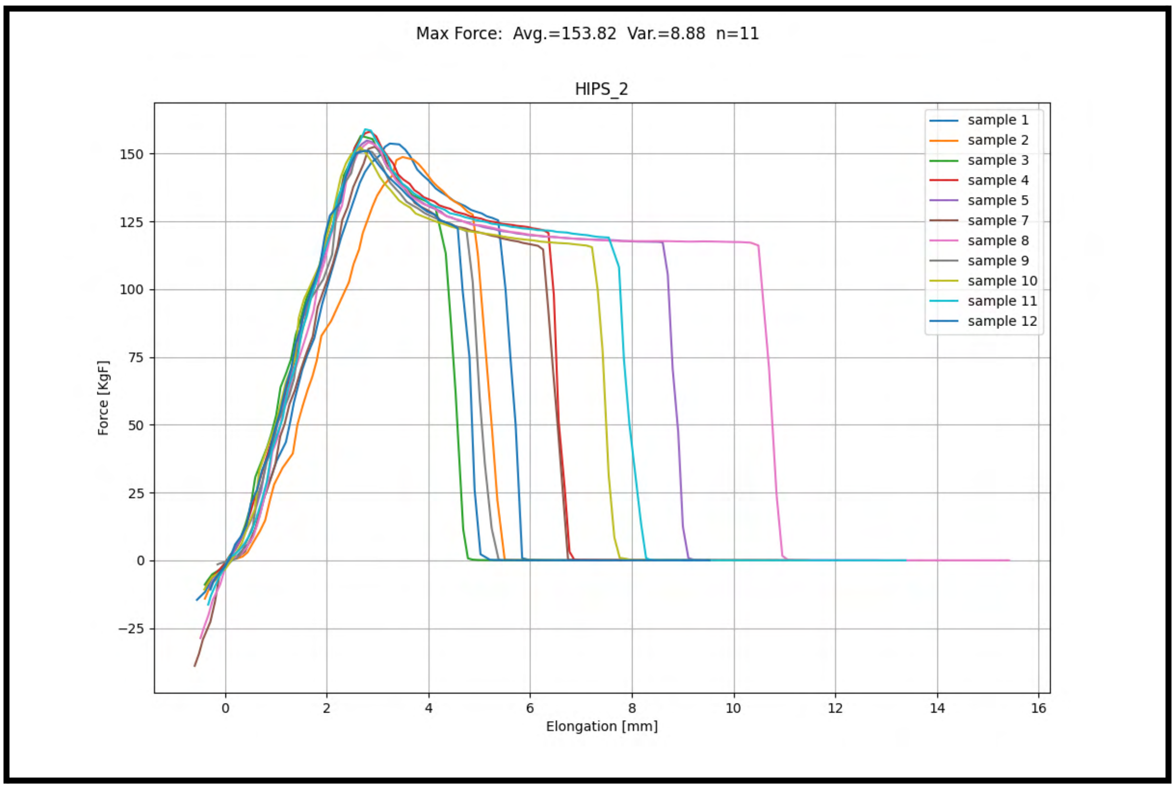

Max Force: Avg.=255.94 Var.=5.06 n=13
ABS_2
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 14

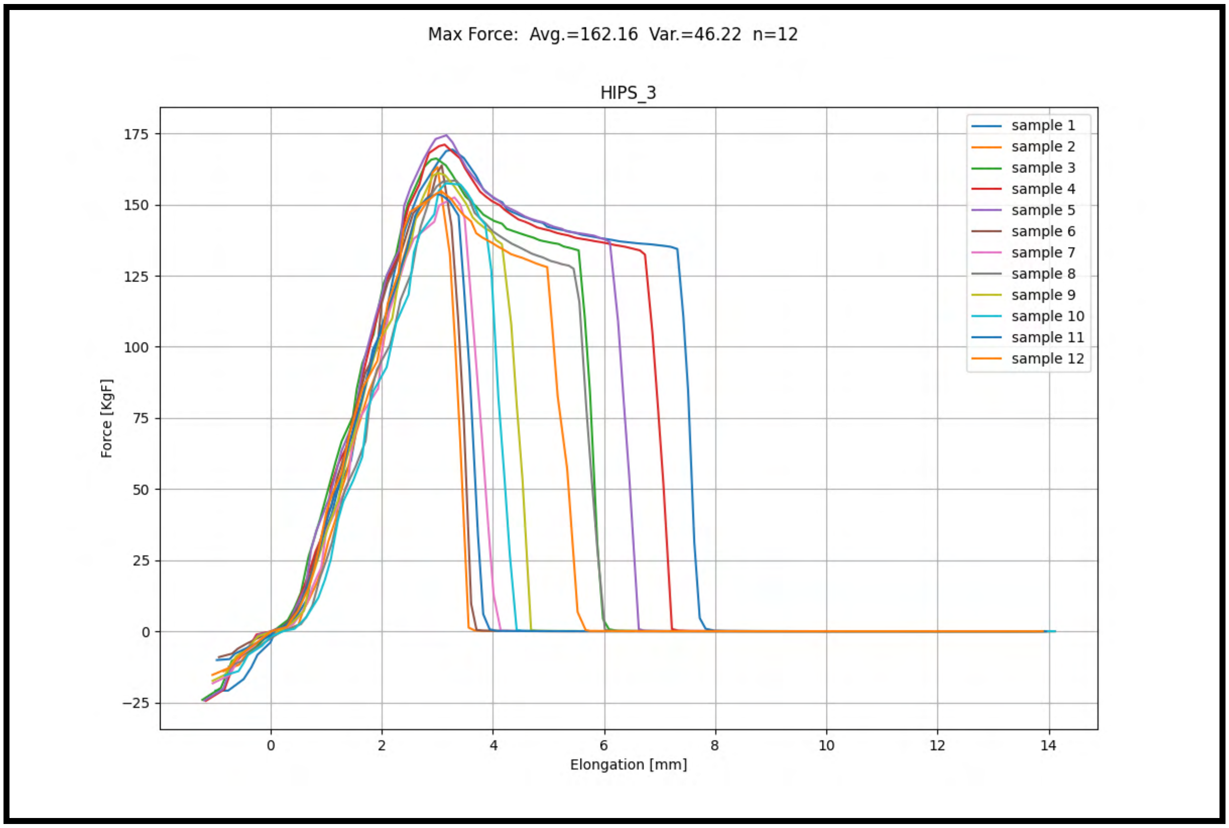

Max Force: Avg.=252.93 Var.=7.98 n=14
ABS_3
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 13
sample 14

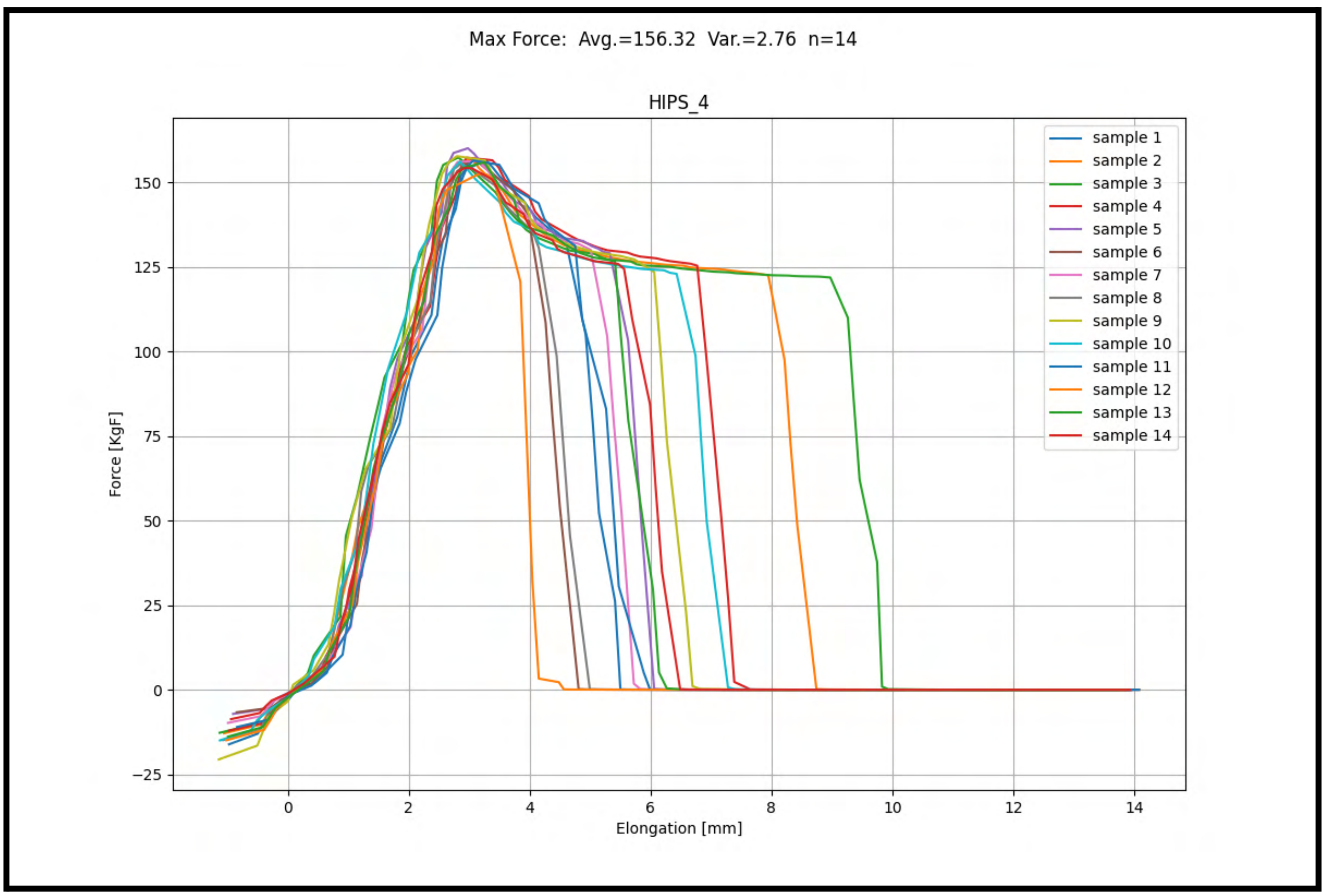

Max Force: Avg.=242.69 Var.=15.54 n=17
ABS_4
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 13
sample 14
sample 15
sample 16
sample 17

HIPS

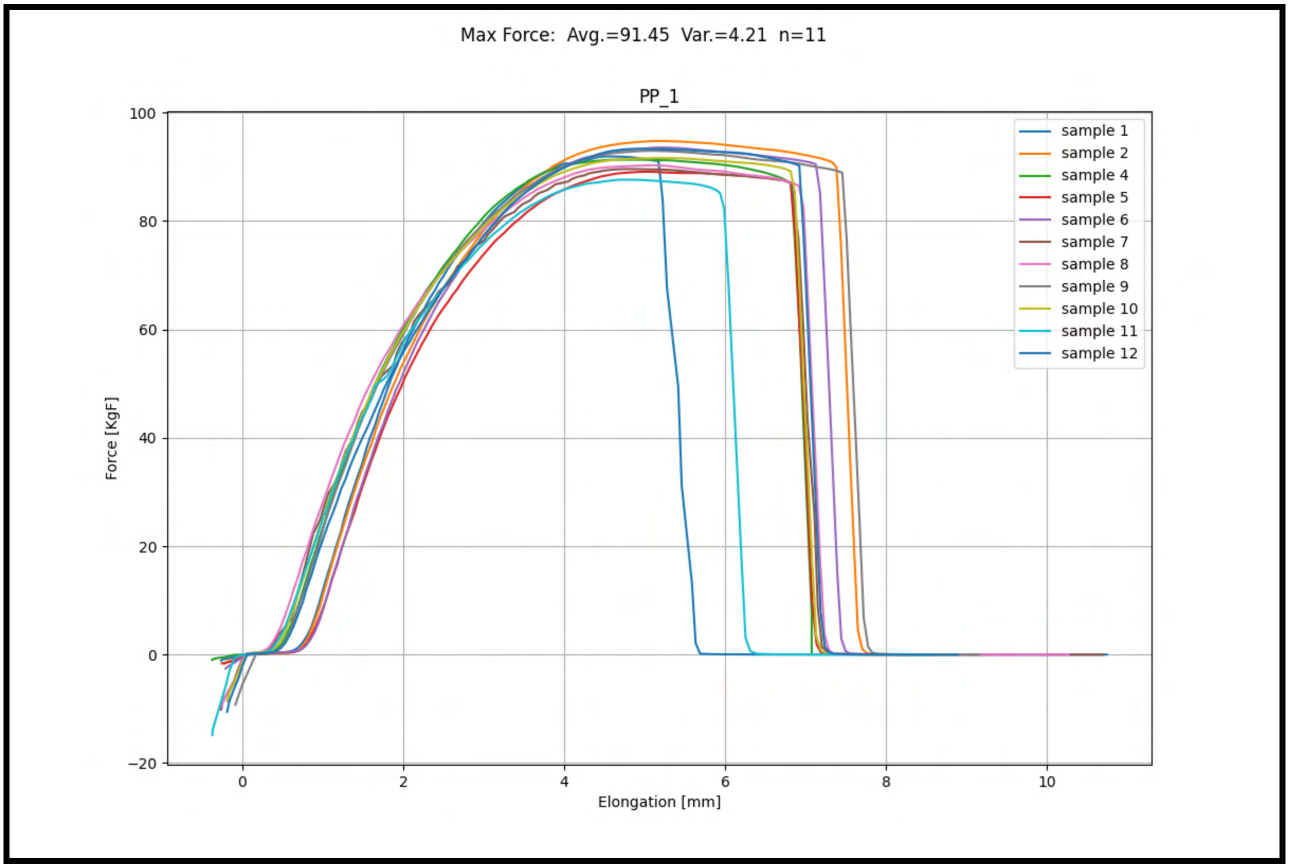

Max Force: Avg.=151.58 Var.=6.52 n=8
HIPS_1
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 7
sample 9
sample 10
sample 11
sample 14
sample 15


Max Force: Avg.=153.82 Var.=8.88 n=11
HIPS_2
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12

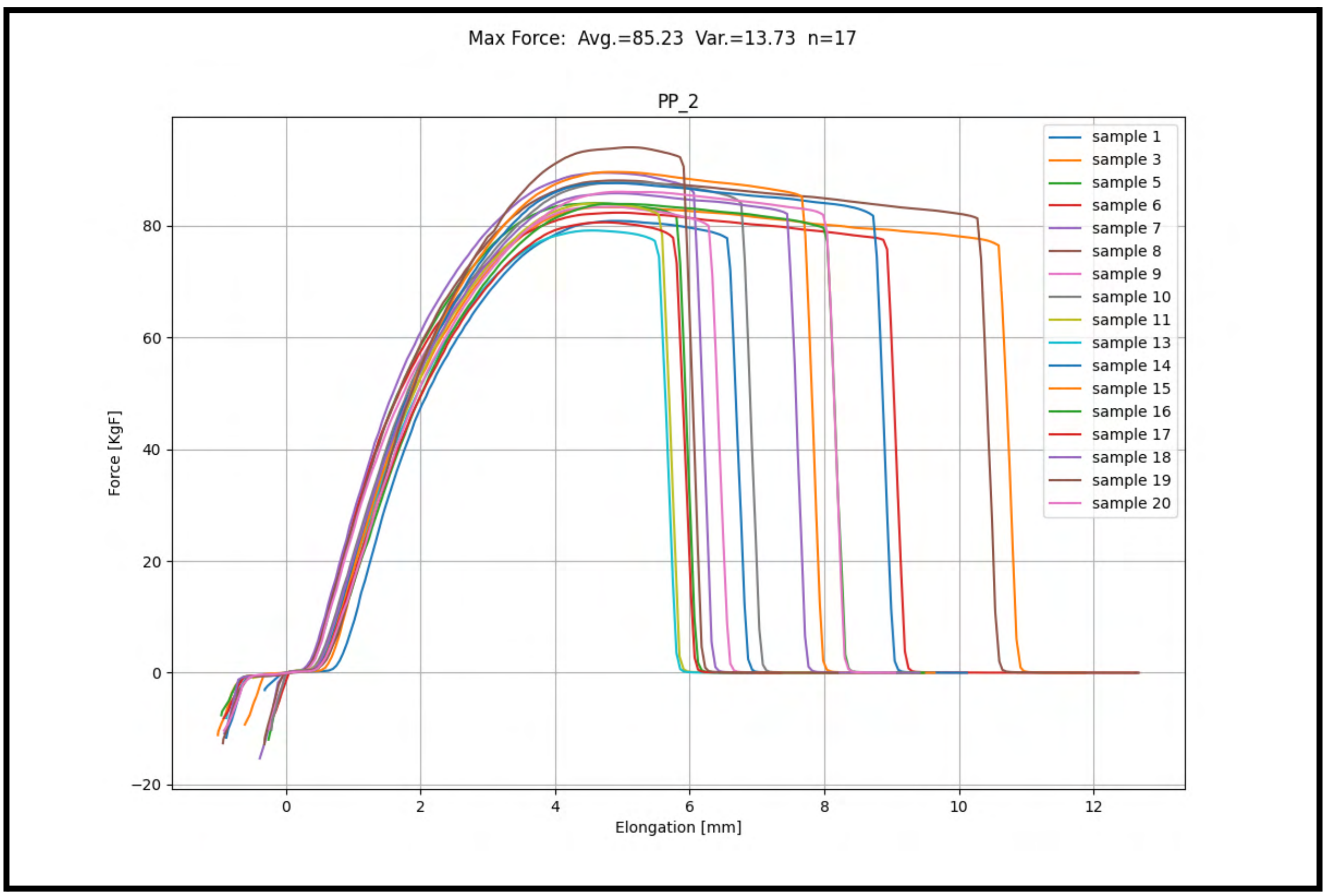

Max Force: Avg.=162.16 Var.=46.22 n=12
HIPS_3
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12


Max Force: Avg.=156.32 Var.=2.76 n=14
HIPS_4
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 13
sample 14

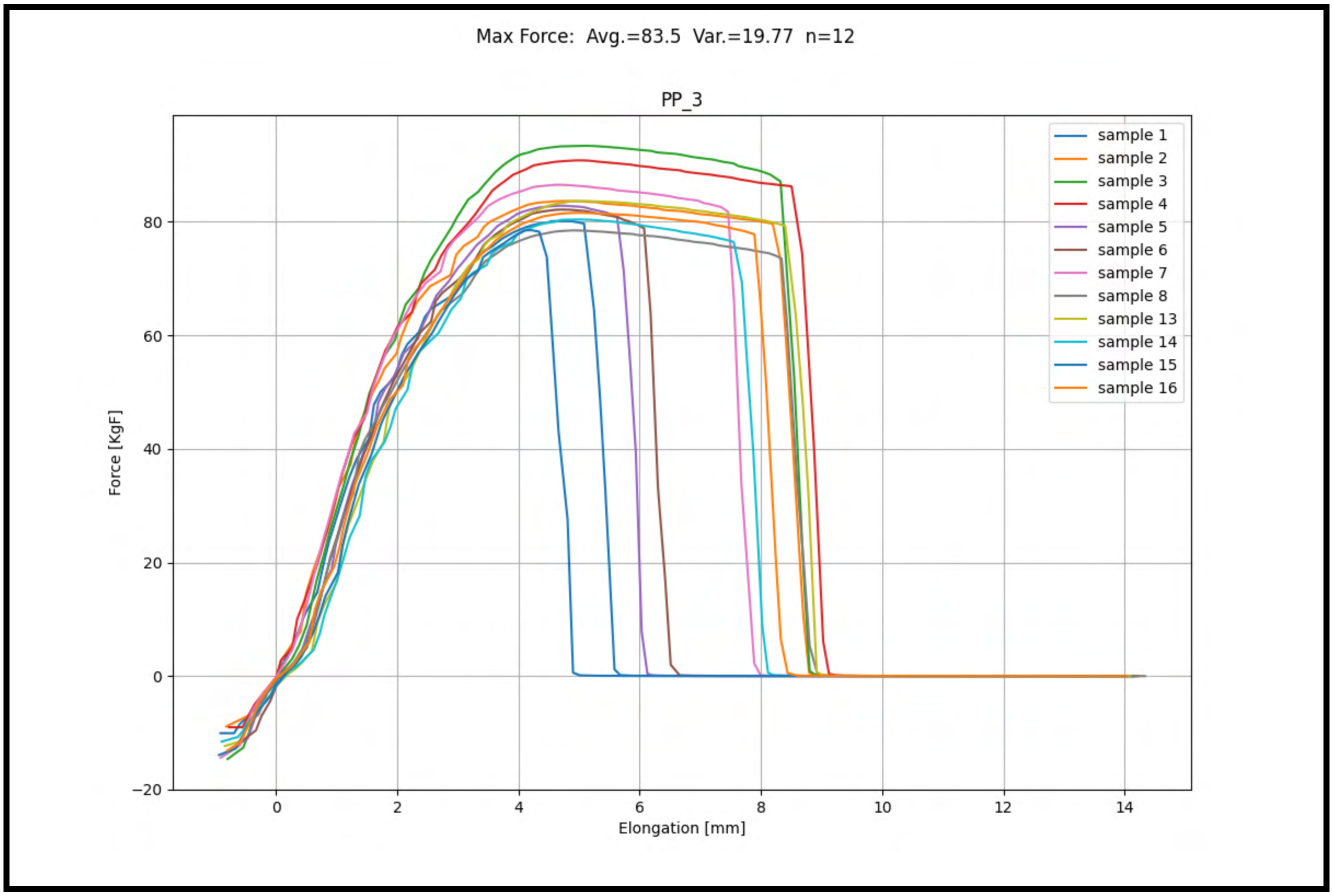
PP

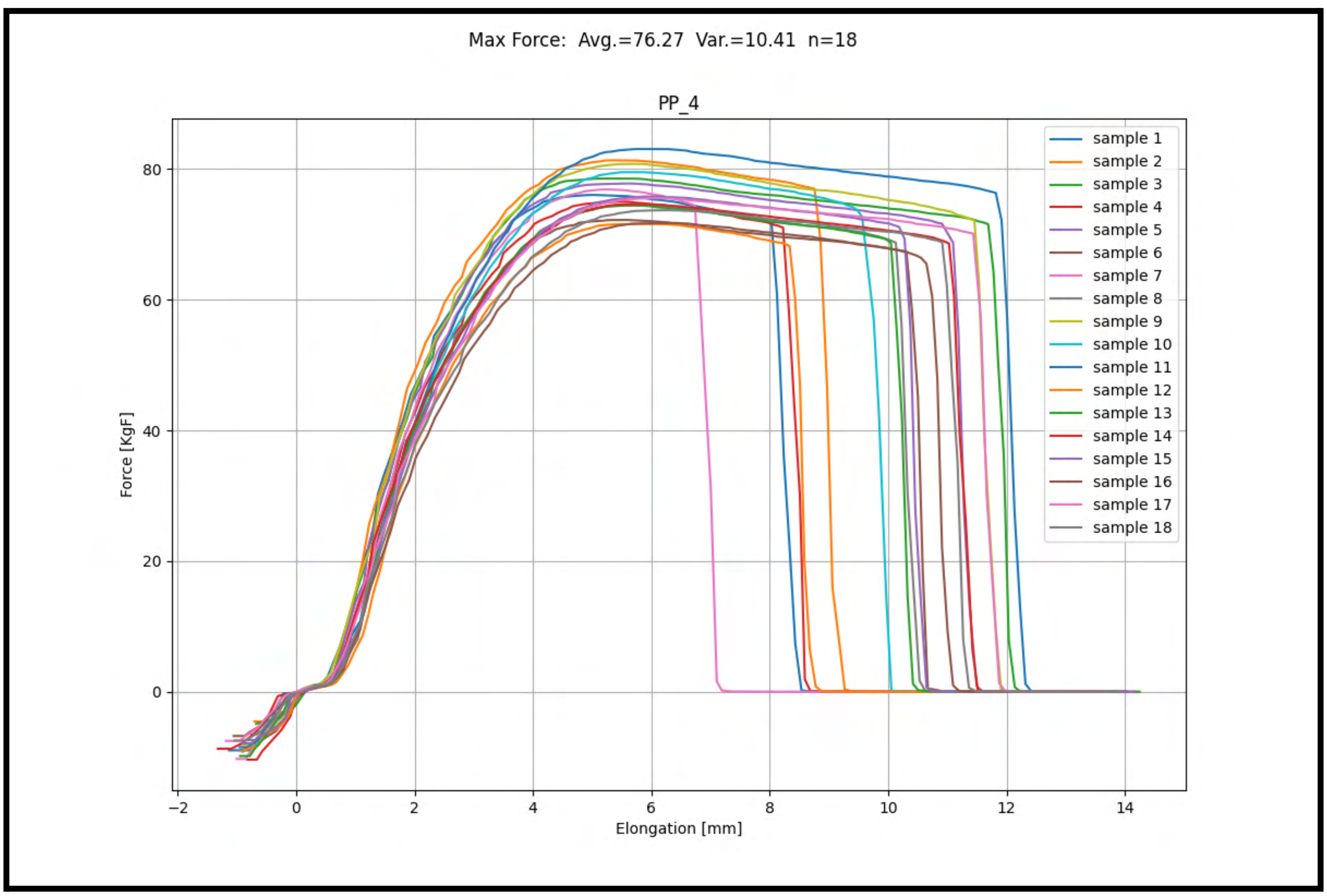


Max Force: Avg.=91.45 Var.=4.21 n=11
PP_1
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12



Max Force: Avg.=85.23 Var.=13.73 n=17
PP_2
Force [KgF]
Elongation [mm]
sample 1
sample 3
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 13
sample 14
sample 15
sample 16
sample 17
sample 18
sample 19
sample 20

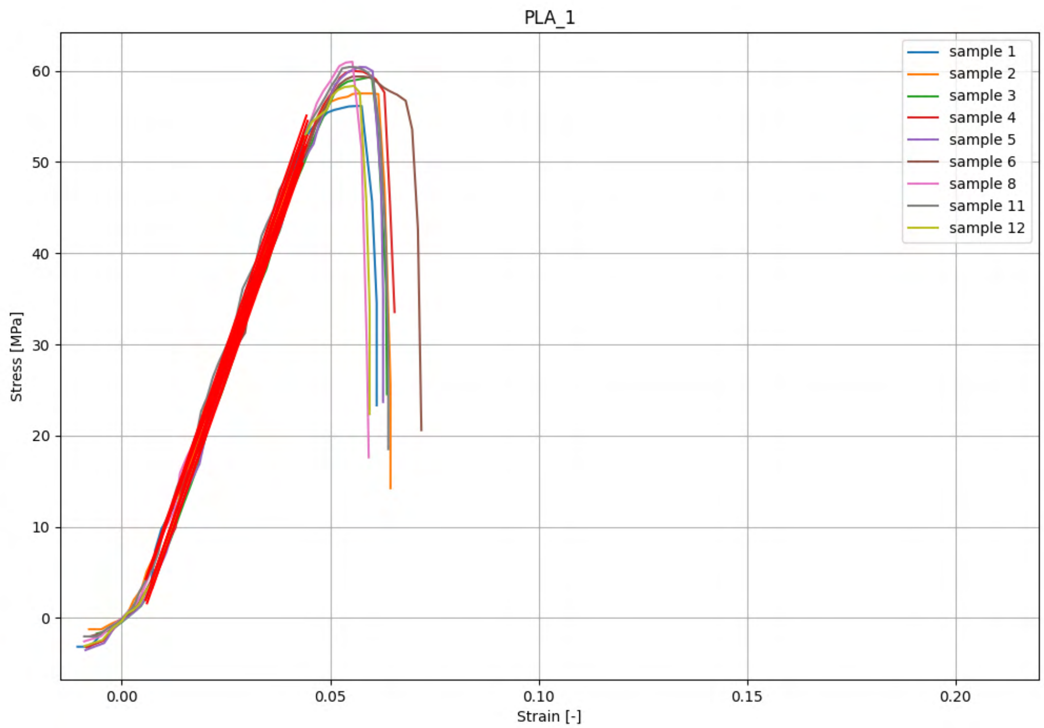

Max Force: Avg.=83.5 Var.=19.77 n=12
PP_3
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 13
sample 14
sample 15
sample 16


Max Force: Avg.=76.27 Var.=10.41 n=18
PP_4
Force [KgF]
Elongation [mm]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 13
sample 14
sample 15
sample 16
sample 17
sample 18

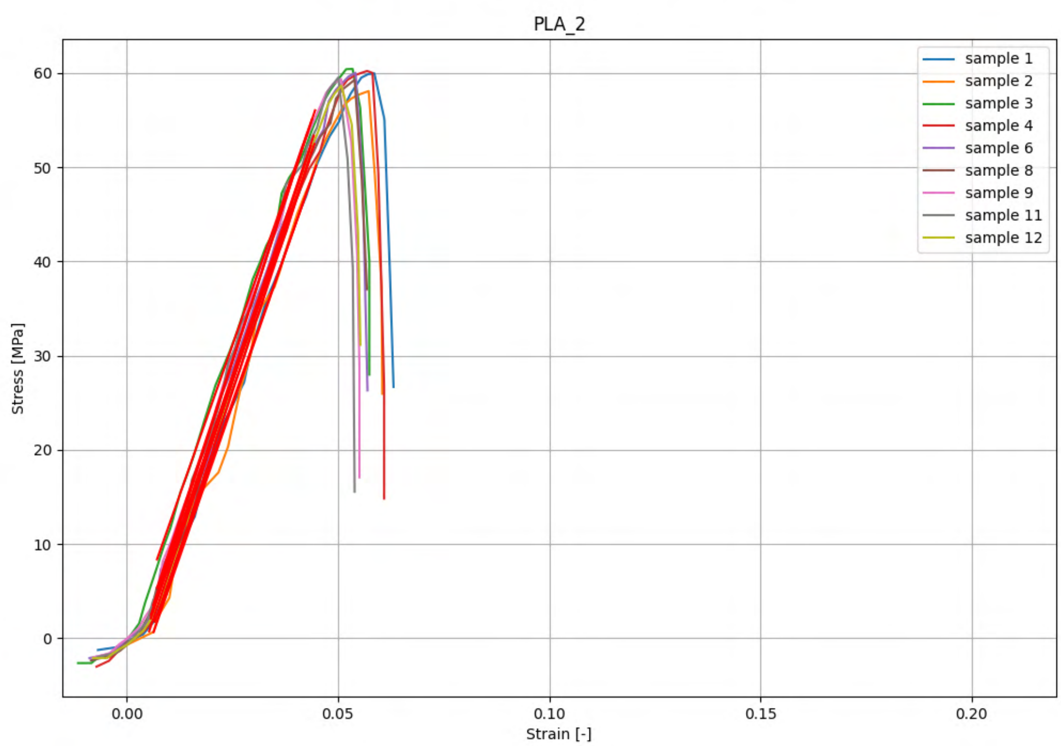
Appendix F: Tensile Testing Modulus Graphs

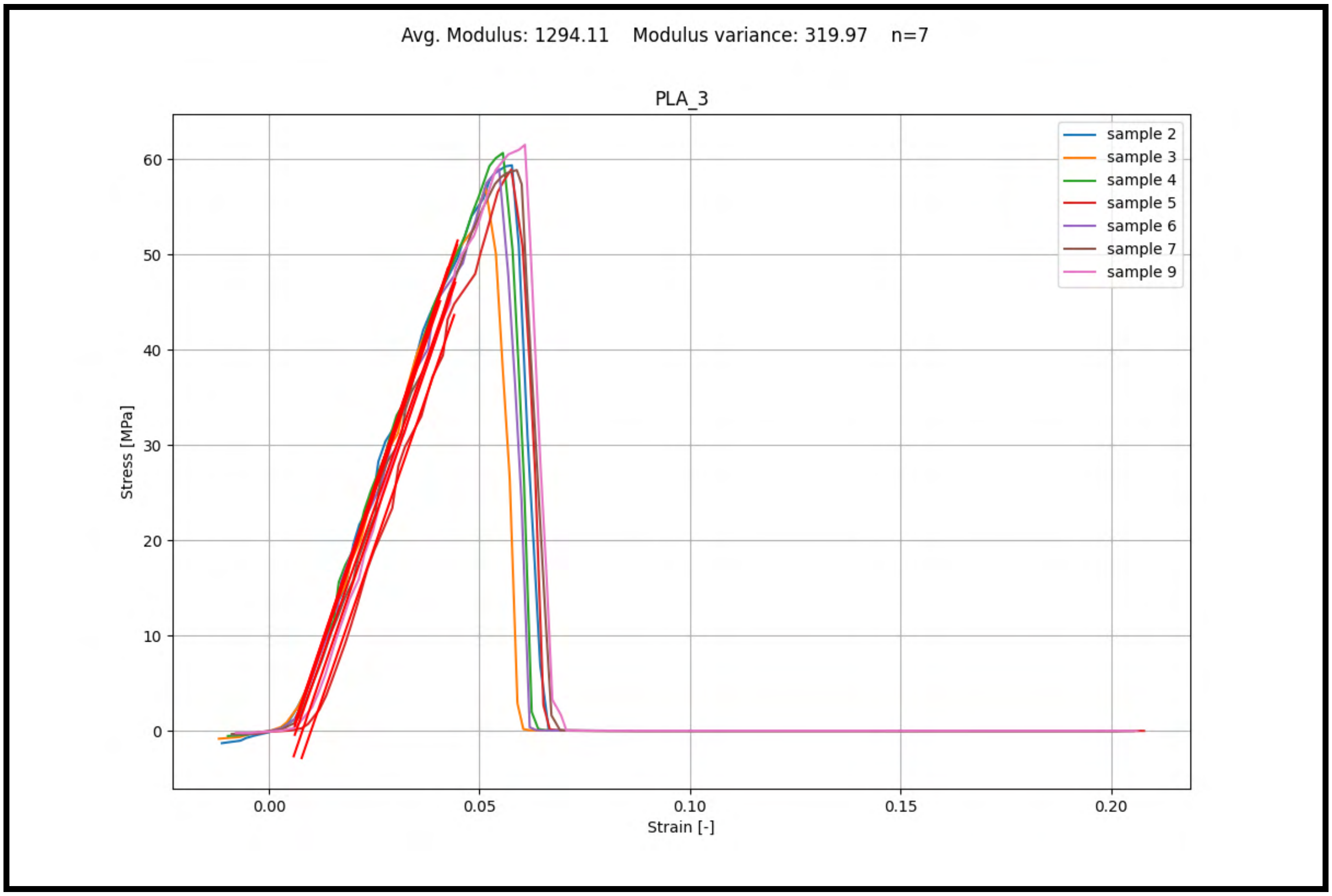
PLA

Avg. Modulus: 1300.68 Modulus variance: 688.84 n=9

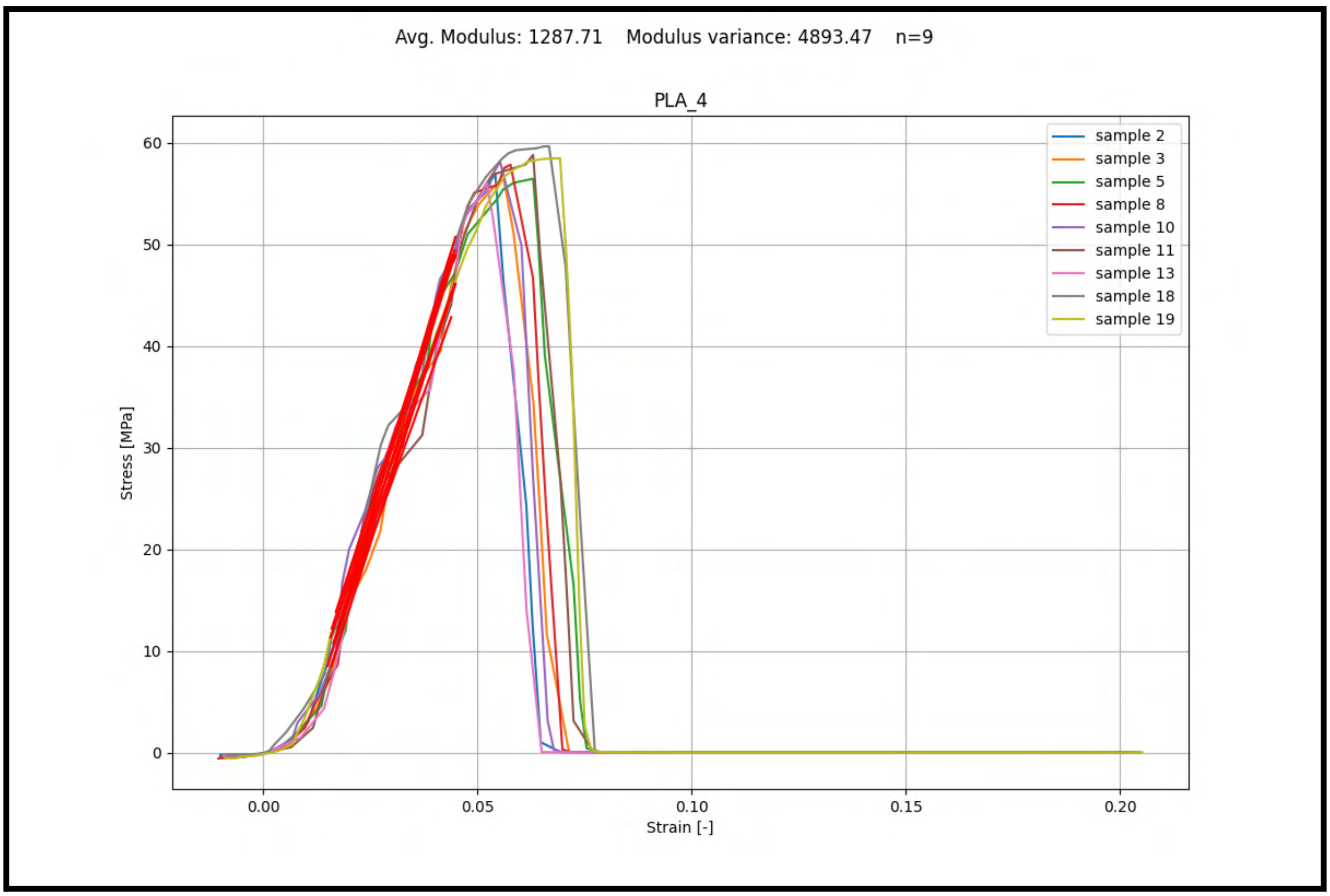


Avg. Modulus: 1318.67 Modulus variance: 1311.18 n=9



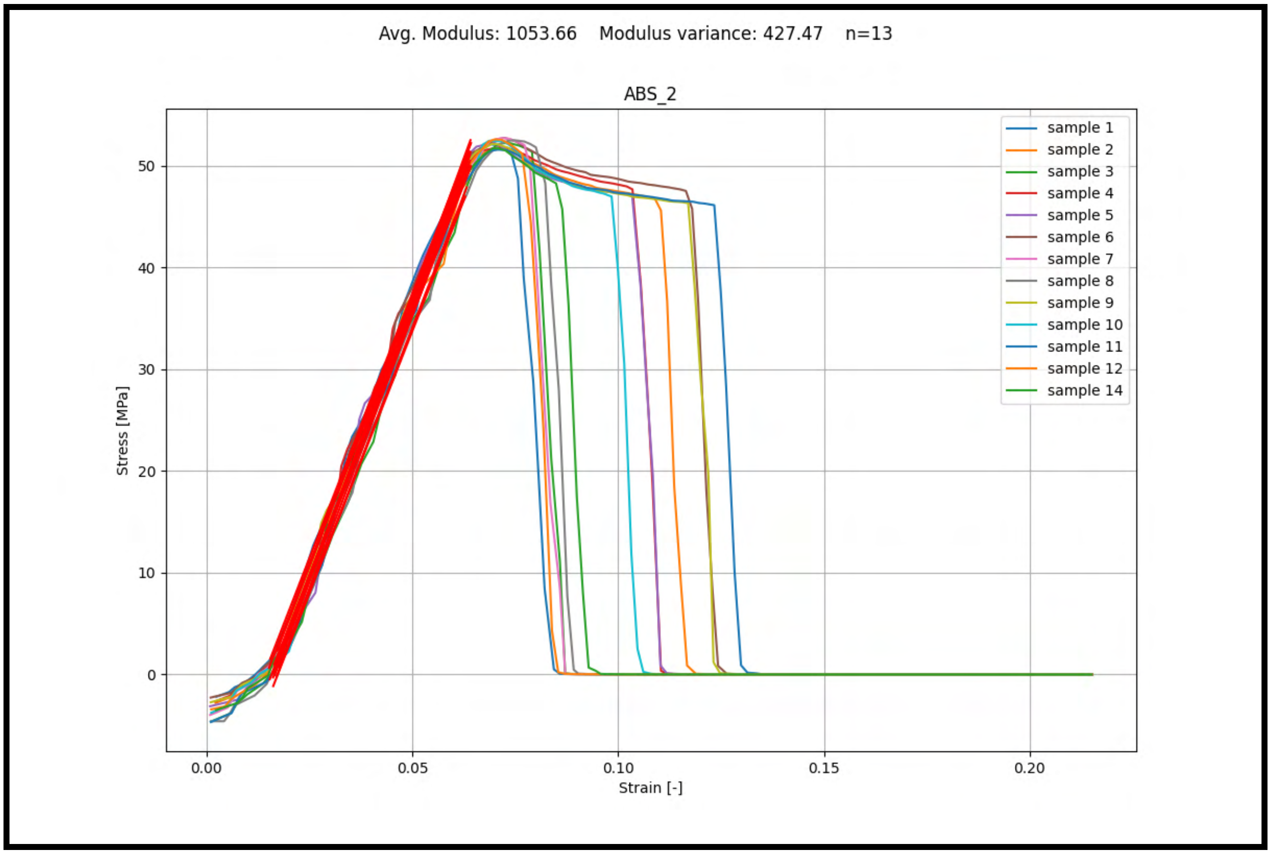


Avg. Modulus: 1294.11 Modulus variance: 319.97 n=7
PLA_3
Stress [MPa]
Strain [-]
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 9

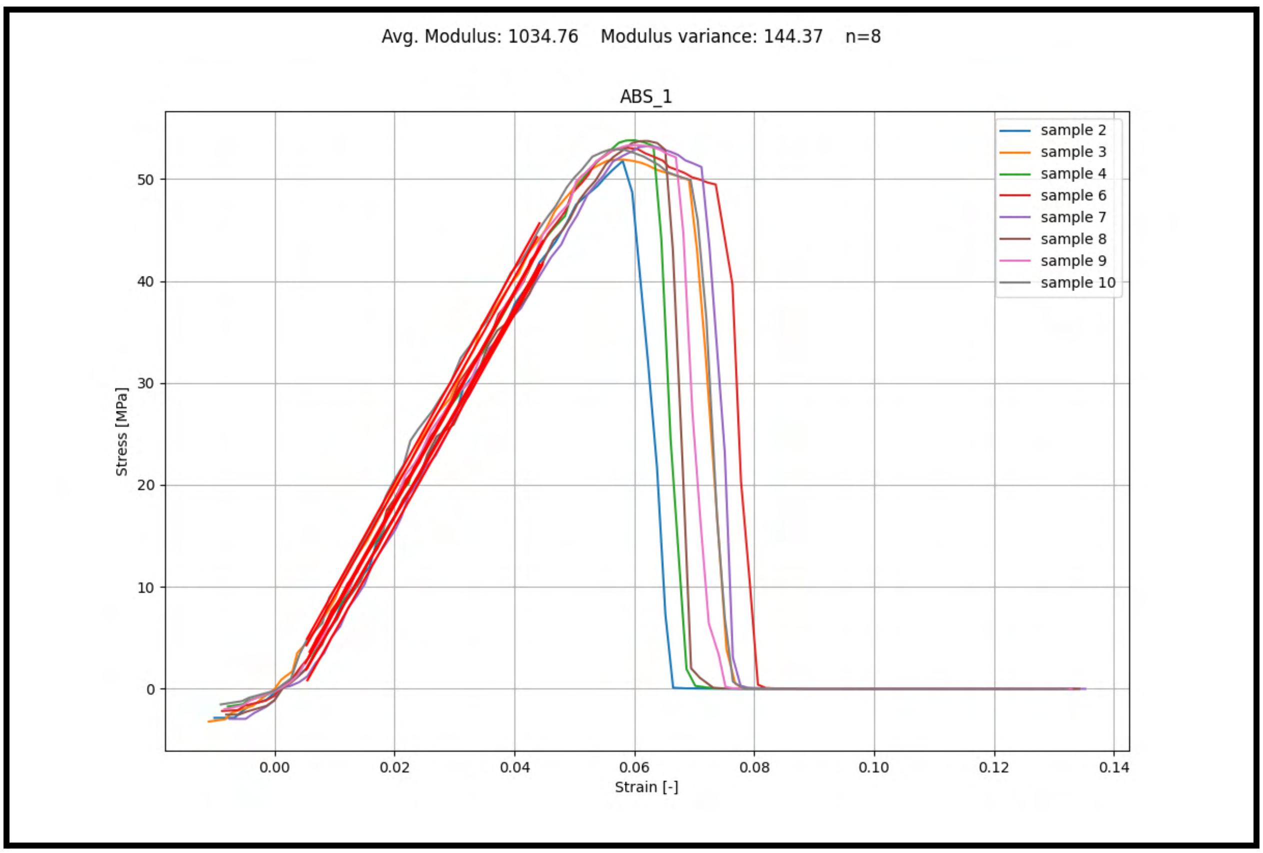


Avg. Modulus: 1287.71 Modulus variance: 4893.47 n=9
PLA_4
Stress [MPa]
Strain [-]
sample 2
sample 3
sample 5
sample 8
sample 10
sample 11
sample 13
sample 18
sample 19

ABS

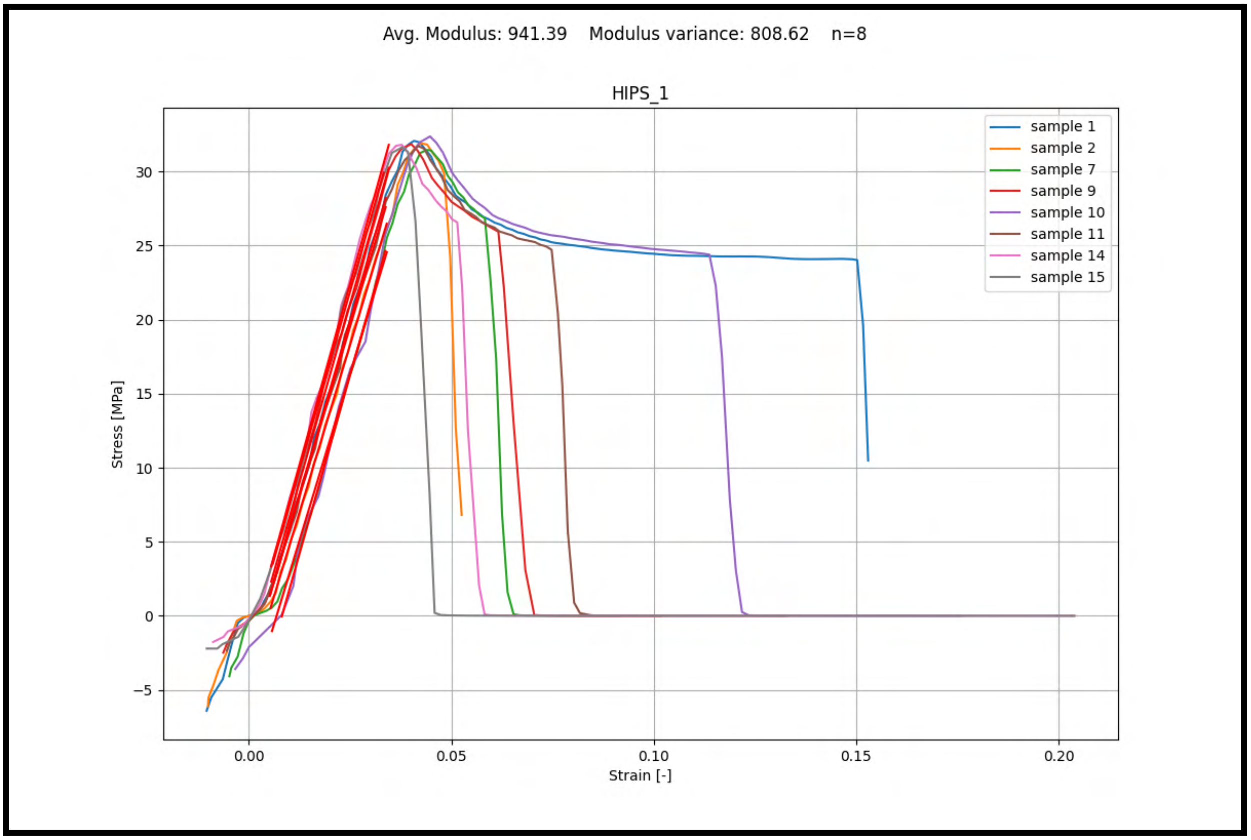


Avg. Modulus: 1053.66 Modulus variance: 427.47 n=13
ABS_2
Stress [MPa]
Strain [-]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 14

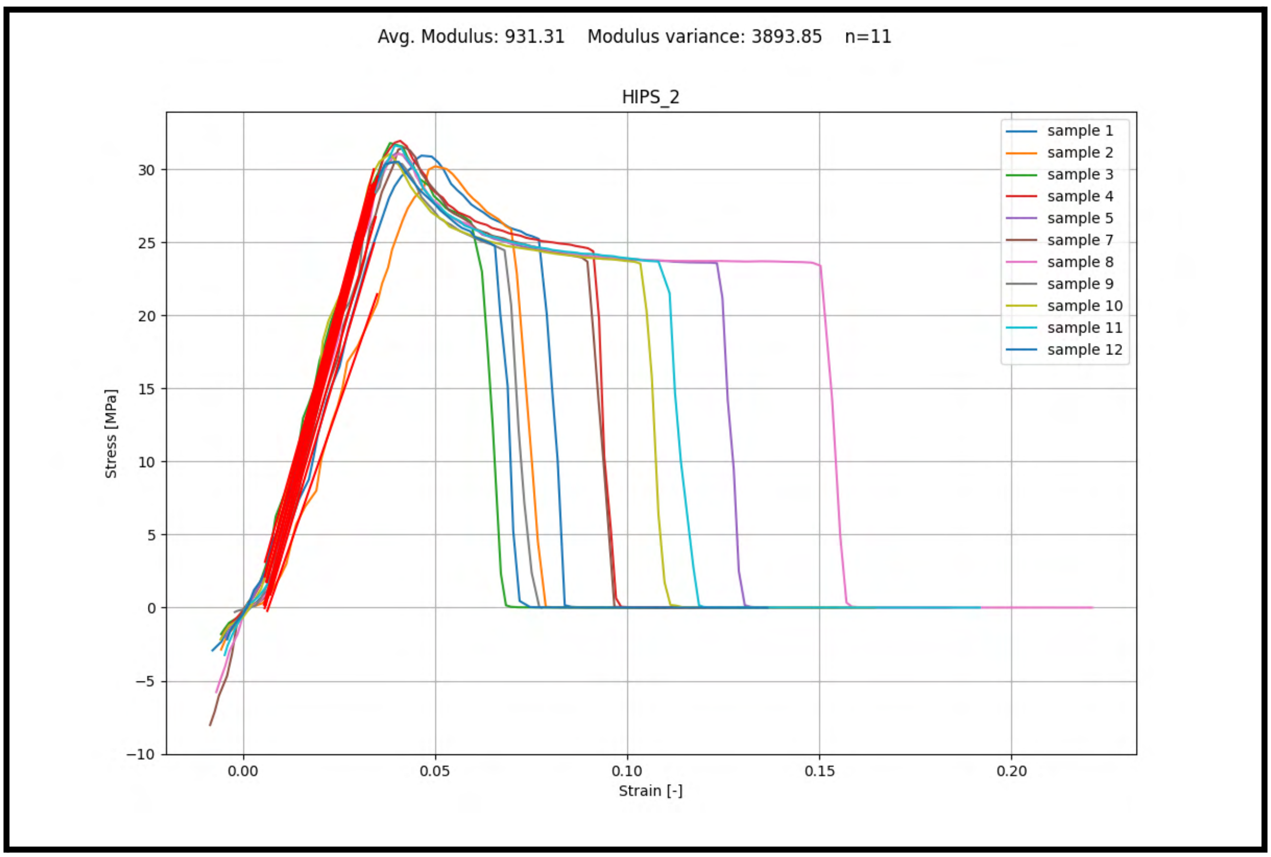


Avg. Modulus: 1034.76 Modulus variance: 144.37 n=8
ABS_1
Stress [MPa]
Strain [-]
sample 2
sample 3
sample 4
sample 6
sample 7
sample 8
sample 9
sample 10

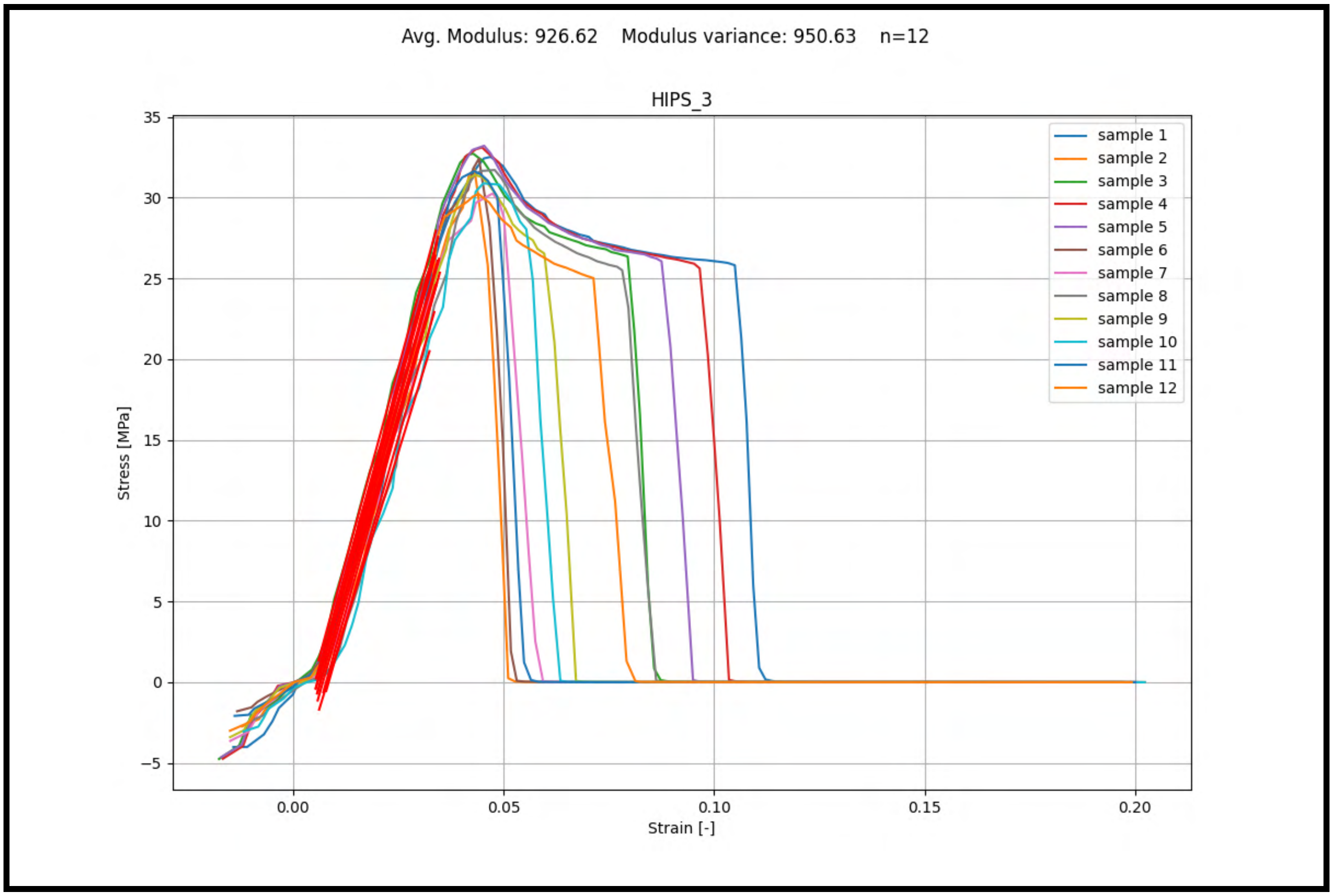
HIPS



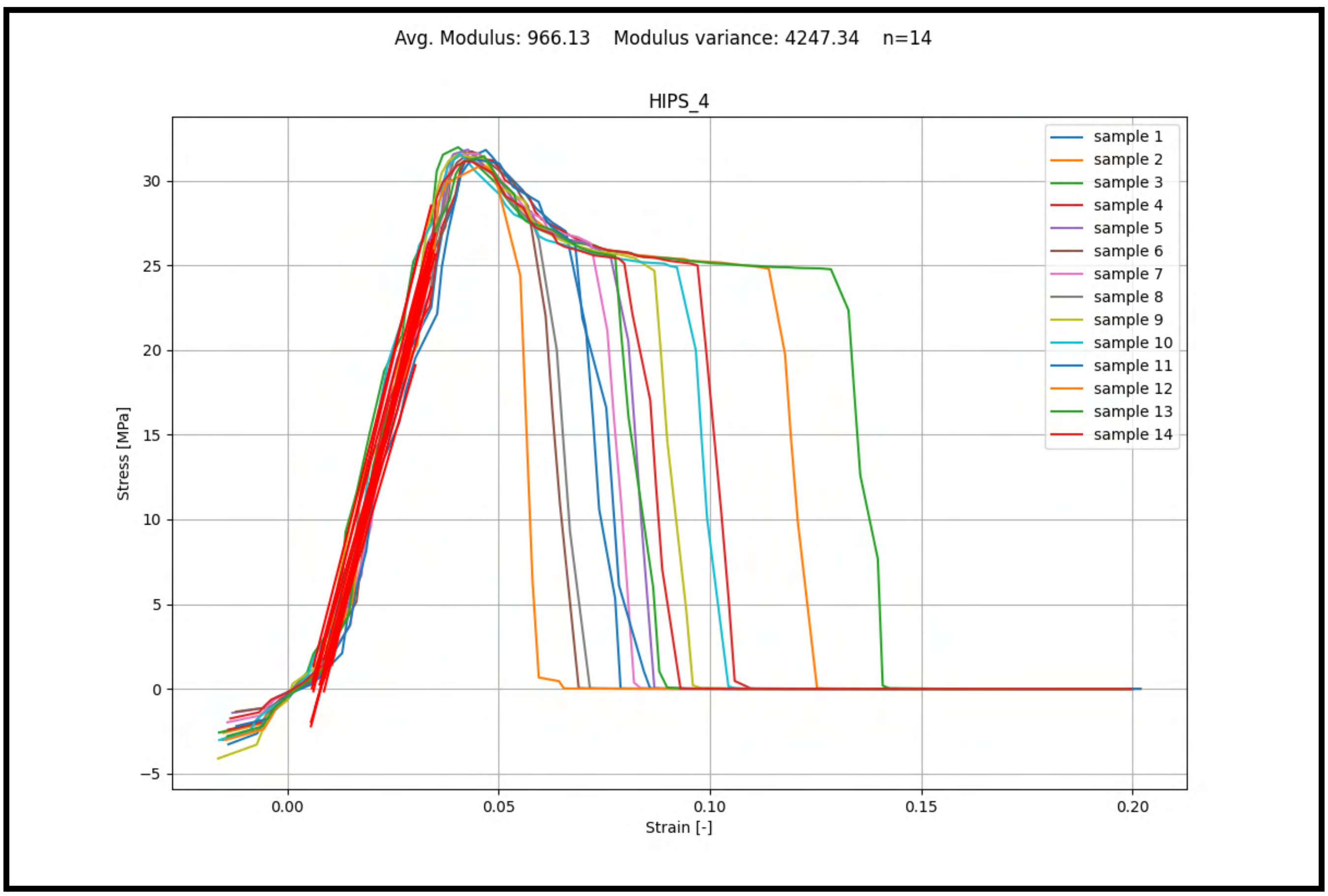
Avg. Modulus: 941.39 Modulus variance: 808.62 n=8
HIPS_1
sample 1
sample 2
sample 7
sample 9
sample 10
sample 11
sample 14
sample 15
Stress [MPa]
Strain [-]



Avg. Modulus: 931.31 Modulus variance: 3893.85 n=11
HIPS_2
sample 1
sample 2
sample 3
sample 4
sample 5
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
Stress [MPa]
Strain [-]

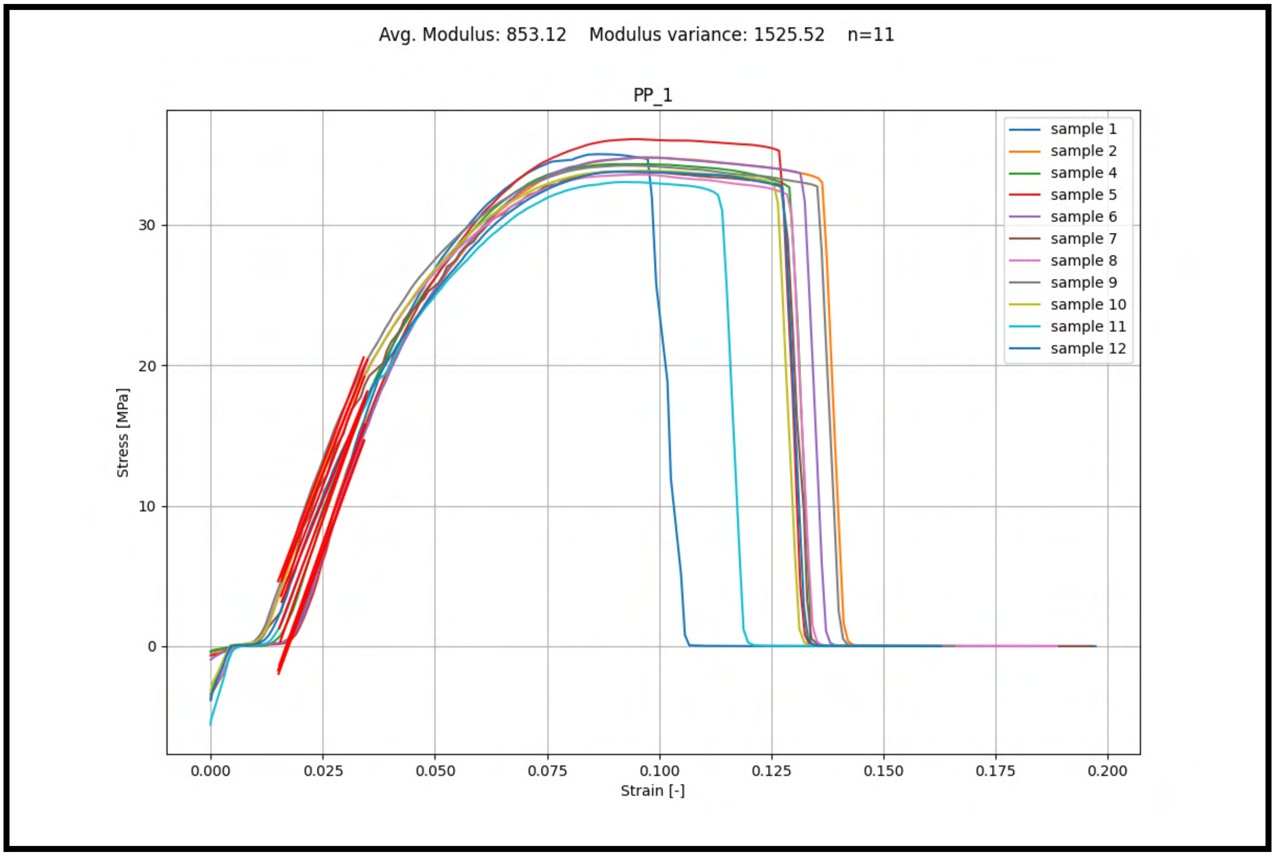


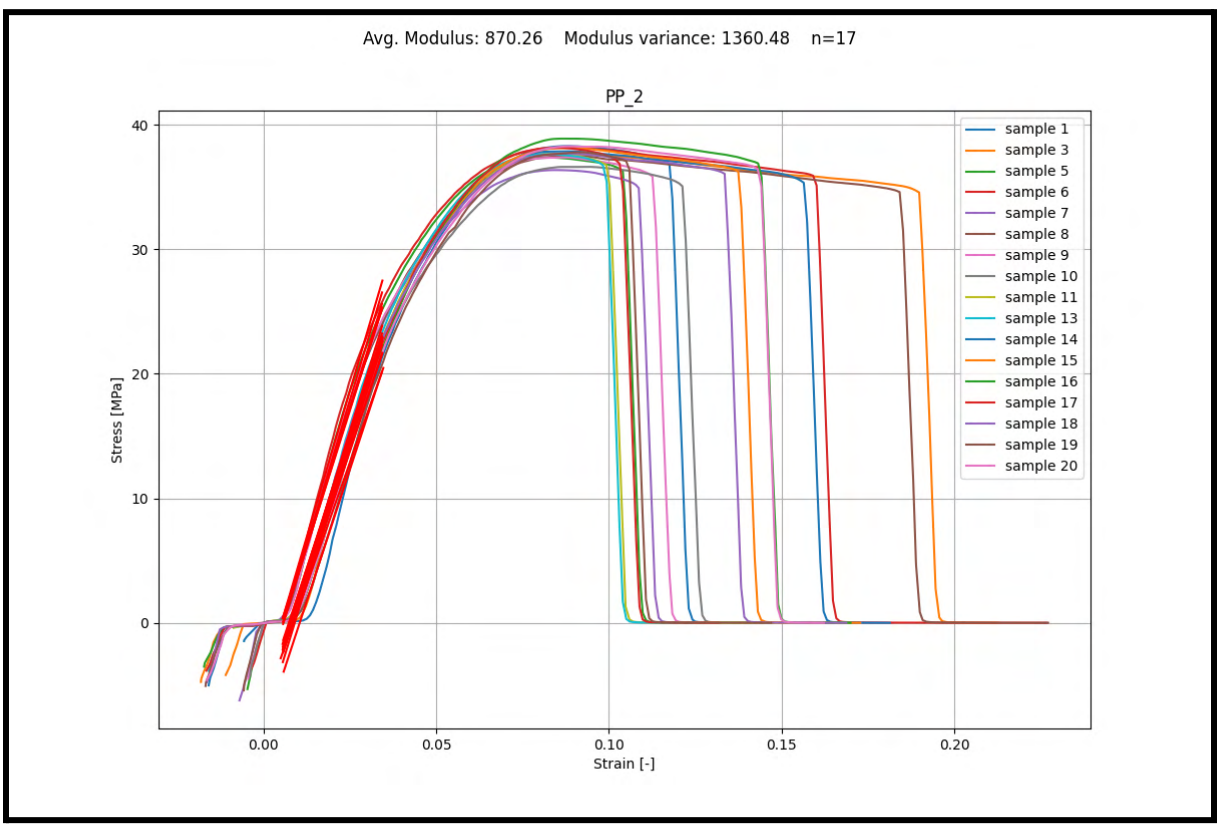
Avg. Modulus: 926.62 Modulus variance: 950.63 n=12
HIPS_3
Stress [MPa]
Strain [-]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12

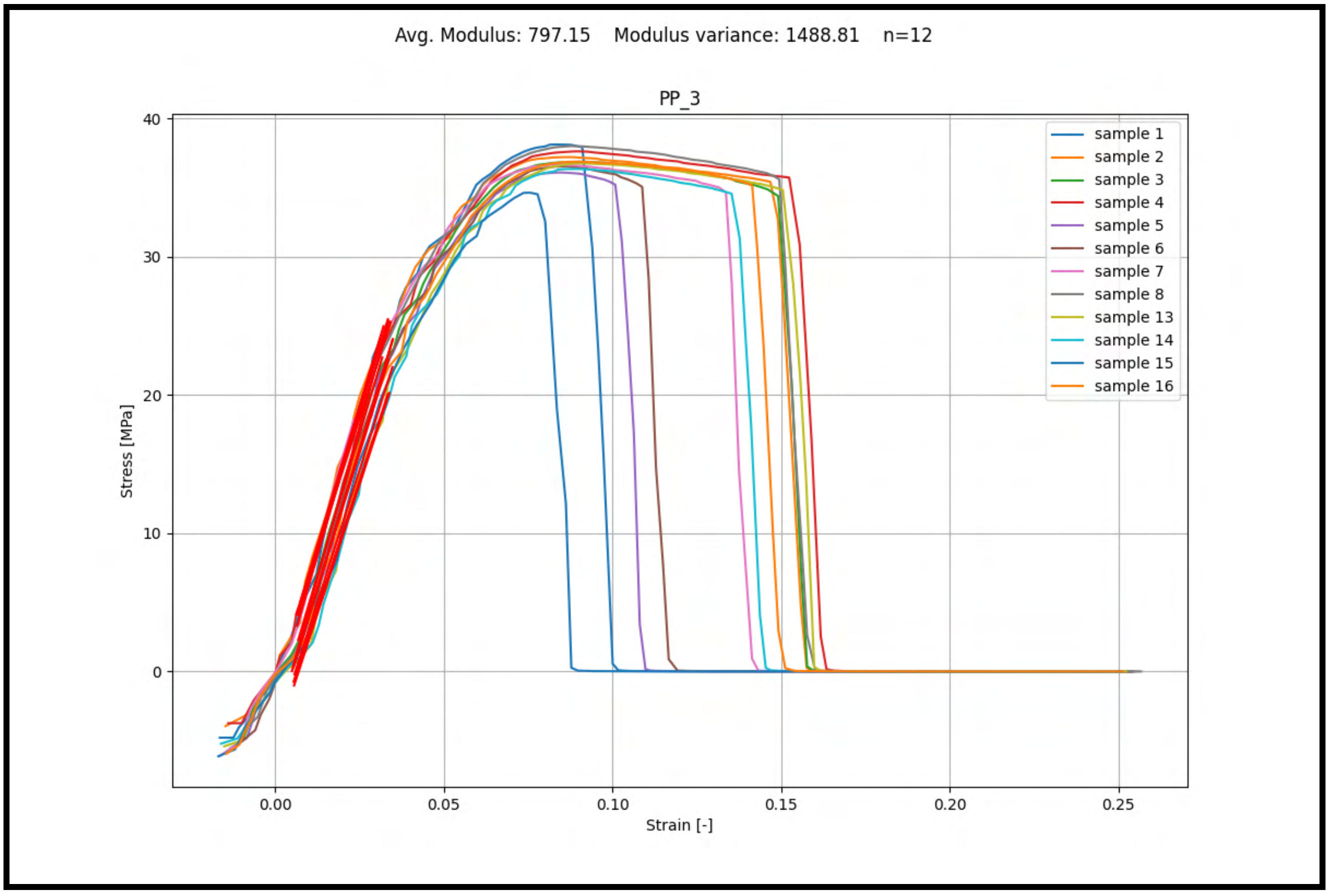


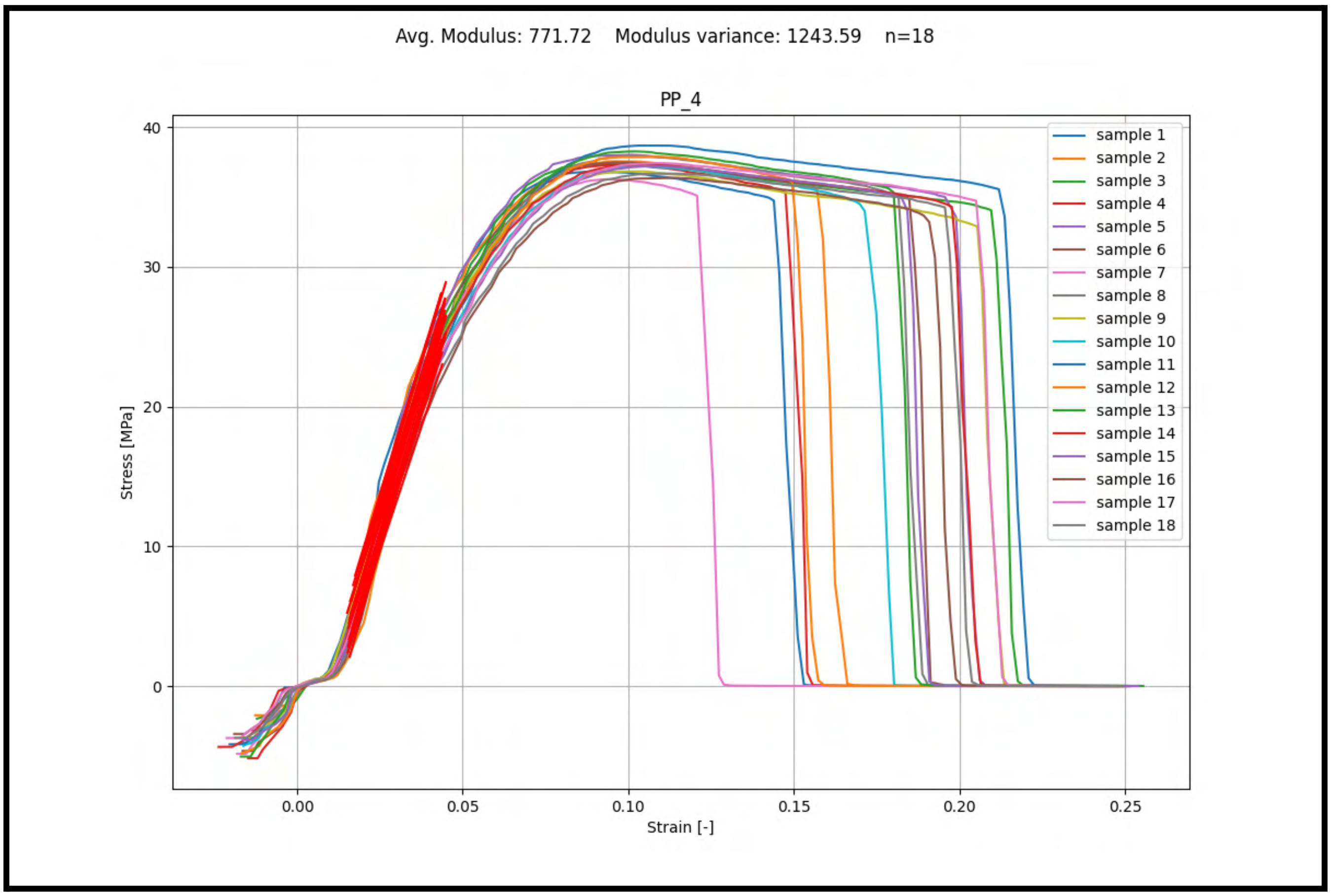
Avg. Modulus: 966.13 Modulus variance: 4247.34 n=14
HIPS_4
Stress [MPa]
Strain [-]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 13
sample 14

PP


Avg. Modulus: 853.12 Modulus variance: 1525.52 n=11
PP_1
Stress [MPa]
Strain [-]
sample 1
sample 2
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12


Avg. Modulus: 870.26 Modulus variance: 1360.48 n=17
PP_2
Stress [MPa]
Strain [-]
sample 1
sample 3
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 13
sample 14
sample 15
sample 16
sample 17
sample 18
sample 19
sample 20


Avg. Modulus: 797.15   Modulus variance: 1488.81   n=12
PP_3
Stress [MPa]
Strain [-]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 13
sample 14
sample 15
sample 16


Avg. Modulus: 771.72   Modulus variance: 1243.59   n=18
PP_4
Stress [MPa]
Strain [-]
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample 8
sample 9
sample 10
sample 11
sample 12
sample 13
sample 14
sample 15
sample 16
sample 17
sample 18