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Recycled Printer Filament

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EXAMINING THE EFFECT OF RECYCLING ON PLA FILAMENT

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Abstract

The purpose of this research is to examine the effects of recycling PLA filament for 3D printing on its material properties. After examining these effects, PLA and carbon fiber additives were mixed with recycled PLA pellets in different ratios to attempt to regain material properties lost in the recycling process. To complete these findings, an experiment was design and executed.

The research found that tensile strength during multiple iterations of recycling remained mostly unaffected, however, the strain degraded exponentially. In the PLA additive study, high ratios of PLA additive were able to increase the strength and strain properties of the material. In the carbon fiber study, the strength and strain properties could not be restored.

Acknowledgements

We would like to express our deep appreciation for our research professor, Dr. Kannan for his continual support, guidance, and encouragement. We would also like to thank Aaron Trexler, Senior Engineering Technician, for all of the technical support he provided for us and users of the 3D printing lab. We couldn't have done our work without your expertise. Finally, we'd like to thank the graduate students and student assistants that help run the equipment in ASEC basement.

Contents

1. Introduction

The College of Engineering and Polymer Science has 18 3D printers in it's 3D printing lab. In a 2-month study of the lab, over 32lbs of waste was collected, comprising of failed prints, unneeded prints or support materials. Despite PLA being biodegradable, this required certain conditions. It will most often just sit in the landfill. If it does degrade, it leaves behind heavy trace metals which are very harmful to the environment.

The purpose of this research project is to examine the effects of recycling PLA filament on it's material properties for 3D printing. An experimental procedure was designed for 3 studies. The first study was to understand the degradation of material properties after several iterations of recycling. The main issues that are faced when recycling PLA is that the ductility decreases as the number of recycling iterations increases. Strength is not as greatly affected. To explore this problem, we added unrecycled PLA and Carbon Fiber in separate studies to the recycled filament to attempt to restore some of the ductility to the filament.

Many of the 3D printing done in the 3D printing lab are prototyping or class projects. These types of prints do not necessarily need to have the best material properties. This allows for the opportunity for the use of recycled filament. Money and material can be saved by using recycled material. Creative projects are another great opportunity to use recycled material. By establishing a robust recycling system, the university can reduce its carbon footprint.

2. Experimental Strategy

The experiment was split into three distinct phases: Iterations of Recycling, PLA Additive, and Carbon Fiber Additive. For each of these studies, we used the ASTM D368 tensile testing standard to determine the ultimate tensile strength of the material along with strain the material experienced to measure its ductility. To perform these tests, we printed out PLA into dog-bone shapes with Ultimakers in the 3D printing lab. The Instron machine in ASEC 1B was used to perform tensile testing. A testing method was set up with a speed of 3mm/minute. This speed is within the range set by the ASTM D368 standard. The dog-bones were run till failure. The raw data was then transferred to a USB drive, where the necessary calculation was done on an excel file to finalize the data.

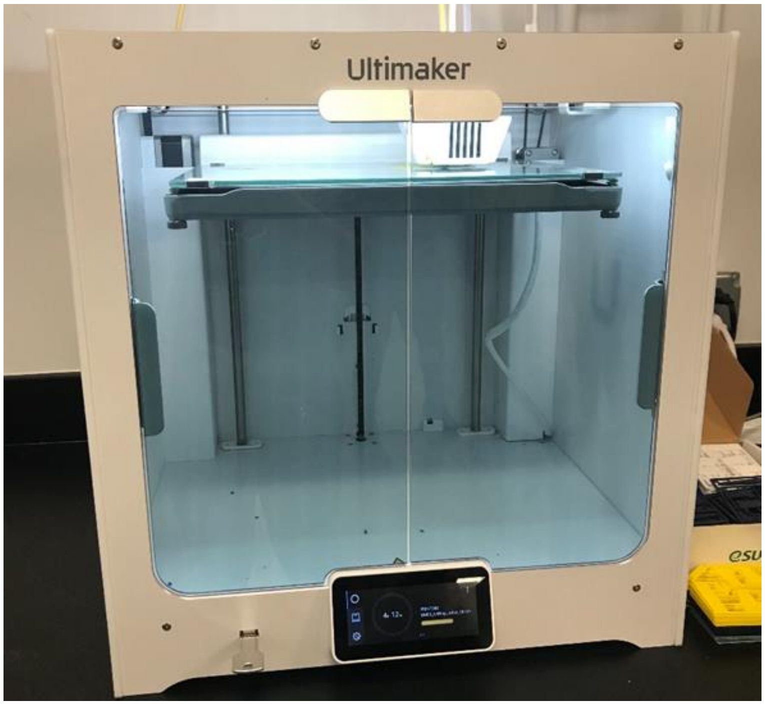

Figure 1: 3D printing test dog bone samples

The Filabot recycling system was used in this project. The system consists of 4 separate machines. The process can begin in two places. When recycling printed specimens, the Filabot Reclaimer was used to break prints into pellets. Alternatively, the Filabot Pelletizer can be used to pelletized filament strands. Next, the pellets enter the Filabot EX2, where the temperature, and extrusion speed where optimized to extrude the pellets into filament. From the extrusion nozzle, the filament goes over the airpath to begin to cool. The speed of the fans can change for different applications. Before entering the last machine, a separate inline measuring system was attached to the spooler. This allows a digital display to track filament diameter. For the application of this project, filament was to be printed between 2.75mm and 3.00mm, and an optimal diameter of 2.85mm. The filament then is pressed and spooled in the Filabot Spooler. The spooling function was not used in this project because the tension of the filament caused the motor of the spooler to stop rotating. Specifications for each study can be found in appendix A.

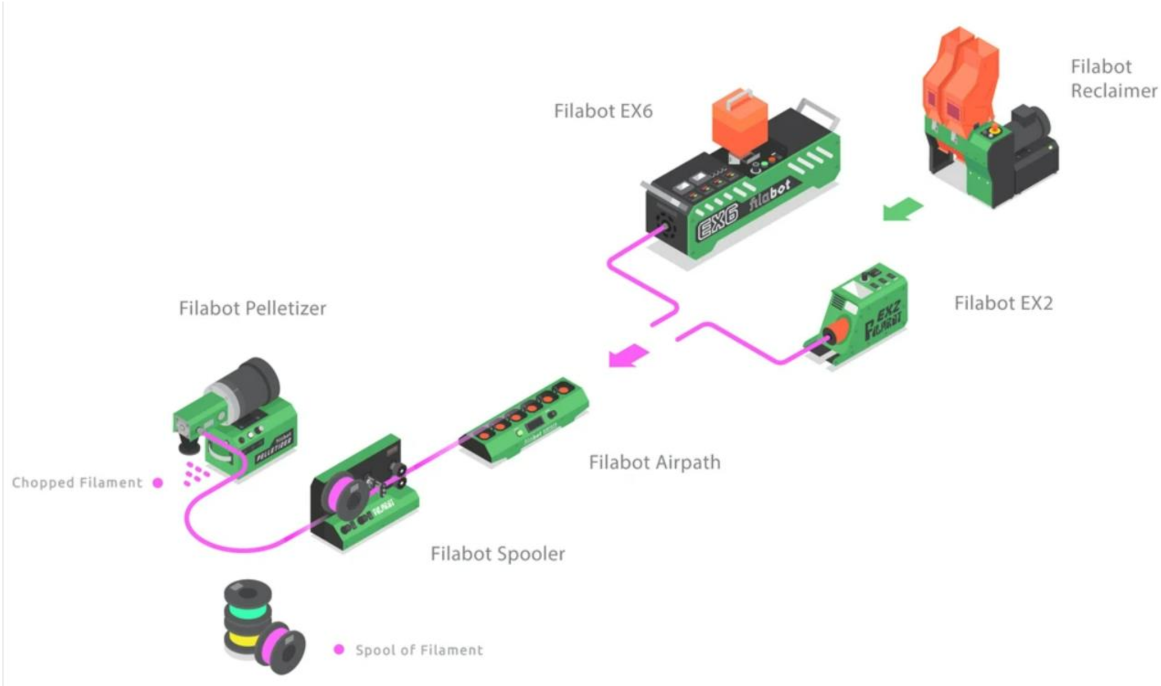

Figure 2: Filabot Recycling System

2.1 Iterations of Recycling

A roll of store-bought PLA filament was used to print dog bone samples. These samples were tensile tested. These are the control samples. The tested and broken samples were the broken down further into pellets and put through the recycling system and made into filament. This filament was used in the 3D printer to make dog bone samples. These samples were tested and the process was repeated for 4 iteration of recycling of the PLA. The tensile test data was analyzed and the strength and stain properties were compared to the control results.

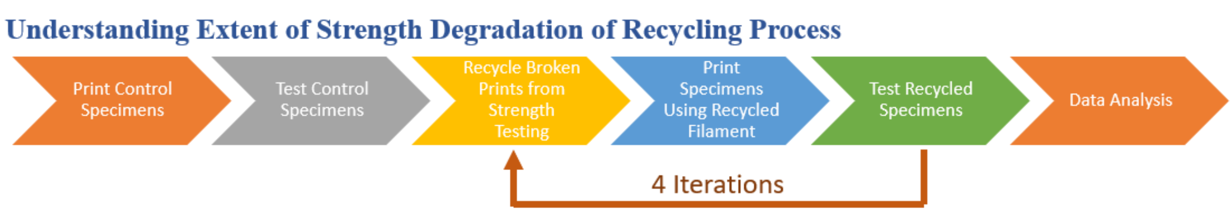

Figure 3: Summary of Design Plan

2.2 PLA Additive Study

Unrecycled pellets were used to make a roll of filament and this filament was used to print dog bone samples. These are the control samples. After being tested, the samples were broken down and recycled into filament. This filament was used to print samples. This is the recycled once data set. These samples were tested and broken down into pellets. The recycled pellets were mixed in 3 ratios, 60% unrecycled/raw pellets to 40% recycled pellets, 70% unrecycled/raw pellets to 30% recycled pellets and 80% unrecycled/raw pellets to 20% recycled pellets. The different ratio of pellets were extruded, printed and tested. The material properties of the ratio samples were compared to the unrecycled control and the recycled once samples.

2.3 Carbon Fiber Additive Study

The control and recycled once data were used from the PLA additive study. Recycled pellets were mixed in 3 ratios, 50% carbon fiber pellets to 50% recycled pellets, 60% carbon pellets to 40% recycled pellets and 70% carbon fiber pellets to 30% recycled pellets.

2.4 Verification

Two tests were conducted prior to the beginning of execution of the design plan to verify the viability of the plan. Sample dog bones were printed to ensure the desired shape, size, and print quality. These samples underwent strength testing to ensure the samples performed correctly to get the results needed.

3. Process Observations

3.1 Iterations of Recycling

A control set of values first had to be set up to have a comparison for the numerous recycled iterations. At the time of starting this control study, we had still not received the Filabot recycling machine and were only able to create and test control samples. Therefore, the control sample size ais very large when compared to the other tests. Once the recycler had been delivered, the group then had to learn how to use the system. When practicing, the team used unrecycled pellets. When the study began and recycled pellets began to be used, we had to adjust settings greatly because the recycled behaved differently.

3.2 PLA Additive Study

The biggest challenge also led to rather large change in our approach. The previous rounds of PLA we were using was not mixing well with the fresh PLA pellets we were given. It would usually lead to inconsistent filament thickness that was outside the margins of error, or in the worst case clog the extruder. This caused a heavy setback. To overcome this compatibility, issue the group extruded and turn some of the fresh PLA pellets into filament and recycled it, creating a new set of recycled filament to mix with our fresh PLA pellets. With this new strategy in motion, the group did had to create a new control for this phase.

3.3 Carbon Fiber Additive Study

The control data gathered in the previous phase was able to be transferred over to this phase since we used the same recycled filament. There were no further compatibility issues however the issues we ran into where much harder to properly solve. A problem we had been encountering for the entire semester was that there was only a limited number of printers available we had access to, and these printers were also available to everyone on a first come first serve basis. This became much larger problem at the end of the semester since the printing lab was in high use due to senior design projects. This contributed to a lot of strain on the 3D printing nozzles causing a lot of prints to fail prematurely. We had to be aggressive in this scenario to get a printer and relied on Aaron a few times to set up prints for us to ensure we received enough dog-bone samples to test. Because of this this phase of the study has the least data and the most uncertainties associated with it.

4. Equipment

Equipment was provided by the College of Engineering and Polymer Science and most materials and equipment were purchase prior to this research project. The only purchase made for this project was Carbon Fiber PLA pellets. The theoretical costs of the project were calculated if equipment was not already readily available.

Theoretical Material Costs	
Item	Cost
Filabot Recycling Machine	$14,399
Instron E3000 + Bluehill	$99,000
Cura	Free
Ultimaker Printer	$6,355
Carbon Fiber Pellets (2x)	$50
PLA Filament Spool (2x)	$50
Total	$199,854

Figure 4: Theoretical Material Costs

5. Results

5.1 Iterations of Recycling

The iterations of recycling study examined the average tensile strength and strain during each iteration of recycling. The number of tested samples decreased for most iterations. This was due to printing issues, testing machine issues and loss of filament during the recycling process.

Iteration of Recycling	# of Samples
0 (Control)	20
1	9
2	7
3	8
4	4

Table 1: Iterations of Recycling Sample Size

The average maximum tensile strength of all iterations was 44.19 MPa with a standard deviation of 3.4 MPa. These results show that the iterations of recycling have little effect on the maximum tensile strength of the PLA plastic. Each iteration of recycling had very low standard deviations. This data had very low variation.

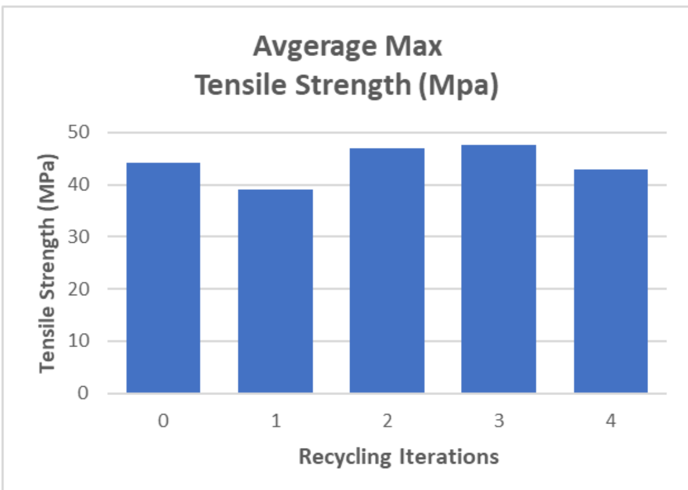

Figure 5: Iterations of Recycling Average Maximum Tensile Strength

Iteration of Recycling	Standard Deviation
0 (Control)	3.94
1	4.17
2	5.42
3	3.94
4	3.64

Table 2: Iterations of Recycling Average Maximum Tensile Strength Standard Deviation

There was a significant degradation in strain after iterations of recycling. The strain of the samples begun at 101.4 με before recycling and after 4 iterations had a strain of 19.11 με. The degradation followed an exponential decay fit line, with a high R^2 value of 0.9603. The standard deviation in each iteration were not similar. The 1^{st} iteration of recycling had the highest standard deviation of 39.17 με and the 4^{th} iteration had the lowest standard deviation of 1.41 με. During testing, it was observed that each iteration, the plastic became increasingly brittle and more difficult to print with. As the iteration increased, we noticed more print failures when printing the dog-bones.

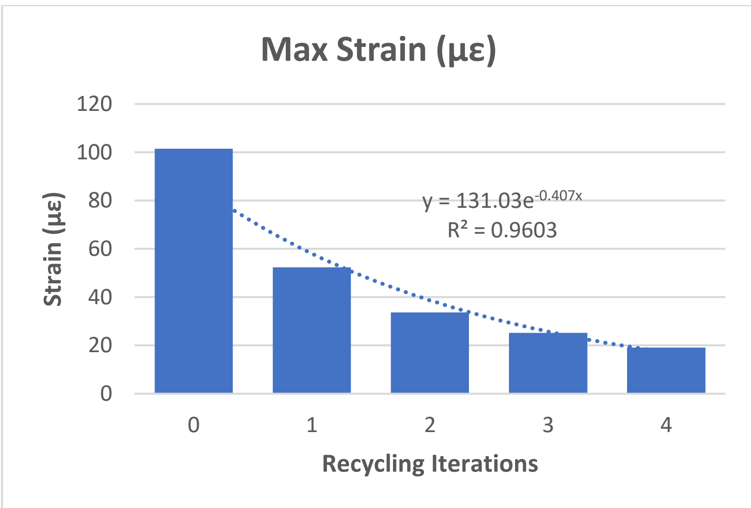

Figure 6: Iterations of Recycling Maximum Strain

Iteration of Recycling	Standard Deviation
0 (Control)	15.46
1	39.17
2	9.28
3	4.16
4	1.41

Table 3: Iterations of Recycling Maximum Strain Standard Deviation

5.2 PLA Additive Study

The iterations of recycling study examined the maximum tensile strength, and strain during each iteration of recycling. Due to complications with recycling and printing, a small sample size was used with 4 or 5 samples tested for each ratio. The different ratios were compared against the recycled once and unrecycled data.

Only the 60/40 and 70/30 raw to recycling filament ratios were able to regain the maximum tensile strength of the unrecycled filament. The 80/20 had an improved tensile strength from one iteration of recycling, but it did not regain to strength of unrecycled filament. There was little variation in maximum tensile strength, with all standard deviation under 1 MPa. It was concluded that adding unrecycled filament pellets to recycled pellets in the right ratio can restore the maximum tensile strength.

PLA Additive Study	
	Maximum Tensile Strength (MPa)
Unrecycled	57.970
Recycled Once	43.289
60/40	59.130
70/30	59.637
80/20	53.332

Table 5: PLA Additive Study Maximum Tensile Strength

Recycling Ratio	Standard Deviation
Control	0.07
1 Iteration	0.73
60/40	0.07
70/30	0.61
80/20	0.78

Table 5: PLA Additive Study Maximum Tensile Strength Standard Deviation

None of the ratio samples were able to regain the strain of the unrecycled samples, but they all performed better than the recycled once samples. It is difficult to regain the strain of recycled PLA materials. The largest ratio of raw pellets was able to improve the strain the most. The was a decent amount of variation in the strain data.

PLA Additive Study		
	Strain (με)	Improvement
Unrecycled	39.564	-
Recycled Once	31.288	-
60/40	35.827	12.7%
70/30	31.321	0.1%
80/20	31.962	2.1%

Table 6: PLA Additive Study Maximum Strain

Recycling Ratio	Standard Deviation
Control	3.94
1 Iteration	4.17
60/40	5.42
70/30	3.94
80/20	3.64

Table 7: PLA Additive Study Maximum Strain Standard Deviation

5.3 Carbon Fiber Additive Study

Adding carbon fiber did not fully regain the maximum tensile strength in any of the ratios, but all samples were better than the recycled once sample. There was little variation in the data as the standard deviation for all tests were relatively low.

Carbon Fiber Additive Study	
	Maximum Tensile Strength (Mpa)
Unrecycled	57.970
Recycled Once	43.289
50/50	47.430
60/40	50.524
70/30	53.855

Table 8: Carbon Fiber Study Maximum Tensile Strength

Recycling Ratio	Standard Deviation
Control	0.90
1 Iteration	0.73
50/50	0.90
60/40	1.71
70/30	0.40

Table 9: Carbon Fiber Study Maximum Tensile Strength Standard Deviation

The 60/40 ratio sample was slimly able to achieve a strain value close the unrecycled sample. The 50/50 and 70/30 samples only achieved a strain better than the recycled once sample. We suspect that the reason the 60/40 results performed better is the very large variance in the data, seen in the standard deviation of 11.58. With the large standard deviation, it is hard to say exactly which ratio of new pellets improved the strain the most.

Carbon Fiber Additive Study		
	Strain (με)	Improvement
Unrecycled	39.564	-
Recycled Once	31.288	-
50/50	34.169	8.4%
60/40	40.224	22.2%
70/30	35.503	11.9%

Table 10: Carbon Fiber Study Maximum Strain

Recycling Ratio	Standard Deviation
Control	3.94
1 Iteration	4.17
50/50	2.05
60/40	11.58
70/30	5.19

Table 11: Carbon Fiber Study Strain Standard Deviation

5.4 Results Discussion

Strain was the most effected material property in recycling. The source of this is believed to be due to the polymer strands in the material. During the recycling process, the polymer links are shortened. When subject to tension, the polymer strands will break sooner because they are shorter and have less distance to stretch and plastic. This phenomenon can be seen in the stress stain curve below. The recycling process shortens the distance between the yield strength and ultimate strength, resulting in a shorten plastic strain.

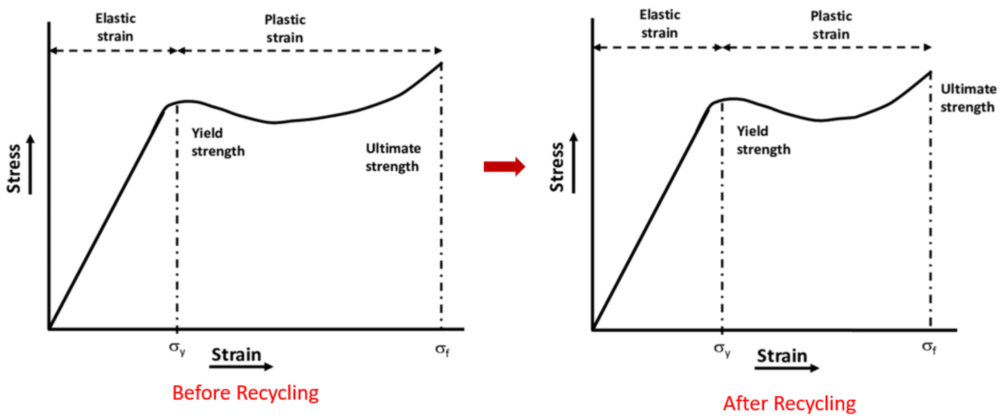

Figure 7: Effect of Recycling on Stress Strain Curve on Plastic

6. Conclusion

As seen by the results above, while the ultimate tensile strength of PLA does not change much when repeatedly recycled, the strain undergoes exponential decay causing the material to become very brittle. Additionally, we saw that introducing a certain ratio of carbon fiber or fresh PLA can help or possibly return the ductility of the plastic, while other ratios due very little.

6.1 Accomplishments

As a result of this project, several goals were accomplished. The team was able to understand the nuances of the recycling systems and communicate the knowledge to faculty for future use. The team was successful in designing and executing an experimental strategy. The data from this experiment gives 3D printing faculty knowledge of the material properties of recycled materials. From a team perspective, the group gained valuable experiences and lessons in communication, time management, planning and deepened their understanding of recycling and material properties.

6.2 Uncertainties

Any measurement made will have some level uncertainty in it since the devices used for measurement do not have a precision of infinity and the most common measurements made were one for area. These measurements were done with a caliper which measured to two decimals points past zero. Some ways to combat this uncertainty was by making several measurements of the dog-bones and then averaging them to get closer to the actual lengths. A much larger and more complicated uncertainty lied in how the printers operated. Towards the early parts of the experiment the printers were consistent with their prints and almost never failed mid print. However, as the material was recycled more and more and the printers got used more and more, it led to them failing mid print rather commonly. This usually led to the prints either skipping parts of a layer or entire layers all together which introduces gaps in the geometry that were either very difficult or near impossible to measure and could not be done with as high as precision due to calipers being a poor tool for this kind of job. This issue was especially prevalent in the carbon fiber section of the study which likely led to the higher standard deviations found in that area along with the overall lower Ultimate tensile strength.

Another issue that leads to heavy uncertainties in the results would be the fact that the Filabot machine is used for research by other groups. Another group used the machines to recycled CD material. This often left the granulator and extruder of the Filabot heavily contaminated with other material that could affect the material properties of the PLA.

Figure 8: Contamination in Extrusion Process Resulting in Melting of Plastic

A way to combat these issues would be with more precise measuring equipment and equipment more suited to measure small gaps in dog-bone geometry. Additionally, if the group had had their own printer that could only be used by them it likely would have put less pressure on the printer and allowed for more clean prints. Additionally, the contamination issued would be much less of an issue if only one group was using the Filabot during research, though other types of contamination like dust would still remain.

6.3 Ethical Considerations

A big part of 3D printing is support generation, which end up being thrown out along with failed prints. As 3D printing becomes more of a mainstream tool, these wastes which are seen as insignificant end up becoming one of the biggest sources of waste in the industry. 3D printing has grown to affect every industry, creative and non. In a study done by Filamentive, it was found that on average each 3D printer ends up using 26.5lbs of filament annually, 10% of which becomes waste. Grand View Research found that in 2021, 2.2 million 3D printers were sold globally. Even if we are to assume that 25% of those printers are in use that still ends up creating over half a million pounds of waste annually. Another factor that comes into play is how, for PLA to be biodegradable, the conditions it must be in are almost impossible to create. The enzyme Proteinase K that is a catalyst to hydrolyze PLA, is very rarely available in the environment. Other than that, the material would have to be in a moisture rich environment that is above 140F to begin the self-hydrolyzation process of reducing its molecular weight from a polymer to a lactic acid. Even in such circumstances when the PLA is able to degrade it happens over such an extended period of time that it ends up leaving behind trace metals. By using a recycling system, the University has the opportunity to reduce it's carbon footprint and avoid a lot of the devastating effects of throwing away PLA plastics.

6.4 Future work

There are many ways this project could be advanced with further work. Restoration of strain could be restored with the exploration of new additives, like Plastistrength®. This additive is for 3D printing and helps improve quality of the material. Further work could also be done with different ratios of raw to recycled pellets and exploration of printing properties, like temperature, layer thickness, infill pattern, etc.

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Appendix A: Machine Settings

Iterations of Recycling Study	
Extrusion Temperature	177.0 F
Extrusion Speed	+
Airpath Speed	98
Drive Speed	1 ¾ turn

PLA Additive Study	
Extrusion Temperature	180 F
Extrusion Speed	+ and a tick
Airpath Speed	95
Drive Speed	2 turn

Carbon Fiber Additive Study	
Extrusion Temperature	180 F
Extrusion Speed	+ and a tick
Airpath Speed	95
Drive Speed	2 turn