Analysis of the Use of Waste Material in 3D Printing

A Senior Project
presented to
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California Polytechnic State University, San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Science

by
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Abstract

Globally, only 9% of plastic by mass is recycled. Allowing consumers to directly convert polyethylene terephthalate (PET) waste into 3D filament can increase the recycling rate by reducing contamination and costs from traditional large-scale recycling methods. This was tested by heating strips of PET to various temperatures within its glass transition region and pressing a roller with a 1.75 mm indentation against it to observe strip deformation. PET was also placed in a hemispherical well with a 1.75 mm diameter hole at the bottom and heated above its melting temperature to determine the mass of PET required to extrude 3D printer filament using gravity. The filament had the best properties when produced at 175 °C, and 12.5 g of PET were required for gravity extrusion in a 5 cm diameter well. Additionally, replacing polylactic acid (PLA) infill material with a wheat straw pulp can reduce plastic consumption for 3D printed parts while still providing structural support. The viability of this substitution was observed by compression testing a 3D printed PLA frame with 50% wheat straw infill by volume. The results were compared to a PLA frame with equivalent PLA infill by mass and a PLA frame with no infill. Wheat straw was determined to be a viable alternative for PLA infill in parts with low strength requirements; however, shrinking during drying made accurate infill printing difficult.

TABLE OF CONTENTS

Introduction

Polyethylene terephthalate (PET) is one of the most commonly used polymers in the world with an annual consumption of over 3.1 million tons being used in everything from plastic bottles to toys each year in the United States alone.[1] As a result, it makes up a significant portion of the plastic waste polluting the environment with 14% of all litter by mass being PET bottles.[2] Fortunately, unlike thermoset polymers which are unrecyclable, PET is a thermoplastic meaning it can be melted down and reformed into a new product. At full scale, this process consumes 76% less energy than using virgin material.[3] Collecting, cleaning, and sorting recyclable materials at a large scale, however, can be time-consuming and costly which is a major contributing factor to the fact that only 9% of polymers by mass are recycled.[4]

To address this issue, the concept of scaling down the recycling process to the consumer level was developed, which will eliminate the mixing and contamination of plastics in the recycling bin. However, scaling down conventional plastic recycling and part production methods (injection molding, blow molding, etc.) would be expensive and not practical because they can only produce one part design at a time. A solution to this would be to convert plastic waste (PET bottles) into a form that is usable by 3D printers. 3D printers are able to produce a wide variety of parts by depositing plastic one layer at a time. Also, because the 3D printing industry is rapidly expanding with a current global market size exceeding $11 billion and projected annual growth of 14% for the next 7 years,[5] an increasing number of plastic consumers will have the ability to reuse their waste. The goal of this project is to directly convert plastic waste (PET plastic bottles) into a usable 3D printer filament that can be used to print new parts. This design will work by cutting a plastic bottle into a thin continuous strip and molding that strip into a filament at a temperature above its glass transition temperature and below its melting temperature.

An additional area of waste that was examined was straw products. Each year, 800 million tons of rice straw are burned or buried in the soil which significantly deteriorates the local air quality and releases harmful greenhouse gases.[6] A unique property that many straws have, however, is the ability to be formed into a pulp by removing the silica and lignin which support the straw's structure.[7] Once these are removed and the pulp is rehydrated, it becomes moldable and can be plastically deformed. It will then retain its shape once dried. Because of this property, it was postulated that the pulp could be used in 3D printing by depositing it a layer at a time. An application where this may be beneficial is in the infill of 3D printed parts. Most 3D printed parts consist of a shell with a pattern providing mechanical support printed inside (infill) that is mostly air. Infill is usually made of the same material as the rest of the part. If the PET infill material is replaced with waste straw pulp, it would reduce the amount of non-biodegradable material in the part. In order for this to be a viable option, the straw infill must be able to support a load comparable to a part with a PET infill. Due to the difficulty of obtaining rice straw in small quantities, and because wheat straw waste is much more common in the United States, tests were conducted with wheat straw as a proof of concept. For these ideas to be worthwhile, they must provide feasible solutions to the world's recycling problem without significantly detracting from 3D printed part's performance or production speed. Also, in the case of the recycled filament production method, it must produce a filament more efficiently and/or with better mechanical properties than a scaled-down conventional extrusion filament production process.

Background

i. PET Filament

The proposed filament is intended to be used in a fused deposition modeling (FDM) 3D printer. An Ender 6 3D printer was used for this project. In FDM 3D printers, a long continuous filament, often made of plastic, is pulled by a driver to a heated nozzle (Figure 1).

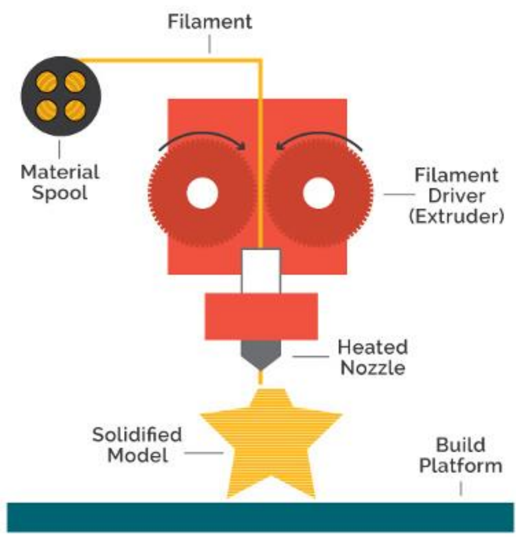

Figure 1. Diagram showing the fused deposition modeling (FDM) 3D printing process.[8]

The temperature of the heated nozzle is maintained above the melting temperature of the filament material (T_m). A layer of the model being printed is then produced by moving the nozzle in the horizontal XY plane to deposit the melted material in the appropriate locations. When the layer is completed, the build platform (or nozzle) moves in the Z-direction a distance equal to the thickness of one layer and the nozzle begins to print the next layer. This process is repeated until the part is complete.

There are a number of requirements that need to be met for a material and a filament production process to be a viable option to produce filament for consumer-grade FDM 3D printers. First, the material used has to be meltable, preferably more than once without significantly degrading. This means that in the case of polymers, it cannot be a thermoset. A second requirement is that the process must be able to form the material into a “continuous” filament which, for the purposes of this study, will be defined as being at least 2 meters in length. This filament must also have a consistent diameter of 1.75 mm with a tolerance of +/- 0.1 mm so it can be used by existing filament drivers and nozzles which are already set up to take filament of this size. PET fits these requirements and both virgin and recycled PET are currently used to make 3D filament. The proposed filament production process starts with a continuous strip of PET that is produced by rotating a cylindrically symmetric PET bottle while a stationary razor blade cuts the PET with a consistent width from the bottle (Figure 2). This process is similar to an apple peeler removing the skin of an apple.

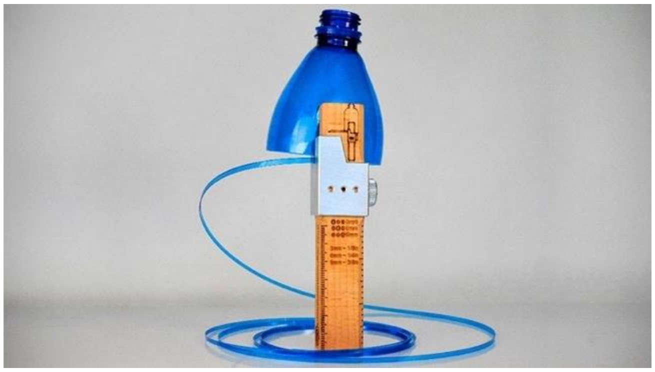

Figure 2. A continuous strip of PET being cut from a bottle with a stationary razor blade.[9]

This strip with a rectangular cross-section will then be heated to a temperature within its glass transition region and fed between two shaping wheels to mold it into a circular cross-section (Figure 3). Each wheel will have a semi-circular indentation around its circumference with a diameter of 1.75 mm. The shaped filament will then be air cooled, to prevent deformation due to handling, and then fed into the filament driver and used to print a new part.

There are two major differences between conventional filaments and the proposed filament. The first is that the proposed filament will be developed by the consumer and not in large-scale processing plants. The second significant difference is that for the proposed design, the plastic will not reach a temperature above T_m until it is being printed. Traditional filament production methods use melt extrusion which reaches temperatures above T_m during filament production.

To examine the viability of the proposed filament production method, two experiments will be conducted. In the first test, strips of PET will be heated to temperatures in the lower, middle, and upper portion of the glass transition region and deformed against a flat surface with a single roller (Figure 4).

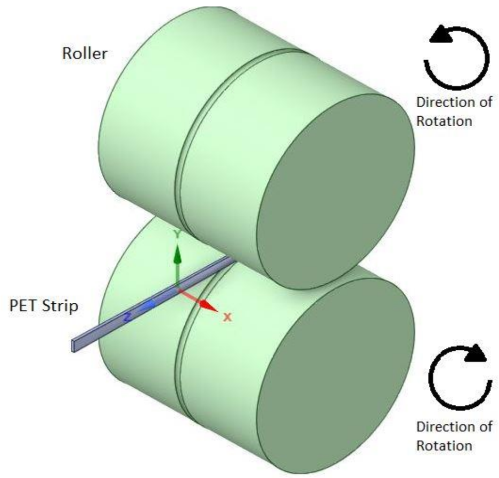

Figure 3. Two shaping wheels designed to change the cross-section of the strip from a rectangle to a circle.

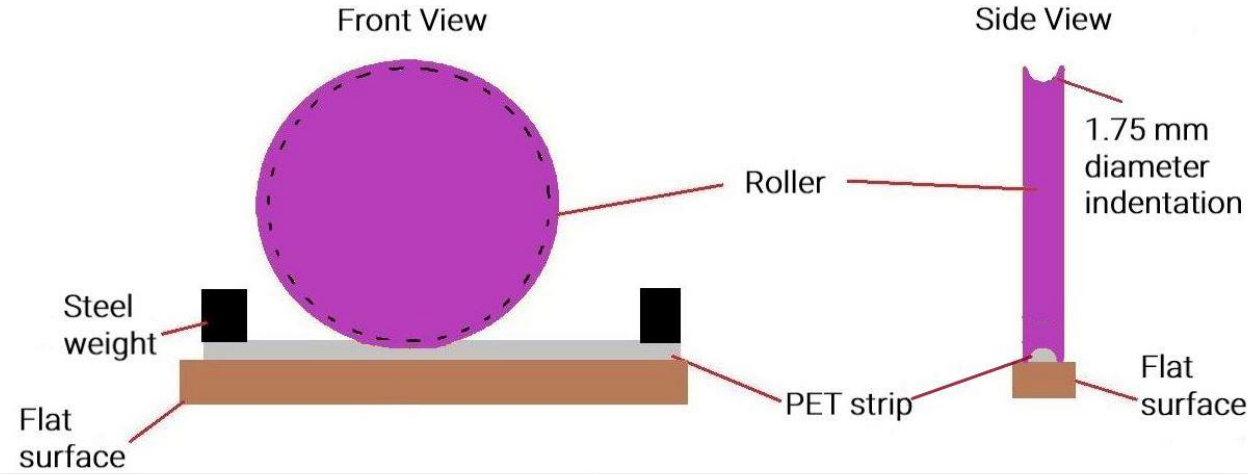

Figure 4. Front and side views of proposed roller model to test whether deformed PET strips produce 1.75 mm diameter filament within the desired tolerance at various temperatures.

The roller's edge will have an imprint of a 1.75 mm filament with a semi-circular cross-section. This experiment will be conducted to determine whether deformed PET strips can produce a 1.75 mm diameter filament within the desired tolerance (+/- 0.05 mm) at various temperatures within the glass transition region.

In the second test, PET strips will be placed in a small well with a 1.75 mm hole at its lowest point (Figure 5). The PET will then be heated above T_m to determine if filament formation by extrusion using gravity is a viable filament production method. The benefit of using only gravity to extrude the filament is that there would be no moving parts required in the filament production process which increases its reliability.

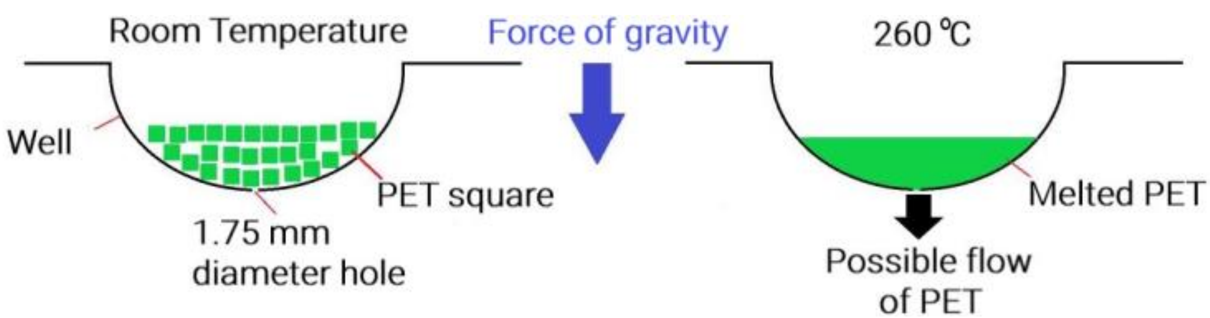

Figure 5. Diagram of gravity extrusion method which is meant to determine if 5 g of melted PET can be extruded by the force of gravity alone.

ii. Wheat Straw

To understand the theory behind 3D printing paper pulp, it is beneficial to learn how the pulping process works. This is done by taking a fibrous plant material (often wood or straw) and boiling it in an 11 g/L solution of NaOH in water for 2 hours which removes the lignin.[10] Lignin is a mechanically reinforcing polymer within the plant tissue so removing it leaves the cellulose, hemicelluloses, and the remaining organelles.[11] As a result, the straw becomes much less rigid, and after draining the NaOH solution, becomes a “mush”. This mush is then pressed through a 1/20th inch mesh screen to remove any remaining large particles.

To determine the viability of the proposed straw infill, this screened mush was deposited layer by layer into 50 mm x 50 mm wide and 25 mm high PLA frames to produce an infill. A 50% wheat straw infill by volume was compression tested and the results were compared to a 12.7% PLA infill sample (which contained an equal amount of material by mass as the wheat straw infill sample) and a 0% infill sample (Figure 6).

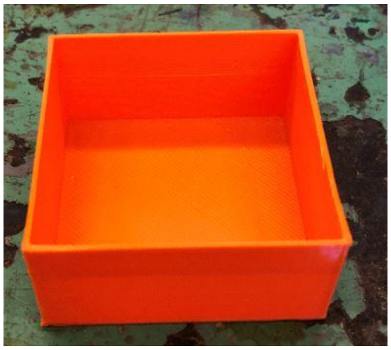

Figure 6. 50 mm x 50 mm x 25 mm 3D printed PLA frame with no infill.

Methodology

i. Heated Plastic Strip and Roller Experiment

To determine the viability of rolling a strip of PET from a plastic bottle into a continuous filament, two rollers were made. This was done by using Craftsmart® polymer clay, which was molded into discs with a diameter of approximately 5 cm and a thickness of approximately 2 cm. A 1.75 mm diameter filament was then held taut while the two clay cylinders were rolled against it to impress the circular cross-section of the filament along the edges of the rollers. Using two rollers ensured that when pressed together along their edges, the rollers would produce a gap with the diameter of the desired filament. However, to make testing easier, only one roller was used to deform the PET strip. A 9 inch long bolt was then pushed through the center of each roller (to serve as a grip) and the clay was cured at 135 °C for 90 minutes (Figure 7).

Figure 7. Side view of one clay roller with filament indentation and 9 inch bolt through its center.

The PET sample strips were cut from Dasani 500 mL water bottles. The label was removed first and then each strip was cut from the same location on the bottle, approximately 10 cm above the bottom of the bottle. The strip was then trimmed to be 1 cm wide and 7 cm long. The strips were then placed on aluminum foil and set on an aluminum tray. Steel weights were then placed on the ends of the strip to hold the strip in place as it was heated, and the tray was placed in a Black+Decker TO1313SBD toaster oven for 20 minutes to ensure it reached the target temperature. Three experiments were done at each temperature setting (95 °C, 175 °C, and 230 °C) which are in the lower, middle, and upper regions of PET's glass transition temperature region, respectively. These temperatures were also chosen because they correspond to pre-set dial locations on the oven allowing for more consistent heating conditions. After the sample had been heated for 20 minutes, the tray was quickly taken out and the clay roller was repeatedly rolled on the softened PET strip until it cooled to room temperature. The strips cooled to room temperature relatively quickly (approximately 5-10 seconds) so only 10 passes could be conducted on average before no more deformation of the strips occurred.

ii. Gravity Extrusion Test

Well above T_g, thermoplastics are much more ductile meaning that it is easy to deform them. To limit deformation due to excess contact with the filament, the feasibility of using gravity to extrude the filament was tested. This was done by using a Teflon-coated steel cake pop baking pan with hemispherical wells, and cutting two of the wells from the rest of the pan. Holes with a 1.75 mm diameter, the same diameter as the filament used in 3D printers, were then drilled into the bottom of the wells. 10 grams of PET squares that were each approximately 1 cm x 1 cm were then cut from the Dasani water bottle and distributed evenly to both wells. A 2 well x 2 well section of the pan was then cut out and placed upside down to provide support for the 2 well x 1 well section with the holes drilled in it (Figure 8).

Figure 8. Melt extrusion setup with a 2 well x 1 well pan with 1.75 mm holes drilled in the bottom, placed on an inverted 2 well x 2 well pan.

This also provided a free space below the hole so any melted plastic had a clear path to flow. The samples were then placed in the toaster oven at 260 °C and allowed to fully melt. Additional PET squares were added in increments of 2.5 g to one well until 12.5 g total were present. No PET was added after 12.5 g because this was the point at which extruded PET was observed below the well. Between each addition of PET, the added material was allowed to fully melt and the extrusion progress was observed for 30 minutes. This test was conducted two times.

iii. Straw Infill Experiment

To produce the wheat straw pulp that would be used as the infill material, EZ-Straw™ brand wheat straw was first cut into 5 cm segments and then washed with tap water to remove contaminants. The straw was then placed on a baking sheet and dried in an oven at 80 °C for approximately 3 hours. Once the blades of straw no longer stuck to one another, they were divided into bunches that each weighed 50 grams. For every 50 grams of straw, 1 liter of solution was prepared which contained 11 grams of NaOH per liter of water. The straw + NaOH solution was then boiled for 2 hours on a hot plate set to 150 °C, with intermittent stirring with a glass rod every 15 minutes. Following this, the straw + NaOH solution was removed from the hot plate, allowed to cool to room temperature, and the NaOH solution was drained into a waste containment bin. The straw was washed with tap water again to cool it back to room temperature and to remove excess NaOH. It was then diced in a 20 oz Oster MyBlend® blender until no straw pieces larger than 1 cm in length could be detected by visual inspection. The pulp was then collected and formed into 5 evenly sized balls that were around 5 cm in diameter and gently squeezed to remove excess liquid until they could maintain their shape. The balls were not simply weighed to obtain the correct material amount because the excess water that was present from the washing and rinsing steps made total mass calculations difficult. Instead, the 50 g of wheat straw that was known to be present in the pulp was divided into 5 equally sized groups to produce pulp with approximately 10 g of wheat straw per ball. These balls were then pressed through a 1/20th inch mesh screen to remove any remaining large particles. The material that passed through the mesh was collected and put into a baker's icing bag with a 2 cm diameter nozzle. The pulp was then extruded into strips and deposited into the 3D printed polylactic acid (PLA) frame with 1.4 mm thick walls (Figure 8). A layer of the straw pulp was deposited in a pattern meant to roughly resemble the 12.7% by volume PLA linear infill pattern (Figure 9).

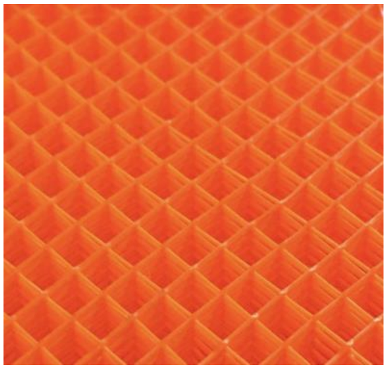

Figure 9. 12.7% by volume PLA linear infill in a 50 mm x 50 mm x 25 mm PLA frame.

Initially, this first layer was partially dried by placing the straw and frame in a furnace at 80 °C for 15 minutes; however, this caused the frame to warp. Another sample was then prepared the same way but allowed to air dry, which took three days (Figure 10).

Figure 10. PLA frame with approximately 50% wheat straw infill.

The PLA had a 12.7% infill density by volume, compared to the 50% infill density by volume of the wheat straw, to ensure the masses of both samples were the same. Because PLA has a density of 1.24 g/cm^3 and wheat straw has a density of 0.3 g/cm^3, to determine the percent infill of PLA that would have the same mass as the 50% wheat straw infill in a 50 mm x 50 mm x 25 mm frame, Equation 1 was used where (V_f) is the volume of the frame, (P) is the percent infill and ρ is the density of the material.

$$(V_f)(P_{PLA})(\rho_{PLA}) = (V_f)(P_{Wheat})(\rho_{Wheat}) \quad (1)$$

This gives a value for P_{PLA} of 12.7% which is the wheat straw infill percentage to compare the two infill materials.

Compression testing was conducted using a Shimadzu mechanical test frame with a 25 kN load cell. This was done by first replacing the upper fixture with a 3 mm thick cylindrical plate with a 7.5 cm diameter circular face to contact the upper surface of the sample (Figure 11).

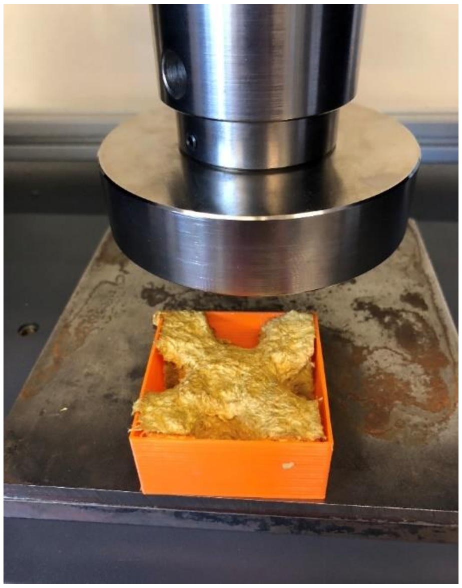

Figure 11. Shimadzu mechanical test frame setup with cylindrical plate crosshead and steel plate base.

The lower specimen holder was replaced with a 15 cm x 15 cm x 1 cm thick steel plate. The emergency stopper was then set to a height around half the height of the sample to prevent damage to the machine. The TRAPEZIUM X software was then opened, a new compression method was selected, and the scale was set to 25 kN. The stroke (or displacement) was set to a 200 mm limit and the compression rate was set to 1 mm/min. This new test method was saved and the force was zeroed prior to commencing the compression test. Next, the saved method was selected again and the specimen's dimensions were entered. The upper cylindrical plate was then brought down to the upper surface of the sample and a preload of 200 N was applied. The force and stroke were zeroed again and the test was run. After the sample failed, the cross-head was raised and the sample was removed. The data was then exported and the next sample was placed in the test frame. This process was repeated for all three samples.

Results

i. Heated Plastic Strip and Roller Experiment

Samples were initially placed on aluminum foil without weights to hold the ends of the strips down. However, after heating at 95 °C for 20 minutes, each sample formed a tightly wound coil that was difficult to unwind and roll. Future experiments included steel weights to hold down the ends of the strips. The plastic samples that were heated to a temperature in the lower part of the glass transition region (95 °C) showed moderate deformation after rolling (Figure 12).

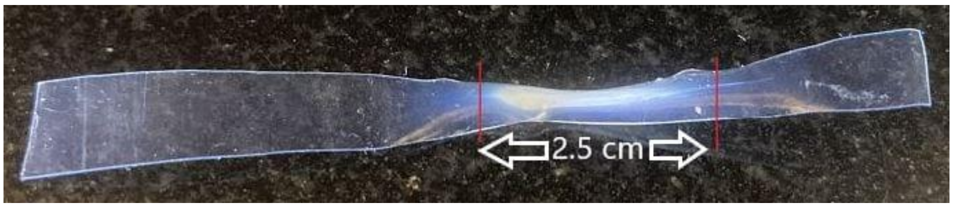

Figure 12. Deformed PET strip after 20 minutes at 95 °C. The area between red lines is the rolled region.

The deformed region (shown between the red lines in Figure 12) displayed a ridge-like curvature with a diameter similar to that of the filament. The area beneath the ridge, however, was still mostly air meaning a solid filament was not fully produced.

The samples that were heated to a temperature in the middle of the glass transition region (175 °C) displayed significant deformation (Figure 13).

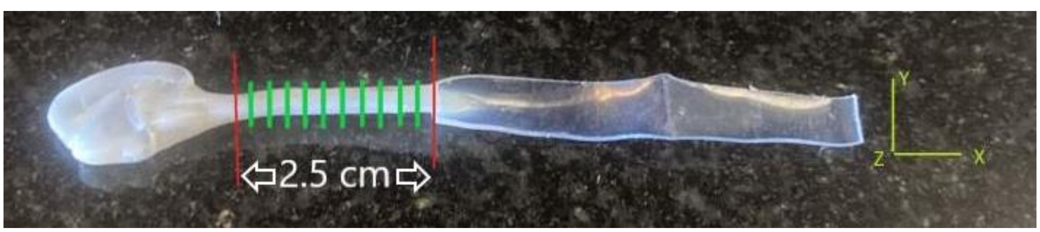

Figure 13. Deformed PET strip after 20 minutes at 175 °C. The area between red lines is the rolled region. The green lines indicate locations where measurements of the diameter of the filament were taken.

The average thickness of the deformed region in the y-direction was 1.5 mm, which is very close to the 1.75 mm target. The 10 measured values which were taken an equal distance from each other in the rolled region (at locations indicated by the green lines in Figure 13) were all within 0.05 mm of the average thickness. The average thickness of the deformed region in the Z-direction was 1.2 mm. Because only one roller was used, the desired thickness was half of the total filament diameter (0.88 mm).

The samples that were heated to a temperature at the upper region of the glass transition region (230 °C) became very sticky and parts of the strip adhered to the roller. This made it difficult to produce filament regions that could be measured.

ii. Gravity Extrusion Test

No PET in either of the two wells made it through the 1.75 mm hole during heating to 260ºC when only 5 g of PET were present in each well. To verify that the PET had been heated enough to flow, the 2 well x 1 well holder was removed from the oven and the plastic was quickly pressed downwards towards the hole. The filament produced can be seen in Figure 14.

Figure 14. A small length of PET (circled in red) extruded from the 1.75 mm hole.

Despite being relatively short (3 mm), the filaments that were produced had an average diameter of 1.8 mm (from a sample size of 4 evenly spaced measurements along the length of the filament), which is very close to the 1.75 mm target.

The PET was then removed and additional PET was added in 2.5 g increments to each of the wells and allowed to fully melt. No extrusion was visible until 12.5 g of PET was present in each well; however, the extrusion rate was slow. After 15 minutes, the filament length was 4 mm. The extended exposure to elevated temperatures had begun to burn the top surface of the PET in the well. After 30 minutes, a strong odor was present and the top surface of the PET was fully burnt (Figure 15). The filament, however, showed no signs of charring.

Figure 15. The burnt upper surface of PET in a well after 20 minutes of exposure to 260 °C.

iii. Straw Infill Experiment

Despite draining excess liquid before deposition, the straw infill material held much more moisture than expected. As a result, the samples were dried for 3 days at room temperature. After this extended drying period, the surface of the infill was yellow rather than brown, indicating that most of the moisture had left the wheat straw pulp. There was also significant shrinkage of the infill during the drying process, which resulted in detachment of the infill from the PLA frame. These gaps were filled in during the drying process with additional pulp which was allowed to dry before mechanical testing took place.

The 12.7% PLA infill sample was tested first and withstood a maximum load of 2700 N before failure. Compression testing was then conducted on the 50% wheat straw infill sample which withstood a maximum load of 1495 N before failure. The 0% infill sample withstood a maximum load of 616 N before failure (Figure 16). Dividing the maximum load by the cross-sectional area of each infill produced maximum stress values of 8.5, 1.2, and 2.1 MPa for the 12.7% PLA, 50% wheat straw, and 0% infills, respectively (Figure 17).

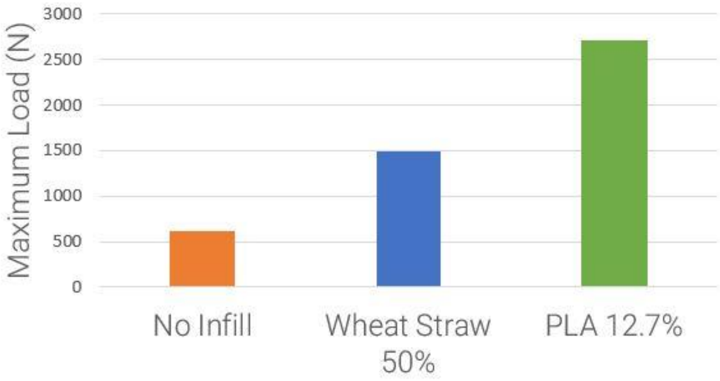

Figure 16. Maximum load before failure on 50 mm x 50 mm x 25 mm PLA frame with various infills.

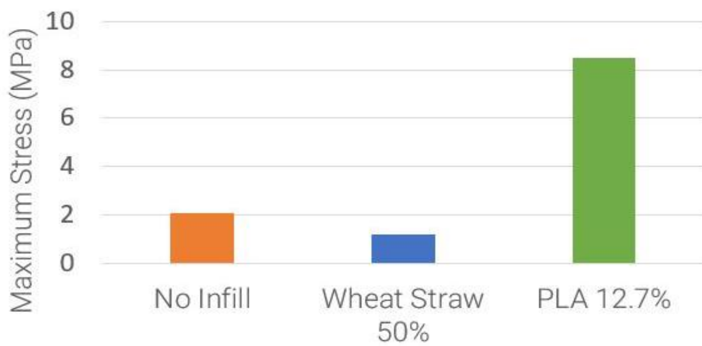

Figure 17. Maximum stress before failure on 50 mm x 50 mm x 25 mm PLA frame with various infills.

Analysis

i. Heated Plastic Strip and Roller Experiment

The problem of the PET strips coiling up is likely because of the discontinuous nature of the samples. All PET bends and deforms when heated, however, in a continuous filament production process, there will be tension between the roller and the plastic bottle which should prevent the strip from coiling. The discontinuous PET strips (without weights) do not have this tension, resulting in coiling.

The PET strips heated to 95 °C did not display any transfer of material from the strip to the roller which is encouraging for filament production. However, only a limited amount of material was able to be deformed due to PET's relatively low ductility at this temperature. A much higher pressure between the rollers may be able to overcome this low ductility; however, forming a continuous solid filament at this temperature does not look like a viable option. This is because in addition to pressing the PET strip into a shape having a circular cross section during rolling process, the PET has to be ductile enough to retain that shape after the pressure from the rollers has been removed. At this low temperature, the PET is barely in its glass transition region, meaning the PET that is pressed together during the rolling process will not adhere to itself to maintain its circular cross section, but instead expand back into a (now bent) rectangular cross section once the pressure from the rollers is removed.

The PET strips heated to 175 °C also did not transfer any material from the strip to the roller but the cross section of the deformed region was solid and semi-circular in shape, which is encouraging for producing a 3D printer filament. The diameter of the deformed strip was close to the desired filament diameter as well. The 0.25 mm difference in diameters may be due to the shrinking of the plastic as it cooled after rolling. PET has a relatively large coefficient of thermal expansion (CTE) of 59.4 $\times 10^{-6}$ K^{-1} compared to other materials like metals, so a change in temperature can significantly change its dimensions.[12] The optimal diameter of the indentation in the roller is likely larger than 1.75 mm. Additional testing will need to be conducted to determine the exact size of the indentation needed in the roller due to the unknown CTE of the polymer clay after curing.

Another contributing factor may be the roller that was used. When manually imprinting the filament shape onto both rollers, more than 50% of the filament (by cross-sectional area) may have been pressed into one roller while less than 50% may have been pressed into the other. This will not be an issue in the full-scale test where both rollers are pressed together. However, for this proof of concept test where only one roller is used, it could significantly change the size of the filament.

ii. Gravity Extrusion Test

The gravity extrusion experiment suggested that liquid PET is too viscous to be pulled through a 1.75 mm hole by gravity alone (at least at a small scale with only 5 grams of PET). To verify this theory, the maximum pressure that gravity can exert on the PET liquid (P_g) can be determined (Equation 2).

$$P_g = \frac{F_g}{A} = \frac{9.81\,\frac{m}{s^2} \times .005\ kg}{\pi \times \left(\frac{1.75 \times 10^{-3}\ m}{2}\right)^2} \qquad (2)$$

where:

P_g = the pressure exerted on the liquid by gravity

F_g = the force of gravity on the liquid

A = the cross-sectional area of the die

This equals 20.4 kPa. To determine whether this is enough pressure to extrude the PET, it must be larger than the minimum pressure required to extrude bottle grade PET, which can be estimated by modeling this process as a billet extrusion[14] (Equation 3).

$$P_{min} = \frac{128 \times L_c}{\pi \times D_c^3 (D_c + 8\alpha)} A_b v_b \eta \qquad (3)$$

where:

P_{min} = minimum pressure required to extrude

L_c = length of the die channel = 2 mm

D_c = diameter of the die = 1.75 mm

α = slip coefficient of the surface = 0.04 for Teflon

A_b = area of the billet = cross-sectional area of the top of the cake pop well = 1.8 x 10^{-3} m^2

v_b = ram speed

η = viscosity of liquid PET used in plastic bottles[15] = 0.8 $\frac{dL}{g}$

To solve for the ram speed, conservation of volume was used by setting the ram speed times the cross-sectional area of the billet equal to the filament production velocity (v_f) times the cross-sectional area of the filament (A_f) (Equation 4).

$$v_b \times A_b = v_f \times A_f \qquad (4)$$

A typical feed rate of PET filament into a 3D printer[16] is 5.6 $\frac{mm}{s}$. Estimating that the "billet" will be melted PET in a cylinder with a cross-sectional area equal to A_b and solving for the cross-sectional area of the 1.75 mm filament, v_b is equal to 7.4 x 10^{-3} $\frac{mm}{s}$. This small feed rate makes sense because of the large cross-sectional area of the cake pop well relative to the cross-sectional area of the filament, and the small feed rate required for the 3D printer.

Inserting this value for v_b into equation 2, a value for P_{min} is determined to be 92.6 kPa. The significant difference between P_{min} and P_g is likely due to the difference in feed rate. Commercial 3D printers have a filament feed rate of 5.6 $\frac{mm}{s}$; however, the observed filament production rate using this gravity feed method was approximately 0.7 $\frac{mm}{s}$. To estimate the minimum amount of PET required to extrude filament at 5.6 $\frac{mm}{s}$ using gravity alone, equation 2 was set equal to P_{min} and used to solve for F_g. This value was then divided by 9.8 $\frac{m}{s^2}$. It was found that 1 kg of PET would need to be melted at all times to continue this production rate which may be difficult in a small-scale extrusion setting. Small-scale filament extrusion using gravity may still be viable if the filament is extruded ahead of time.

The diameters of the filaments produced from the gravity feed method were more accurate than those produced using a roller. This may be because the lengths of the measured filaments were much smaller in the extrusion method. The samples that were measured were too small to be of practical use in a 3D printer and may not be indicative of a longer filament. To determine if this method using a 1.75 mm filament die can produce a continuous filament with the desired diameter, it would be beneficial to run tests with a larger amount of PET which should produce longer filaments.

iii. Straw Infill Experiment

The PLA 12.7% infill sample withstood a much higher load than the 50% wheat straw and 0% infill samples. This was expected because PLA is much stiffer than straw and the adhesion between the PLA layers comprising the infill was much stronger as well. In applications where high strength is not a major concern, however, wheat straw may still be a viable infill option. The 50% wheat straw infill sample withstood a 240% larger load than the 0% infill sample suggesting that the wheat straw infill significantly improves the strength of the part.

The 50% wheat straw infill failed at a much lower stress than the 12.7% and 0% PLA infill samples. This was because the wheat straw infill had a much larger surface area than the other two infill options. While these samples did not have a surface above the infill, most 3D printed parts will, meaning the infill will be completely encased in a shell. As a result, the cross-sectional area of the part in contact with the load will be the same for all three infills, meaning the maximum load is a better indicator of infill performance.

The excessive time required to dry the wheat straw infill makes wheat straw an unattractive option for the fast-production world of 3D printing. This is particularly problematic because one of the main benefits of 3D printing is the ability to quickly produce parts for proof-of-concept tests without having to send build requests to an outside company.

A solution that may allow wheat straw to be used as an infill without being concerned about shrinkage due to drying or long drying times is to mass-produce large sheets of infill and cut sections of these sheets to size to infill parts as needed. This process is similar to the process used to make honeycomb fire-resistant doors[17] and can reduce processing times by printing the infill material ahead of time.

Conclusions

Heating a strip of PET to a temperature in the middle of the glass transition region (around 175 °C) produced the best filament for 3D printers among the temperatures tested because no material was transferred to the roller during deformation, and a strip with a solid cross-section was produced. Additionally, at small scales (less than 1 kg of PET), molten PET cannot be extruded by gravity at rates fast enough to be fed directly into consumer 3D printers as they print. Producing the PET filament ahead of time through extrusion and then feeding the filament into the printer afterward may be a solution to the slow production rate. Finally, wheat straw can be a viable infill material for parts with low strength requirements; however, shrinking and long drying times make it unattractive for parts with short production times. A solution to this may be to mass-produce wheat straw infill in sheets which will then be dried ahead of time and added to the 3D printed part as an intermediate step.

Recommendations/Future Work

To explore the differences in properties between the two types of straw infills, it may be beneficial to examine infills made from rice straw pulp in the future.

References

(1) PET By the Numbers. http://www.petresin.org/news_PETbythenumbers.asp (accessed Feb. 11, 2021).

(2) Plastic Pollution Facts: PlasticOceans.org/the-facts. https://plasticoceans.org/the-facts/ (accessed Mar. 30, 2021).

(3) Hutchinson, A. Is Recycling Worth It? PM Investigates its Economic and Environmental Impact. https://www.popularmechanics.com/science/environment/a3752/4291566/ (accessed Feb. 11, 2021).

(4) Franklin-Wallis, O. 'Plastic recycling is a myth': what really happens to your rubbish? https://www.theguardian.com/environment/2019/aug/17/plastic-recycling-myth-what-really-happens-your-rubbish (accessed Feb. 12, 2021).

(5) 3D Printing Market Size https://www.grandviewresearch.com/industry-analysis/3d-printing-industry-analysis (accessed Mar. 30, 2021).

(6) Dominguez-Escriba, L. Rice straw management: The big waste. https://www.researchgate.net/publication/229861210_Rice_straw_management_The_big_waste (accessed Feb. 12, 2021).

(7) Khaleghian, H.; Molaverdi, M.; Karimi, K., Silica Removal from Rice Straw to Improve its Hydrolysis and Ethanol Production. https://pubs.acs.org/doi/10.1021/acs.iecr.7b02830 (accessed Feb. 12, 2021).

(8) 3D Printing Basics: Florida State University Libraries. https://www.lib.fsu.edu/3d/printing-basics (accessed Mar. 12, 2021).

(9) Plastic Bottle Cutter. https://www.kickstarter.com/projects/910418035/plastic-bottle-cutter (accessed May 29, 2021).

(10) Zheng, Q.; Zhou, T.; Wang, Y.; Cao, X.; Wu, S.; Zhao, M.; Wang, H.; Xu, M.; Zheng, B.; Zheng, J.; Guan, X., Pretreatment of wheat straw leads to structural changes and improved enzymatic hydrolysis. https://www.nature.com/articles/s41598-018-19517-5 (accessed Feb. 14, 2021).

(11) Mullen, A.; Alvarez, C.; Pojic, M.; Hadnadev, T.; Papageorgiou, M. ,Food Waste Recovery: Classification and target compounds. https://doi.org/10.1016/B978-0-12-800351-0.00002-X (accessed Mar, 14, 2021).

(12) Coefficients of Linear Thermal Expansion. https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html (accessed Mar. 10, 2021).

(13) Bei, J.; Monro, T. M.; Hemming, A.; Ebendorff-Heidepriem, H., Reduction of scattering loss in fluoroindate glass fibers. https://www.osapublishing.org/ome/fulltext.cfm?uri=ome-3-9-1285&id=260160 (accessed Mar. 10, 2021).

(14) Elert, G., Coefficients of Friction for Teflon. https://hypertextbook.com/facts/2004/GarvinTam.shtml (accessed Mar. 11, 2021).

(15) Awaja, F.; Pavel, D., Recycling of PET. https://www.researchgate.net/publication/222220710_Recycling_of_PET (accessed Mar 11, 2021).

(16) Default feed rate and maximum feed rate https://forum.simplify3d.com/viewtopic.php?t=4877#:~:text=For%20example%2C%201.75mm%20ABS,MakerBot%20or%20FlashForge%20style%20printer. (accessed Mar. 11, 2021).

(17) Passive Fire Protection. https://www.bristol-fire.com/solutions-products/passive-fire-protection/steel-fire-rated-doors/honeycomb-fire-rated-doors/ (accessed Mar. 11, 2021).