TURNING FAST FOOD WASTE OIL INTO 3D PRINTING RESIN

A Major Qualifying Project submitted to the Faculty of

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Abstract

Stereolithography (SLA) 3D printing is an indispensable manufacturing technique that enables rapid and precise fabrication of specialized parts through the viscoplastic manipulation of photopolymer resins. Petrochemicals have long served as the preferred precursor for resin synthesis since the inception of SLA printing, as they are the ideal substrate for functional modification. These methods are entirely unsustainable and the toxic effects inherent to the production, application, and eventual degradation of these compounds poses profound environmental damage. Naturally derived olefins, such as plant oils, represent a sustainable alternative to petrochemicals and offer many benefits such as tunable mechanical properties and a capacity for functionalization (piezoelectric, photostrictive, and otherwise). In this project, we demonstrate that waste cooking oil, which is the most readily available source of plant oils, can be chemically transformed to a photocuring resin that has excellent mechanical properties and is compatible with SLA printing.

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Background

SLA Printing

SLA (stereolithography) 3D printing is an additive manufacturing method using UV curable resins instead of an extruded filament. Several methods of SLA printing exist, including DLP (digital light projection) and LCD, but the only distinction between these methods is the way the light is diffused to cure the resin. SLA printing has a much higher resolution and smoother surface finish than typical FDM extrusion printers because the UV light is much more precise than the extruder physically moving across the platform. SLA printers use thermoset polymers, which are special resins that irreversibly cure when exposed to heat or certain wavelengths of radiation. Studies have been done on more cost effective and smart ways to create these resins for widespread use, as the current market options are too expensive for effective use. These options are all based on acrylate and epoxide monomers, which can be synthesized from soybean oil (Carmel, 2021). The way SLA printing works is initially the build platform is first dropped into a bath of uncured resin. As the build platform is slowly raised, the printer shines a UV light through a device that is able to turn certain pixels on or off to make the shape of one layer of the printed part. The UV light interacts with the resin in the bath and cures one layer which sticks to the bottom of the build platform. The build platform continues to rise slowly as the pixels on the device change to make every layer of the part. SLA printing was first patented in 1986, but it has been more practical to use typical extrusion printing because of the expensive resins.

Thermoset Polymers

Thermosets are a type of polymer that cures when exposed to certain kinds of radiation, in this case UV radiation (Hanson et. al., 2022). Epoxy thermosets are desired because of their incredible physical properties once cured and for their ability to change the rate of crosslinking with additives such as a photoinitiator.

Plant Oil Based Polymers and Environmental Precedents

Polymers and polymer-based composite resins have an extensive range of applications across nearly all industries. Their excellent mechanical properties, ease of synthesis, resistance to chemical corrosion, and low manufacturing costs have elevated these materials to a near ubiquitous importance in modern industry and their prevalence has proven crucial in the acceleration of technological development. Though despite their many benefits, our reliance on polymers has raised a growing concern regarding their lack of sustainability and the significant damage they cause to the environment. Petrochemicals have long served as the primary substrate in synthesizing the constituent monomers of the plastics which have come to comprise a majority of consumer goods.

The environmental consequences of petroleum-derivatives are universally recognized so far as their applications in combustion processes (natural gas, motor gasoline, diesel fuel, etc), but environmental scientists and synthetic chemists alike had discounted the long-term effects of the plastic microparticles and polymeric matrices accumulating in the environment since they were first observed in the Sargasso Sea in 1972 (Carpenter and Smith, 1972). The first major publication to designate these particles as “microplastics” and call attention to the scope of their impact would not come until 2004, when a group collected sediment from beaches as well as estuarine and subtidal sediments around Plymouth, UK and identified one third of the particles as synthetic polymers (Thompson et al, 2004). In the years following this study, research publications on the topic of microplastics would increase dramatically, several of which would prove to be particularly impactful through their research of topics such as: the total quantity of microplastics in the world's oceans (Brown et al, 2012), the correlation between physiological changes in fish and microplastic presence (Rochman et al, 2015), the capacity of microparticles to transfer toxic chemicals to fish and the implications for human health (Wright et al, 2016), and many more. As of

March, 2023, Google Scholar indicates that over one thousand research articles that mention microplastics have been published in the past 90 days. The rising frequency of landmark publications garnered substantial media coverage, amplifying anti-pollution sentiments thousands of times over and forcing the hands of politicians worldwide, leading to the Microbead-Free Water Act of 2015 and at least two other legislative motions which are on course to becoming the law by the end of this century. The adoption of synthetic polymers into modern industry is a brief history, spanning less than a century, but the triumphs and consequences of this epoch have reverberated across every nation in the world, and threaten to do damage far beyond what might have been a pessimistic outlook just 20 years ago. With the same fervor that brought us to what some have termed the Plastocene - the Age of Plastics, we now find ourselves desperately striving towards sustainable alternatives so that we may undo the damage we've done to the natural world.

Crude oil is the most chemically accessible source of aliphatic hydrocarbons, but it is not the only source. Plant oil is more than just an etymological mirror of its crude counterpart, but it exhibits striking chemical similarities which predispose it to similar malleability in a synthetic environment. They can serve as a precursor for a myriad of polymers and some have demonstrated significant advantages over traditional substrates such as increased biodegradability, sustainability, and reduced health consequences. Such products have been used extensively for applications such as coatings, inks, plasticizers, lubricants, agrochemicals, and toughening agents in polymers. The polymerization of vegetable oils typically begins through an initial conversion to a reactive monomer. Triglycerides contain several active sites that are susceptible to reaction: the double bond, the allylic carbons, the ester group, and the carbons alpha to the ester group. Polymerizable groups can be introduced to these sites through the same methods applied in the synthesis of petrochemical-based polymers. In designing reactions to develop such a product, one must consider M_W, crosslinking density, and supplementary chemical functionalities, as these are the primary determinants of the mechanical properties of the resulting polymer. Aromatic or cyclic structures are popular choices for functional moieties as they can enhance rigidity, hardness, and in some cases, contribute to photo-induced crosslinking by producing free radicals (Wool, 2005).

Plant oil has been researched as a replacement for petroleum in many other cases beyond 3D printing resin application. About 142 million tons of plant oil are produced a year, leading to heavy amounts of waste oil and a need to find other purposes (Carlsson, 2009). Some current uses of waste cooking oil include turning it into biodiesel fuel and animal feed (Awang et al., 2022). Developing a process to turn this oil into 3D printing resin has big implications for the 3D printing industry. If a home user wanted to be sustainable and cost effective with their SLA printer, this process could potentially be applied to create their own resin from cooking oil. Having easier access to thermoset resins like this We decided to use soybean oil not only because of the tests that have already been done involving resins synthesized from soybean oil but also because we can acquire waste soybean oil from the dining halls on WPI campus and repurpose the waste. If we perfect our process, we can potentially apply this process to soybean oil from fast food restaurants in the nearby area. Other studies using similar processes and oils have found results that are comparable to market alternatives (Bing, 2020). With the acrylated waste oil they were able to create a resin that showed similar resolution to standard market alternatives when printed. This resin also had comparable physical properties and was shown to be more biodegradable than typical 3D printing resin. We will be doing our own mechanical testing on the completed parts but this study shows that it is feasible to create a UV curable resin with commercial grade strength. In this study, the same acrylation process was used as in our own.

Biochemical Background

Fatty Acids

A fatty acid is a carboxylic acid with an aliphatic chain. In most higher lifeforms, they are stored as one of three types of esters: triglycerides, phospholipids, and cholesteryl esters. They are distinguished according to their characteristic double bond character and carbohydrate chain length, as these properties define their chemical behavior.. The most common types of fatty acids vary in length from 14 to 22 carbons and have 0 to 3 double bonds. If a fatty acid has at least one double bond, it is considered to be unsaturated, as the molecule does not possess the maximum possible number of bonded hydrogens since the bonding electrons from two adjacent carbons are occupied by a pi type interaction. Unsaturated fatty acids can be further distinguished based on the geometric configuration of the double bond(s). When the respective hydrogen atoms in a C=C double bond are rotated 180 degrees relative to each other, it is considered a *trans* fat. Such structures maximize the effective surface of the molecule which increases dispersion interactions between adjacent macromolecules, causing most *trans* fats to be solid at room temperature. In *cis* fats, the hydrogen atoms are not rotated, and the decreased relative steric bulk of the side lacking hydrogen atoms induces a bend into the molecular structure, reducing dispersion forces. Because of this, *cis* fats tend to be liquid at room temperature. Contrary to unsaturated fats, saturated fats do not have any double bonds. These molecules tend to be more chemically stable than their counterparts, as the pi type bond in a double bond is electrostatically weak and geometrically exposed (Wool, 2005).

Triglycerides as Monomers and Polymer Chemistry

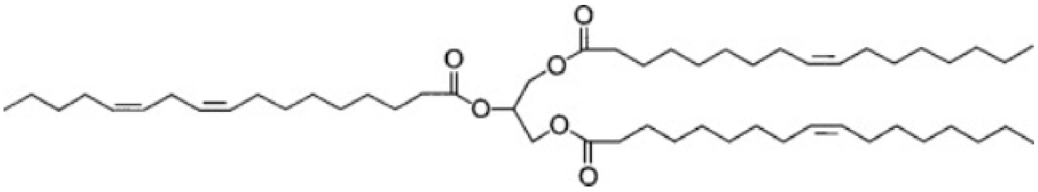


Figure 1. Basic structure of a common plant oil.

In plant-oil-based polymers, triglycerides act as the constituent monomers and they are composed of three fatty acids joined at a glycerol juncture. The most common types of fatty acids (by a significant margarine) found with triglyceride structures are oleic acid (18 carbons, 1 double bond) and linoleic acid (18 carbon atoms, 2 double bonds), but many other types are found in varying quantities depending on the type of oil. The percent composition by fatty acid accounts for the unique properties of an oil and can vary significantly depending on the source.

Within the scope of polymer chemistry, double bond content is the most substantially represented property in derivative products, as it directly correlates with the chemical reactivity of the fatty acid. In this respect, the double bonds of a triglyceride can be considered a “function”, which is defined as a region of the monomer where a reaction can readily occur. A bifunctional monomer (2 regions of reaction) will form a linear polymer, whereas a monomer with $f>2$ is capable of forming a polymer network. Such characteristics cannot be defined as “ideal” for polymer synthesis, as polymers are designed with a myriad of intended functions and applications, so the relative value of a given oil must be considered with respect to the purpose and target market.

Soybean Oil Polyesters

According to a report by the Environmental Protection Agency, 17.3 million tonnes of vegetable oil were consumed in the United States from 2021 to 2022, with 11.3 million tonnes from soybean oil alone (EPA, 4-2023). And according to the North American Renderers Association, about 2 million tonnes is collected as used cooking oil, most of which is used for biodiesel (NARA, 2023). While it can safely be assumed that much of the cooking oil not accounted for as recycled waste is consumed and metabolized, there is still a large quantity of waste oil which is disposed of irresponsibly and illegally each year. As soybean oil is the most commonly consumed in the United States, it has also found a niche in polymer chemistry and is currently sold by major chemical distributors as acrylated epoxidized soybean oil, which acts as a photocuring resin when combined with a photoinitiating species or blended with another resin. Considering these environmental demands and the biochemical precedents which will be further explored, we have dedicated this project to the synthesis, characterization, and sustainability analysis of acrylated epoxidized soybean oil.

Soybean Oil Properties

In an effort to synthesize a rigid and mechanically sound product, soybean oil was chosen as the monomer for all subsequent biochemical and mechanical methodologies. In addition to the established environmental background, this decision was strongly influenced by the favorable chemical characteristics of soybean oil. It exhibits an average double bond content of about 4.6 per triglyceride (Kundu et al., 2016) making it a fitting substrate for a polymer network. Figure 3 depicts one triglyceride likely to be found in soybean oil and Table 1 shows the general fatty acid contents of soybean oil, with the 3 most common being oleic acid, linoleic acid, and linolenic acid (Figure 4).

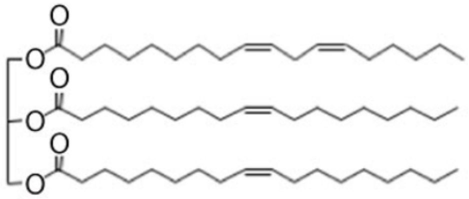


Figure 2. Linoleic acid, II. Oleic Acid, III.Oleic Acid

One possible triglyceride found in soybean oil.

Table 1. Soybean oil percent composition by fatty acid. From R. Wool,l 2005.

Fatty Acid	Soybean (% comp.)
Myristic	0.1
Myristoleic	0.0
Palmitic	11.0
Palmitoleic	0.1
Margaric	0.0
Margaroleic	0.0
Stearic	4.0
Oleic	23.4
Linoleic	53.2
Linolenic	7.8
Arachidic	0.3

Gadoleic	0.0
Eicosadienoic	0.0
Behenic	0.1
Erucic	0.0
Lignoceric	0.0

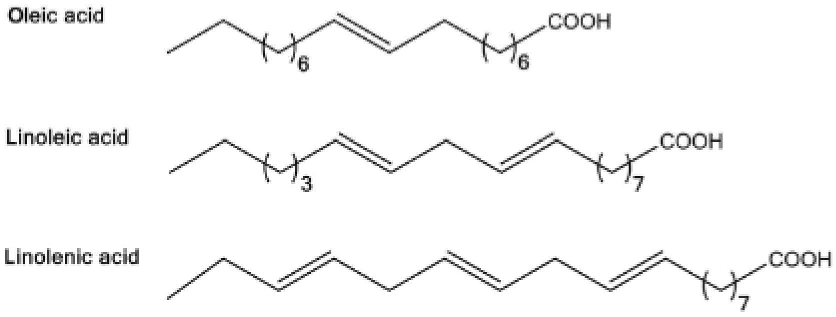


Figure 3. Most common fatty acids found in soybean oil.

Polymer Synthesis and Modifications

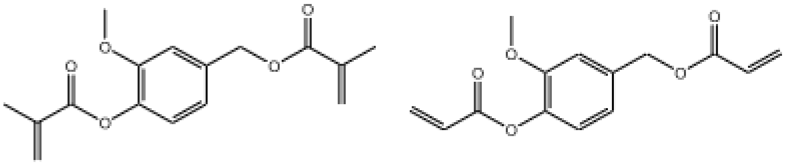
The synthesis of AESO, and polymerizable soybean oil resin in general, proceeds by first inducing chemical functionalities onto the constituent triglycerides, creating a highly reactive monomeric intermediate. An initial activation of the molecule can be achieved through treatment with peroxidic compounds, as the vinylic and allylic carbons of unsaturated triglycerides are particularly susceptible to electrophilic addition. This yields an epoxidized precursor which can be further transformed to an effective monomer by the 1,2 addition of acrylic acid, catalyzed by a tertiary amine such as triethylamine, via epoxide ring opening. This reaction was found to have first-order dependence with respect to epoxidized soybean oil and second-order dependence with respect to acrylic acid (Scale et al., 2002). This is represented in the equation below:

$$[AESO] = k[ESO][AA]^2$$

The acrylic acid residues in the resulting compound can react with each other through a Michael-type addition to form a cross-linked polymer product. By manipulating the reaction conditions or by incorporating reactive aromatic comonomers such as styrene, the mechanical properties of the resin can be finely tuned to fit a particular application. Furthermore, there is an extensive catalogue of bulk and surface functionalizations which can be achieved in these materials such as pressure sensitivity and electrical conductivity. AESO has been used extensively for surface coatings and in the derivation of urethanes and amines for coating and ink applications. One notable modification is the reaction with cyclohexane dicarboxylic anhydride which forms oligomers and increases entanglement density. This introduces cyclic rings which stabilize the polymer (Khot et al, 2001). Another is the reaction with maleic acid to form oligomers and introduce more double bonds (Can, 1999).

Photoinitiators

The polymerization of plant oil resin has so far been described as requiring the presence of a photoinitiating species, which gives off free radicals upon exposure to certain wavelengths of light (generally UV), in order for polymerization to occur. While this remains the case, modern photoinitiators used at an industrial scale pose significant harm to the environment (Noirbent et al., 2021) and counteract some of the benefits of adopting plant-oil alternatives. As such, the experimental design of this project has been reoriented to integrate a more environmentally friendly approach to photo initiating species. One study demonstrated that acrylated epoxidized soybean oil can form a photosensitive resin without the use of a photoinitiator when incorporating vanillin dimethacrylate or vanillin diacrylate (Navaruckiene, 2020).



VDM VD

Figure 4. Vanillin dimethacrylate and vanillin diacrylate

It was experimentally demonstrated that the homopolymer of acrylated epoxidized soybean oil and the copolymer of acrylated epoxidized soybean oil and vanillin dimethacrylate are suitable materials for rapid 3D microstructuring by the direct laser writing lithography technique and spatial features of 1 μm and a 6900 voxels/second throughput were achieved. Since the 3D cross-linking of the plant-derived materials was initiated using ultrafast laser inducing multiphoton absorption and avalanche ionization, it does not require the usage of any photoinitiator and opens a new pathway for green 3D μ-printing as a flexible tool for rapid prototyping or advanced additive manufacturing (Lebdevaite et al, 2020). Further research resolved the apparent similarity of vanillin dimethacrylate and vanillin diacrylate. Vanillin diacrylate-based polymers had higher values of yield of insoluble fraction, thermal stability, and better mechanical properties in comparison to vanillin dimethacrylate-based polymers (Navaruckiene et al., 2020). A study was done with many different variations of vanillin diacrylate, vanillin dimethacrylate, and the presence of a solvent (dichloromethane) made into a thermoset polymer resin which found that the optimal polymer was created when vanillin diacrylate was used and no solvent was used, as the solvent seemed to slow down the cross-linking process resulting in weaker polymers. We made efforts to synthesize this compound and though we constructed a theoretically sound reaction framework, the execution was precluded by our inability to find a lab space.

Market Alternatives

AnyCubic plant-based resin ($42 / 1 kg)

Figure 5: Anycubic standard plant based resin

Anycubic claims that this material has a higher "bending resistance" than other standard resins. Anycubic's standard resin has a self-reported flexural strength of 50-70 MPa and a flexural modulus of 1200-1800 MPa, while the Eco resin has a strength of 40-60 MPa and a modulus of 1200-1400 MPa (Anycubic, 2022). This difference is hardly enough to draw any reasonable conclusions.

Elegoo plant based rapid curing resin ($31 / kg)

Figure 6: Elegoo plant based resin

Elegoo plant based resin has considerably less technical specifications readily available. The resin has an extension strength of 27.46±10% MPa and a flexure strength of 19.86±10% MPa, similar to that of the Anycubic resin (ELEGOO, 2022). As a cheaper option, this resin has comparable mechanical properties to the competitor. However, users online claim to experience frequent layer adherence issues with this resin.

Materials and methods

Over the duration of this project, we were completely unable to find any lab space to perform any of the reactions necessary. Biochemical methodologies henceforth are presented as prospective experiments, the theoretical effectiveness of which has been verified through extensive research.

Acrylated Epoxidized Soybean Oil Synthesis

Initially, we had intended to synthesize acrylated soybean oil without the initial epoxidation. This protocol is described below.

The following was purchased from Sigma-Aldrich:

1.) Acrylic acid
2.) Boron trifluoride diethyl etherate
3.) Hexane
4.) Sodium Bicarbonate
5.) Filter paper (d=15cm, pore size = 25 micrometers)

The experiment would then proceed through the following steps in the appropriate lab environment (adapted from Wu et al., 2020):

1. Waste oil filtered using filter paper (d=15cm, pore size=20-25m, Whatman)
2. 44mL acrylic acid, 100mL waste oil, 8mL BF3 + Et2O added to a three-neck 500mL flask with condenser with magnetic stirring
3. Mixture heated to 80C for 4h
4. Mixture cooled to room temp and stirred for 18 hours
5. 400-450mL hexane added to dissolve organic components
6. 5% aqueous NaHCO3 and NaCl wash to remove unreacted acrylic acid and catalyst (which can be further recycled)
7. After washing and drying, the resulting clear solution was evaporated under vacuum and hexane was recycled

Vanillin Diacrylate

Vanillyl alcohol diacrylate is an aromatic, natural photoinitiating and comonomeric species which acts as a substitute for its industrial counterparts such as Irgacure and styrene. We have devised two synthetic methods through which this product can be achieved, though we were unable to finalize a lab protocol as there were no labs available.

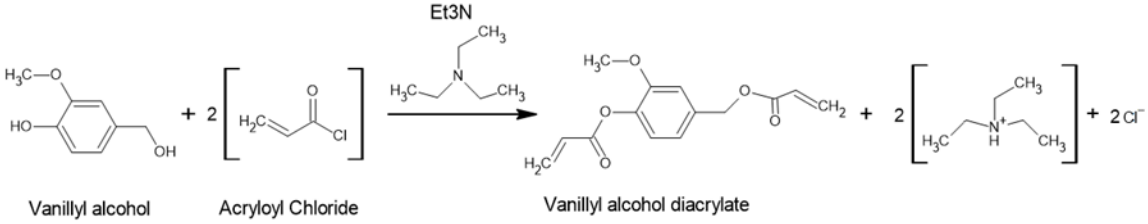


Figure 7: Addition with acryloyl chloride and triethylamine

The first pathway is a base-catalyzed addition of acryloyl chloride. This must be performed at a low temperature, since acryloyl chloride is incredibly volatile and since the product is a strong Michael acceptor. This would proceed under the following principles:

1. This reaction will be performed with 2 molar equivalents (eq) of acryloyl chloride and 2.1eq triethylamine (Et3N) using dichloromethane (DCM) as a solvent.
2. Et3N acts as a weak base.
3. The carbonyl carbon is electron deficient and is thus a strong electrophile.
4. Et3N deprotonates the hydroxyl groups of vanillyl alcohol, allowing for electrophilic attack by acryloyl chloride.
5. Cl- is a great leaving group.
6. Chloride ion leaves and is stabilized by Et3N, forming triethylamine hydrochloride.
7. Wash out Et3N HCl with water.

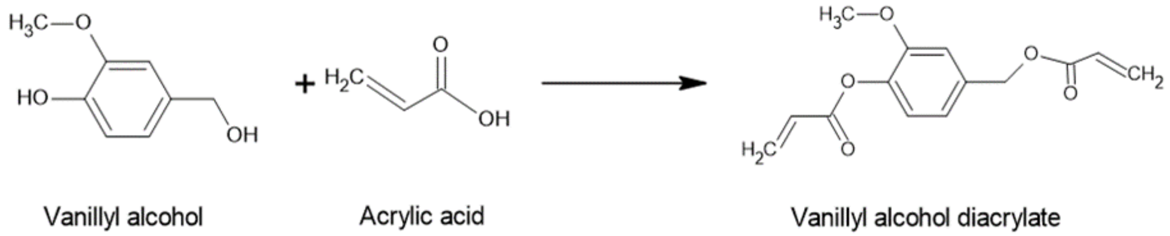


Figure 8: Acid catalyzed Fischer esterification

The second pathway is an acid catalyzed Fischer esterification with acrylic acid. This reaction is markedly more convenient to execute, though it is less chemically reliable as acrylic acid is especially prone to self-polymerization at the temperatures needed for this process to occur efficiently. A lower yield should be anticipated from this method, though the relative benefits of using less volatile compounds should also be considered. This would proceed under the following principles:

1. This reaction will be performed in water in the presence of a strong acid such as H2SO4, which creates a more reactive electrophile.
2. Because the reaction is reversible, it will need to be performed with a large excess of alcohol or while constantly removing water.
3. Acrylic acid is a good Michael Donor/Acceptor so it will be susceptible to self-polymerization at high temperatures. Therefore, this reaction must be performed at a low temperature over a long period of time.

In the conditions under which we would be performing these reactions, this is simply not a practical solution - however, we already have access to acrylic acid and it is much less volatile than acryloyl chloride. These factors must be considered when choosing between these reactions.

Mechanical Methodology

To print the resin, we planned to use a standard Anycubic printer at first. Once we realized that our resin would not have a photoinitiator and would not cure in the quick exposure time of such a printer, we had to create a new solution to cure the resin into dog bone shape. We designed a mold that we could pour the resin into and leave under a UV light for several hours until it cured naturally. The lack of a photoinitiator is an extreme hindrance to the printability and convenience for end users.

To test the resin, we will do two categories of tests. We will do resolution tests and mechanical tests. Resolution tests will involve printing a complex shape and seeing how accurate it is printed compared to standard resins. Visual testing will suffice for this one, as we just have to compare the two specimens side by side. For this, we decided to print the butterfly shown in Figure 1. Three iterations of this need to be printed and compared side by side to determine the resolution and consistency of the resin. Mechanical testing will involve tensile testing. We will print our resin into the shape of the ASTM D638^2 Type IV dog bone for our testing device, which is the standard for mechanical testing machines (Miller, 2019). Our testing device will measure and provide a stress / strain graph. Interpreting this correctly is the key to finding the tensile and bending moduli. The two mechanical tests we planned to do include one tensile strength test and one bending strength test. We believe these tests will generate properties that we could directly compare to the market alternatives mentioned earlier. Tensile strength is the primary way resins are compared, so tensile testing is a must-have. The bending strength and bending modulus are also extremely important when comparing resin strength, as this is the primary cause of failure in completed prints.

Figure 9: Butterfly

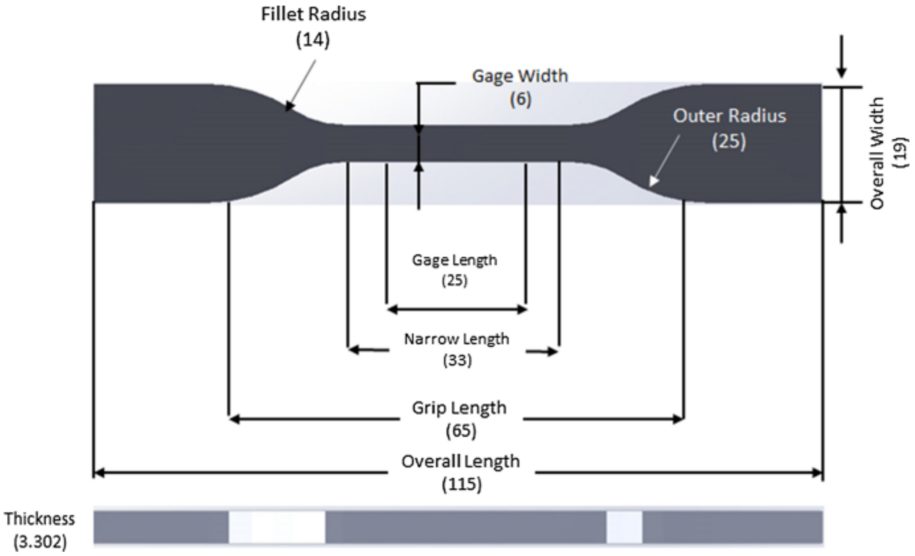


Figure 10: Dog bone specs

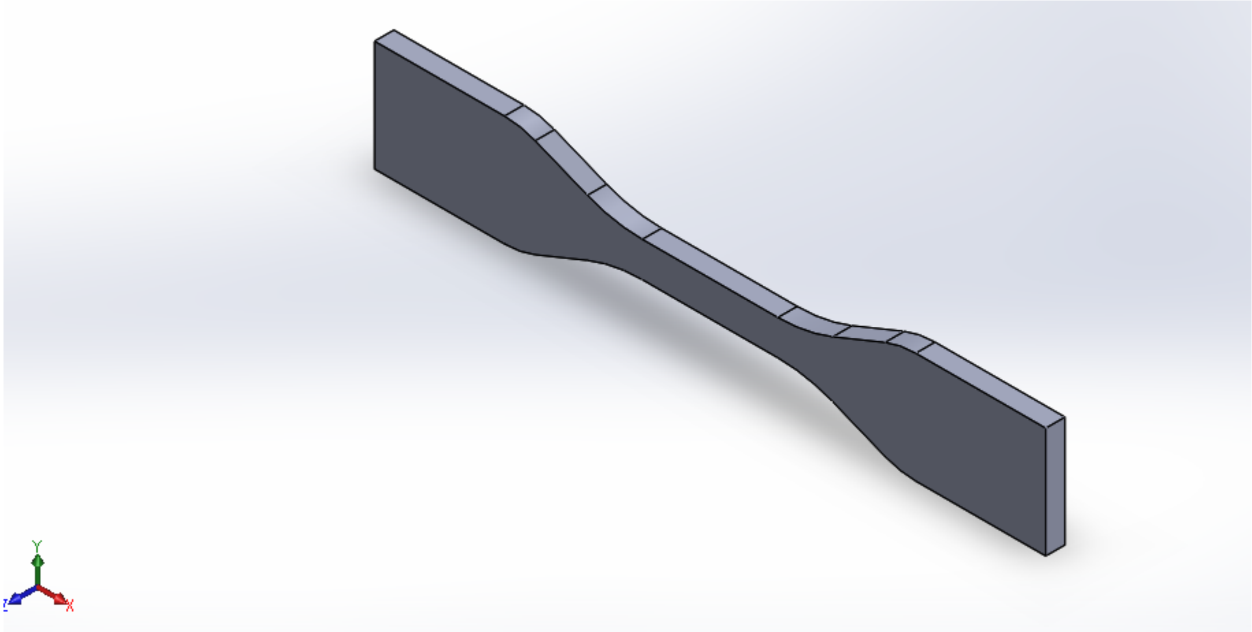


Figure 11: CAD model for dog bone specimen

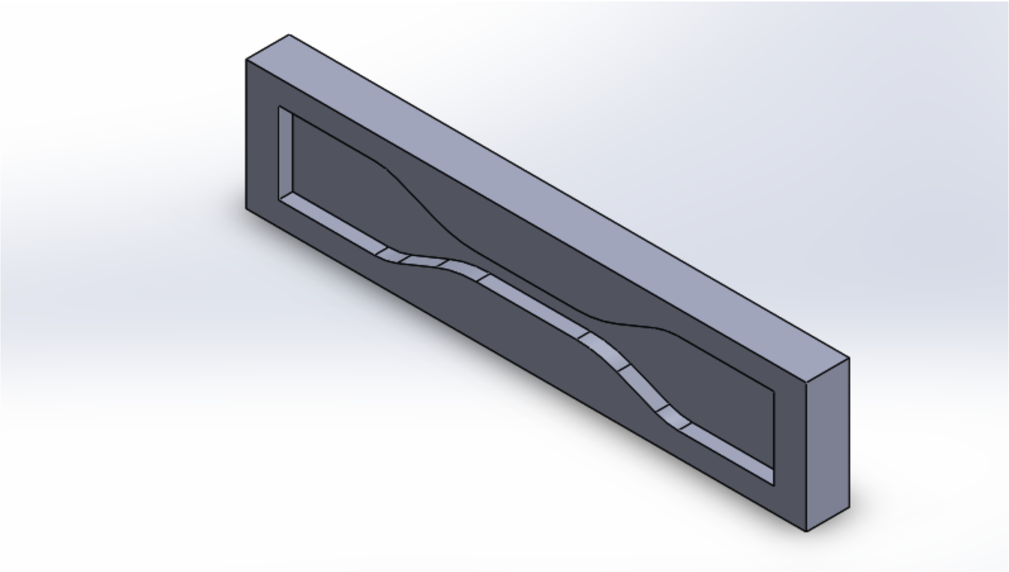


Figure 12: dog bone mold CAD model

After this, we realized the machine actually takes a slightly differently shaped dog bone. For 3 point bending, the sample is just a long rectangle specimen. These two are shown in figure 5 and 6.

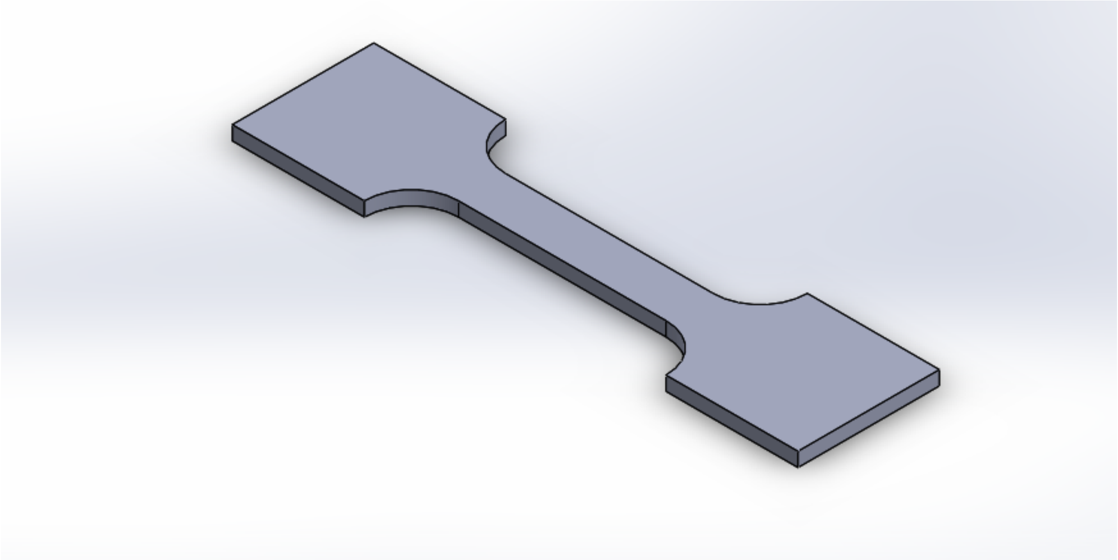


Figure 13: final dog bone mold CAD model

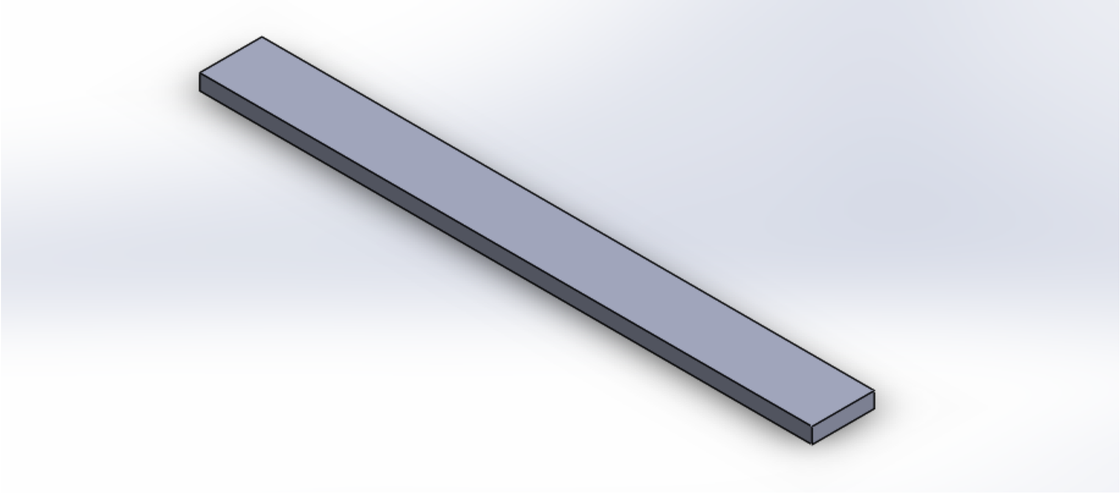


Figure 14: 3 point bending specimen CAD model

Results

Our project had numerous setbacks along the way, both on our side and uncontrollable. We were unable to secure the correct lab space from WPI, making it near impossible to safely complete any chemical reactions necessary to acrylate the soybean oil. This caused us to have to purchase acrylated epoxidized soybean oil straight from a chemical vendor. After the team acquired the AESO, an Anycubic 3D resin printer was used to try and print the AESO by itself. After several attempts, there was no adhesion to the base plate layer. Supporting documentation dictates that the cure time for AESO as a photocuring polymer was about 200s per layer. This was impossible to achieve, as the Anycubic printer only has a max setting of 60s layer time exposure. This is most likely why it was not adhering whatsoever.

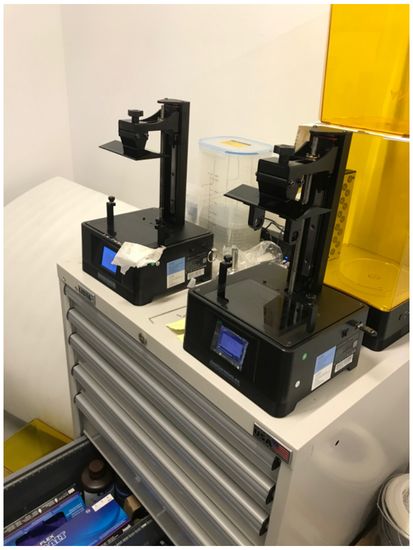


Figure 15: Anycubic 3D printer setup.

Even after adjusting the exposure time, it was clear another solution was necessary. After some deliberation, the team tried mixing the AESO with regular Anycubic epoxy based resin in a 1:1 ratio. This worked somewhat, but yielded extremely thin printed pieces. When the butterfly was printed, it was impossible to remove it from the base plate without breaking the entire structure. This method of a 1:1 AESO:Epoxy resin was the final solution used to print parts for testing. 4 bending test specimens and 4 tensile test specimens were printed.

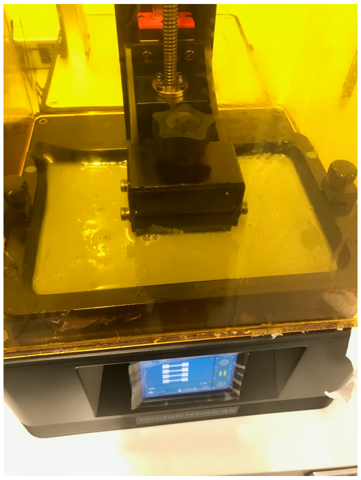


Figure 16: AESO/epoxy resin composite before printing

The test specimens were taken to the WPI Mechanical Engineering experimentation lab for testing. For the tensile test, the specimen was fitted between two clamps and pulled at three different strain rates. Figure 9 shows the results for the resin material. The yield strengths and the strain rates were calculated in the table below.

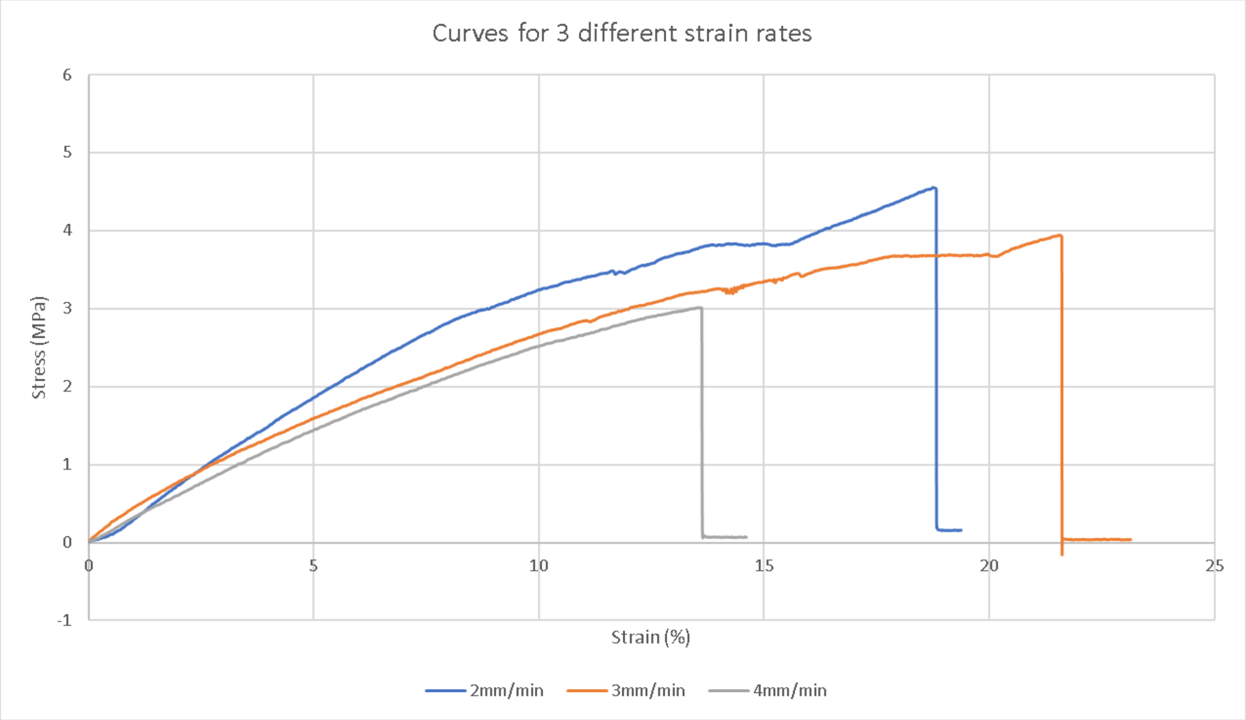


Figure 17: Stress-strain curve from tensile testing

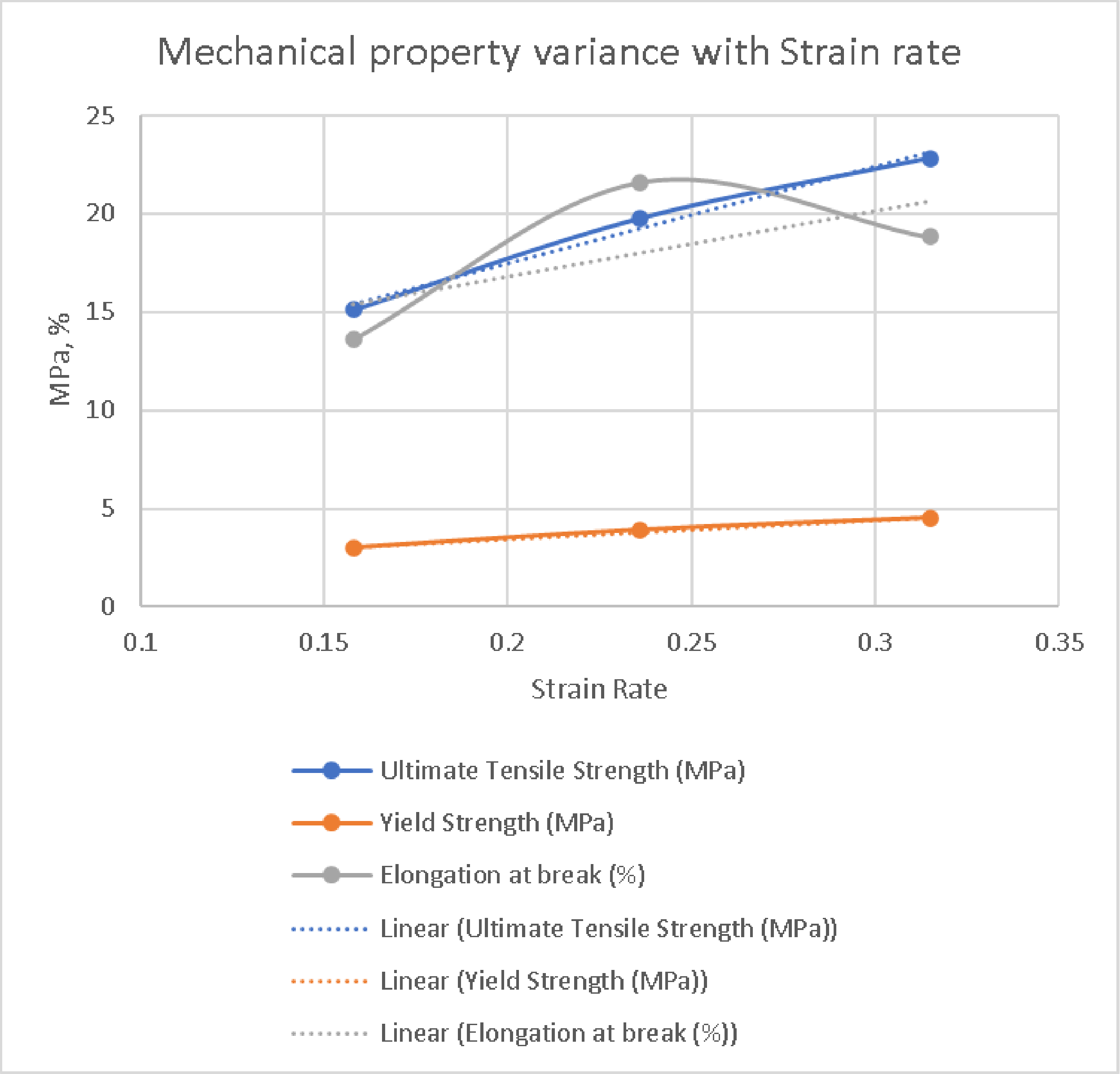


Figure 18: Mechanical properties over strain rate

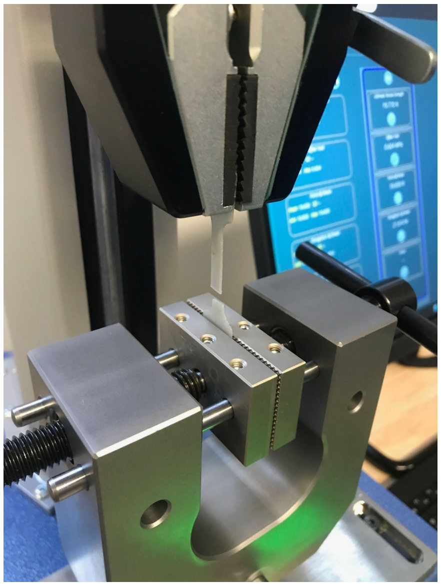


Figure 19: Tensile testing machine

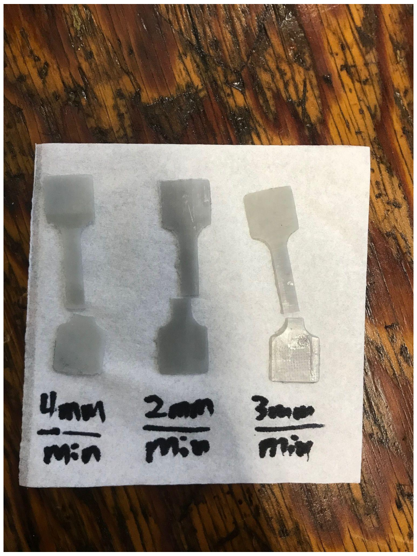


Figure 20: Three tensile test specimens with strain rates

Strain rate	Yield Strength (MPa)	Offset Yield (MPa)	Force @ Break (N)	Elongation @ Break (%)	Young's Modulus
0.158 1/s	3.00	0.647	15.085	13.62	0.22
0.236 1/s	3.92	0.604	19.658	21.614	0.18
0.315 1/s	4.53	1.144	22.691	18.827	0.24

Table 1: Tensile test results for different strain rates

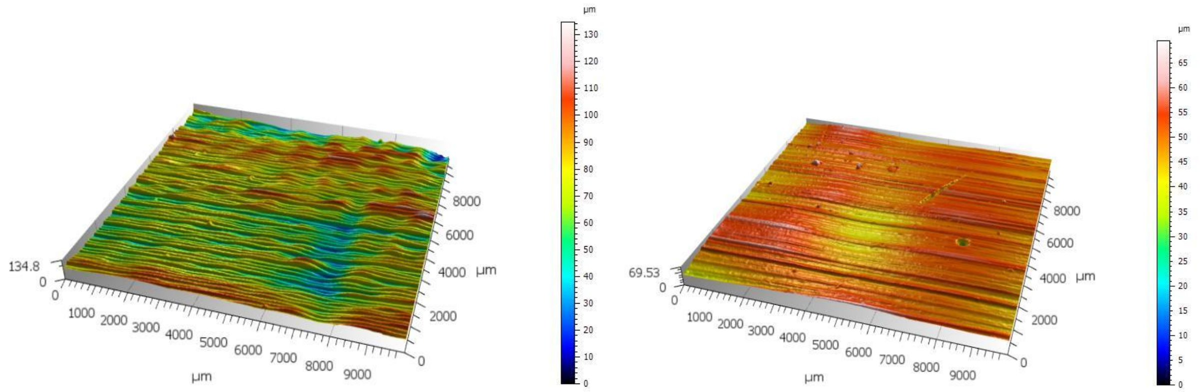


Figure 21: Comparison of surface finish PLA vs AESO composite Resin

Above are the results from the tensile test and surface analysis. The material did not perform very well in the tensile strength test, providing an extremely low Young’s Modulus. The material shows a positive correlation between strain rate and yield strength with the values we tested, implying that the ideal strain rate for maximum tensile strength is most likely above the highest value we tested. In an analysis of the various mechanical properties and how they vary over different strain rates, an interesting correlation was found. As strain rate increased, the ultimate tensile strength, the elongation at break %, and the yield strength increased as well. In the surface analysis, it is clearly shown that the surface of the resin is much smoother and more consistent than that of PLA from an FDM printer. Because of the thin nature of the printed material, performing a bending test was not possible on any of the samples. They were too flexible to give an accurate reading in the machine.

Discussion and Moving Forward

Many critical components of creating a soybean oil-based resin were identified in this project. The underlying chemical process was heavily researched and the relevance against other resins was analyzed. In future iterations, it is recommended to secure lab space early to perform the reaction to make AESO. It is not guaranteed that the quality of the AESO we acquired will be the same as the experimental version. Another important point is the use of a photoinitiator, which would have reduced cure times to the expected length for an SLA printer. There are many different photoinitiators and they bind to different resins differently, so research to find the appropriate photoinitiator is a must. We researched the possibility of adding compounds like styrene or vanillin diacrylate to increase the cross-linking effectiveness and increasing mechanical strength, and this would need to be tested. Additionally, since this project has a large chemical component it is recommended that future teams have engineers with chemical expertise. They will be able to understand and communicate on the physical problems when printing this material that may arise. Based on the mechanical properties for this material and the specific method in which they behave under stress, this material would not be a good choice for parts undergoing intense stress. The surface finish of the resin material was smoother than PLA leading to parts that look cleaner, indicating that this material would also be beneficial for parts that are required to slide against each other, as friction would be minimized. The nature of SLA printers in general allows for better resolution on parts with small and intricate shapes. An ideal application would likely be in prototyping, but specifically decorative or complex shape parts, such as a casing for electronic devices or for model casting.

References

Anders S. Carlsson, Plant oils as feedstock alternatives to petroleum – A short survey of potential oil crop platforms, Biochimie, Volume 91, Issue 6, 2009, Pages 665-670, ISSN 0300-9084, https://doi.org/10.1016/j.biochi.2009.03.021.

Anthony, M., Niven, S. J., Galloway, T. S., Rowland, S., & Thompson, R. F. (2013). Microplastic Moves Pollutants and Additives to Worms, Reducing Functions Linked to Health and Biodiversity. Current Biology, 23(23), 2388–2392. https://doi.org/10.1016/j.cub.2013.10.012

"Anycubic Plant-Based UV Resin 1KG." *ANYCUBIC 3D Printing*, https://www.anycubic.com/collections/plant-based-uv-resin/products/anycubic-plant-based-uv-resin-1kg

Awang, Muhamad Sn, et al. "Effect of Addition of Plastic Pyrolytic Oil and Waste Cooking Oil Biodiesel in Palm Oil Biodiesel–Commercial Diesel Blends on Diesel Engine Performance, Emission, and Lubricity." Energy & Environment., vol. 33, no. 6, 2022, pp. 1061–1089., https://doi.org/10.1177/0958305X211034822

Barrett, L. W., Sperling, L. H., & Murphy, C. D. (1993). Naturally functionalized triglyceride oils in interpenetrating polymer networks. Journal of the American Oil Chemists' Society, 70(5), 523–534. https://doi.org/10.1007/bf02542588

Bing Wu, Atiqurrehman Sufi, Rajshree Ghosh Biswas, Arika Hisatsune, Vincent Moxley-Paquette, Paris Ning, Ronald Soong, Andrew P. Dicks, and André J. Simpson, "Direct Conversion of McDonald's Waste Cooking Oil into a Biodegradable High-Resolution 3D-Printing Resin", ACS Sustainable Chemistry & Engineering 2020 8 (2), 1171-1177 DOI: 10.1021/acssuschemeng.9b06281

Biopolymers from Vegetable Oils via Catalyst- and Solvent-Free "Click" Chemistry: Effects of Cross-Linking Density. (2022). ACS Publications. https://pubs.acs.org/doi/10.1021/bm201554x

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Vito Felice Uricchio. (2020). A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. International Journal of Environmental Research and Public Health, 17(4), 1212–1212. https://doi.org/10.3390/ijerph17041212

Carmel. "FDM vs. SLA vs. SLS vs. DLS: Battle of the 3D Technologies." Sculpteo, Sculpteo, 28 July 2021,https://www.sculpteo.com/en/3d-learning-hub/3d-printing-technologies-and-processes/compare-fdm-sla-sls-dls/

"Elegoo Plant-Based Rapid UV-Curing Resin for LCD 3D Printers." *ELEGOO Official*, https://www.elegoo.com/products/elegoo-plant-based-rapid-resin

Cywar, R. M., Rorrer, N. A., Hoyt, C. B., Beckham, G. T., & Eugene Y.-X. Chen. (2021). Bio-based polymers with performance-advantaged properties. Nature Reviews Materials, 7(2), 83–103. https://doi.org/10.1038/s41578-021-00363-3

Guillaume Noirbent, & Frédéric Dumur. (2021). Photoinitiators of polymerization with reduced environmental impact: Nature as an unlimited and renewable source of dyes. European Polymer Journal, 142, 110109–110109. https://doi.org/10.1016/j.eurpolymj.2020.110109

Fernanda, L., José Carlos Sá, & Lima-Neto, B. S. (2016). Plant Oil-Based Polyester. https://doi.org/10.1016/b978-0-323-35833-0.00005-0

Fox, A. (n.d.). Synthesis and Properties of Acrylated Epoxidized Soybean Oil Copolymers and Their Composites with Natural Fillers. Retrieved April 27, 2023, from https://digitalcommons.bucknell.edu/cgi/viewcontent.cgi?article=1344&context=honors_theses

Hanson, Kalin G, Ching-Hsuan Lin, and Mahdi M Abu-Omar. “Crosslinking of Renewable Polyesters with Epoxides to Form Bio-Based Epoxy Thermosets.” Polymer the International journal for the Science and Technology of polymers. 238 (2022): n. pag. Web.

Khot, S.N., Lascala, J.J., Can, E., Morye, S.S., Williams, G.I., Palmese, G.R., Kusefoglu, S.H. and Wool, R.P. (2001), Development and application of triglyceride-based polymers and composites. J. Appl. Polym. Sci., 82: 703-723. https://doi.org/10.1002/app.1897

Koelmans, A. A., Nor, M., Hermsen, E., Kooi, M., & Svenja Mintenig. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water Research, 155, 410–422. https://doi.org/10.1016/j.watres.2019.02.054

La, J. J., & Wool, R. P. (2002). The effect of fatty acid composition on the acrylation kinetics of epoxidized triacylglycerols. Journal of the American Oil Chemists’ Society, 79(1), 59–63. https://doi.org/10.1007/s11746-002-0435-4

Math, M. C., Kumar, S., & Chetty, S. V. (2010). Technologies for biodiesel production from used cooking oil — A review. Energy for Sustainable Development, 14(4), 339–345. https://doi.org/10.1016/j.esd.2010.08.001

Migle Lebedevaite, Jolita Ostrauskaite, Edvinas Skliutas, & Malinauskas, M. (2019). Photoinitiator Free Resins Composed of Plant-Derived Monomers for the Optical μ-3D Printing of Thermosets. Polymers, 11(1), 116–116. https://doi.org/10.3390/polym11010116

Miller, Arielle, et al. "Guidance on the Use of Existing ASTM Polymer Testing Standards for ABS Parts Fabricated Using FFF." *Smart and Sustainable Manufacturing Systems*, ASTM International, 17 Dec. 2019, https://www.osti.gov/pages/servlets/purl/1669703.

Navaruckiene, A.; Skliutas, E.; Kasetaite, S.; Rekštytė, S.; Raudoniene, V.; Bridziuviene, D.; Malinauskas, M.; Ostrauskaite, J. Vanillin Acrylate-Based Resins for Optical 3D Printing. Polymers 2020, 12, 397. https://doi.org/10.3390/polym12020397

Oilseeds: World Markets and Trade. (n.d.). https://downloads.usda.library.cornell.edu/usda-esmis/files/tx31qh68h/5999ph96b/kp78hx20f/oilseeds.pdf

Patit Paban Kundu, & Das, R. (2016). Development of Biobased Polymers and their Composites from Vegetable Oils. John Wiley & Sons, Inc. EBooks, 287–320. https://doi.org/10.1002/9781119117360.ch8

Photocurable, Thermally Reprocessable, and Chemically Recyclable Vanillin-Based Imine Thermosets. (2020). ACS Sustainable Chemistry & Engineering. https://pubs.acs.org/doi/10.1021/acssuschemeng.0c06248

Piccolo, D., Vianello, C., Lorenzetti, A., & Maschio, G. (2019). Epoxidation of soybean oil enhanced by microwave radiation. Chemical Engineering Journal, 377, 120113–120113. https://doi.org/10.1016/j.cej.2018.10.050

Rothstein, S. I. (1973). Plastic Particle Pollution of the Surface of the Atlantic Ocean: Evidence from a Seabird. The Condor, 75(3), 344–345. https://doi.org/10.2307/1366176

Shrikant Khot, LaScala, J. J., Can, E., Morye, S. S., Williams, G., Palmese, G. R., Küsefoğlu, S. H., & Wool, R. P. (2001). Development and application of triglyceride-based polymers and composites. Journal of Applied Polymer Science, 82(3), 703–723. https://doi.org/10.1002/app.1897

Sigita Kasetaite, Deimante Valaityte, Motiekaityte, G., & Jolita Ostrauskaite. (2021). Bio-Based Crosslinked Polymers Synthesized from Functionalized Soybean Oil and Squalene by Thiol–Ene UV Curing. Materials, 14(10), 2675–2675. https://doi.org/10.3390/ma14102675

Used Cooking Oil (UCO) as biofuel feedstock in the EU. (n.d.). https://www.transportenvironment.org/wp-content/uploads/2021/07/CE_Delft__200247_UCO_as_biofuel_feedstock_in_EU_FINAL%20-%20v5_0.pdf

Wool, R. P. (2005). POLYMERS AND COMPOSITE RESINS FROM PLANT OILS. Elsevier EBooks, 56–113. https://doi.org/10.1016/b978-012763952-9/50005-8

Zhang, Y., Vijay Kumar Thakur, Li, Y., Garrison, T. F., Gao, Z., Gu, J., & Kessler, M. (2018). Soybean-Oil-Based Thermosetting Resins with Methacrylated Vanillyl Alcohol as Bio-Based, Low-Viscosity Comonomer. Macromolecular Materials and Engineering, 303(1), 1700278–1700278. https://doi.org/10.1002/mame.201700278