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The Effect of Extended Saltwater Absorption and UV Cure on the Compressive Properties of MSLA 3D-Printed Photopolymer Resin Samples with Printing Variations

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by

Suzanne Dixon

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We, the undersigned committee, hereby approve the attached thesis,
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Abstract

Title: The Effect of Extended Water Absorption and UV Cure on the Compressive Properties of MSLA 3D-Printed Photopolymer Resin Samples with Printing Variations

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Liquid Crystal Display (LCD) 3D printers, also known as Masked Stereolithography Apparatus (MSLA), is a type of vat polymerization printing technique that cures liquid resin into a solid object. This technique is relatively new. Consequently, there is a shortage of detailed research on the impact of long-term environmental exposure on the MSLA-printed materials. The research within this document informs engineers and scientists of resin compressive properties after extended exposure to saltwater and ultraviolet (UV) light. Saltwater absorption of the material was analyzed at atmospheric pressure, 30-psi, 60-psi, and 90-psi; the samples reached saturation in saltwater after 56 days. The variation in pressure did not significantly affect the compressive properties. On average, saltwater immersion samples, compared to control samples, caused Young's modulus to decrease by 18.52% and yield strength to decrease by 52.2%. The post-processing UV cure times tested independently of saltwater absorption were 6-, 15-, 30-, 60-, 120-, and 240-minutes. The compressive properties reached a plateau as the cure time approached 240-minutes. For all samples, the resin supplier source and the quality of the washing solution were varied. However, this did not significantly impact most compressive property results. The effects of saltwater immersion and UV cure on the material properties of MSLA resin are significant and should be considered for designs that are exposed to similar conditions.

Table of Contents

List of Figures

List of Tables

List of Keywords

Vat Polymerization

Masked Stereolithography Apparatus (MSLA)

Stereolithography (SLA)

Liquid Crystal Display (LCD)

Photosensitive Resin

3D Printing

Water Absorption

Long-term Exposure

UV Cure

List of Acronyms

Component	***Requirement***
ASTM	American Society for Testing and Materials
DLP	Digital Light Processing
FDM	Fused Deposition Modeling
LCD	Liquid Crystal Display
MSLA	Masked Stereolithography Apparatus
SLA	Stereolithography
UV	Ultraviolet
UTL	Underwater Technology Laboratory
UTM	Universal Testing Machine
SOC	Siraya Tech resin, Old alcohol, Control sample
ANC	Amazon resin, New alcohol, Control sample
AOC	Amazon resin, Old alcohol, Control sample
SNC	Siraya Tech resin, New alcohol, Control sample
ANUV	Amazon resin, New alcohol, UV cure sample
AOUV	Amazon resin, Old alcohol, UV cure sample
SOUV	Siraya Tech resin, Old alcohol, UV cure sample
SNUV	Siraya Tech resin, New alcohol, UV cure sample
YSI	Yellow Springs Instruments

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Chapter 1
Introduction

SLA (Stereolithography) and MSLA (Masked Stereolithography Apparatus) 3D-printing technologies are increasingly being used to print ocean-going parts, including watertight submersible housings [1, 2, 3]. These two vat polymerization technologies use ultraviolet (UV) light to cure liquid resin before the parts are washed in isopropyl alcohol and cured in a UV cure machine. Because of the resin material and printing process, these 3D-printed parts are less susceptible to water intrusion than parts printed with the more common Fused Deposition Modeling (FDM), which prints with plastic [4]. Since MSLA is generally cheaper than SLA and uses similar photosensitive resin, it has the potential to become commonplace in the ocean engineering community for parts more resistant to water intrusion. However, 3D-printed parts in the marine environment may experience UV light from the sun, water absorption, and pressure which are common in marine applications. Extended testing of those effects is limited for SLA printers and even more limited for MSLA printers. This research investigates those three exposures (water absorption, water absorption under pressure, and extended UV-cure). It compares them to control samples to determine the effect of the exposures on the compressive properties of MSLA-printed parts.

First, samples were immersed in saltwater at different atmospheric pressures, 30-, 60-, and 90-psi, until the samples reached saturation as determined by the change in percent weight over time. Theoretically, water absorption may cause the compressive properties to degrade after immersion in water occurs.

Second, samples were exposed to UV cure times, well past the manufacturer's recommendations (times of 6-, 15-, 60-, 120-, and 240-minutes) in the MSLA post-cure machine. UV cure may cause the samples' yield strength and elastic modulus to reach a maximum before decreasing again.

Third, all exposed samples were compression tested following ASTM D695-15 to quantify the impact of exposure on the material properties [5]. Control samples were also printed and tested to compare with the exposed samples.

Variables that could impact the compressive properties during printing include the quality of the post-processing washing solution (new versus cloudy isopropyl alcohol) and different suppliers of the same resin (Amazon versus Siraya Tech). These variation possibilities were applied to all experimental samples. Comparisons of the samples' elastic moduli and yield strengths determined the effect of the resin supplier and the post-processing cleanliness of the washing solution on the samples. The theoretical ideal variation conditions were resin directly sourced from the manufacturer (Siraya Tech) to limit shelf life and a newer washing solution with fewer residual resin particles from previous washings. The optimal variation method should have the least amount of water absorption over time by percent weight and retain compressive properties closest to the control samples.

Over the course of the project, 200 samples were printed and then compression tested before their data was analyzed. The research aims to assist those who plan to use MSLA prints in the marine environment, such as engineering solutions applicable in industry prototypes and college-level research.

Chapter 2
Importance and Audience

Resin-printed parts and prototypes have been used in the ocean engineering community and other fields of research. For example, a study by the Massachusetts Institute of Technology (MIT) printed stereolithography (SLA) resin propellers to test their open-water performance [6]. Another study used SLA-printed fins as propulsion for an Unmanned Underwater Vehicle (UUV) [7]. The University of Rhode Island (URI) created a submersible robotic gripper with the SLA-printed parts [3]. URI researchers also printed an SLA pressure housing deployed from a research vessel down to 200 m depth, where it collected pressure data [2]. Other researchers in the field of oceanography collaborated with engineers to model the hydrodynamics of several SLA-printed boxfish [8]. Each of these studies demonstrates the increasing use of vat polymerization printed parts going not only into the water but also under ocean-like pressures. Longer-term applications involve the deployment of components with a mechanical purpose that requires engineering analysis. In that case, the initial properties used to determine the limitations and safety factor may no longer be valid after effects such as water absorption. This may be an issue for NOAA, where scientists created end-caps for their waterproof enclosures that collect water samples and hold them underwater until the enclosure can be picked up [9]. An enclosure such as this will have a depth-rating stating that the enclosure should not be immersed deeper than the material limit. The depth rating would be based on the compressive properties of the printed material. Any degradation of material properties due to water absorption or UV cure could cause the actual safety factor to be smaller than the original calculated safety factor. In other words, if the enclosure goes deep enough, it could implode at a shallower depth than was expected due to changes in its compressive properties.

The above articles came from research-oriented institutions with large budgets for printer purchases or available resources for printer use. Of the articles listed, MIT, URI, and

NOAA used Formlabs SLA printers to create their parts. When this research was conducted, the Formlabs SLA printer cost above $2,000, which is a large investment for cost-limited applications of this technology [10]. The Anycubic Photon Mono X, an MSLA/LCD printer, costs 26% less than the Formlabs SLA printer [11]. The MSLA printer's low cost increases accessibility to lower-budget applications such as smaller colleges or high schools.

In the ocean fields, Remotely Operated Vehicles (ROVs) are ideal for incorporating vat polymerization technology. Competitions such as Marine Advanced Technology Education (MATE) and SeaPerch design and build ROVs with limited budgets and materials, while others, such as RoboSub, promote higher-level engineering with autonomy [12]. These competitions could use MSLA-printed parts to make cheap, watertight enclosures, but they would be applying the technology for shorter lengths of time. Applying MSLA technology in the lower-level competitions opens the opportunity to introduce more technologies to younger minds and further STEM education. In contrast, college university researchers have the potential to use this technology for longer-term deployment applications. The nature of college research provides more opportunities to intensely test the use of MSLA in the ocean environment than high school or college-level ROV competitions.

With knowledge about the effect of extended submersion on material properties, aspiring engineers can comfortably deploy SLA-printed parts for longer periods of time. The theoretical applications for this technology were confirmed by corporate interest in this research during the Oceans 2022 conference presentations. Several questions were asked about the extended use of the resin-printed parts in the marine environment [1]. The investigation of the MSLA properties after longer-term exposure in this research seeks to provide awareness of the various use-cases for the MSLA technology and a foundation for further research.

Chapter 3
Background

3.1 3D Printing Technology

Vat polymerization methods have become increasingly popular for applications requiring high-resolution, detailed models with specific material properties. Although stereolithography was the first type of 3D printing created before it became commercially available in the mid-1980s [13], the creation of companies such as Formlabs, Anycubic, and Elegoo in the 2010s began opening accessibility to vat polymerization printers [14, 15, 16]. These printers cure photosensitive liquid resin in different ways to form a solidified printed part. During curing vat polymerization methods, chemical reactions create bonds between layers. These bonds create a more continuous object than Fused Deposition Modeling (FDM) methods, causing less water absorption [4]. FDM printing involves a spool of plastic fed into an extruder that melts it and places layers next to each other, creating mechanical bonds between layers. The mechanical bonds create air voids between them, which causes water to permeate the bonds and fill the voids. The resin material is a thermoset because it bonds chemically, preventing the printed object from being reshaped after curing. The opposite type of polymers are thermoplastics, which can be reshaped after curing. Common FDM filaments, unlike the vat polymerization materials, can be re-melted after they are printed, so they are thermoplastics.

SLA is a type of vat polymerization process that uses lasers to cure the resin. Other types of vat polymerization also include Digital Light Processing (DLP), and Liquid Crystal Display (LCD) types. LCD machines are also known as Masked Stereolithography Apparatus (MSLA). Figure 1 depicts the differences between the three types of vat polymerization methods.

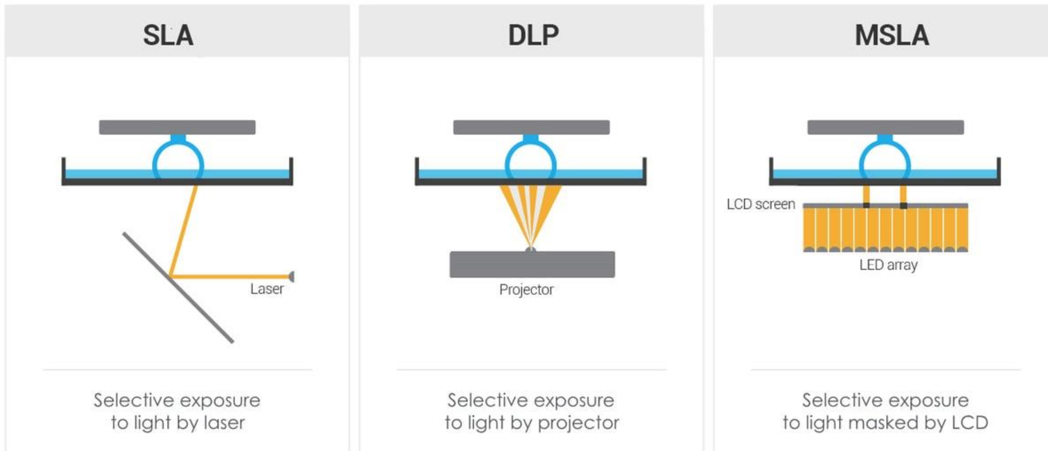


Figure 1: Vat Polymerization Techniques [17]

To solidify the resin, SLA printers use lasers to trace and fill the shape for each layer. DLP printers use a projector that outputs light in the shape of each layer to cure one layer at a time. MSLA printers emit UV light, which is filtered into the shape of an object's cross-section by the LCD screen.

The printing process for the three vat polymerization methods begins in the computer-aided design (CAD) before exporting to a slicer software. The slicer reads the STL file and prepares the object for production with the 3D printer. Figure 2 shows an MSLA machine's components.

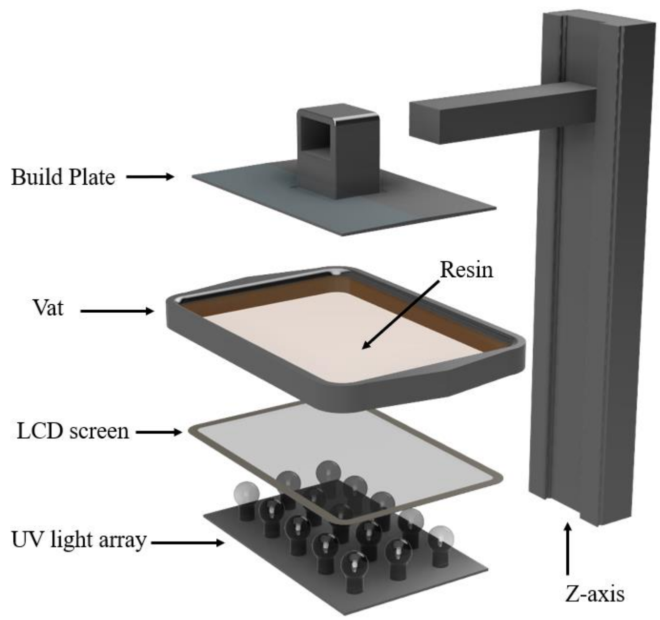


Figure 2: MSLA Printer Parts

The printer used for this research is an MSLA printer called the Photon Mono X made by Anycubic that projects UV light upwards through a filtering screen into the vat full of resin and onto the build plate [11]. The printed object begins to cure layer by layer, where each new consecutive layer bonds to the previous layer. The object's shape is controlled by the filtering LCD screen that only allows UV light through in the shape of that layer. Between layers, the print bed moves upwards into the air and downwards back into the vat to uniformly coat the previous layer with more liquid resin. The process ends with post-processing, where the user removes and cleans the object. In this research, Anycubic's Wash and Cure 2.0 was used for the post-processing [18]. An alcohol bath washes the part to remove any excess resin. When the object is dry, a set of UV lights in the cure station finishes fully curing the printed object. To ensure a clean and defined print, a calibration test is recommended by the manufacturer to optimize the print quality [19]. Adjusting the exposure time affecting UV light per layer can cause a lack of detail if the layers are underexposed or overexposed.

Previous research tested several different resins with a range of cure times to compare their material properties and create waterproof pressure housings [1]. Only a limited number of resins (Blu Emerald Blue, Blu Clear V2, and Sculpt Clear) from Siraya Tech were tested. Of the resins tested, Sculpt Clear, made by Siraya Tech with the samples UV cured for 6 minutes, had the best combination of the highest elastic modulus with a high yield strength. This means that Sculpt Clear, with the 6-minute cure time, was the stiffest of the resins tested and can undertake higher pressures before deforming permanently, which is ideal for parts under ocean-like pressures. Thus, Sculpt Clear was used for this research, and 6-minute cure times were used as the base-level cure time for all samples except when the UV cure was varied. The UV power of the machine throughout [1] was 62% and not tuned with a calibration print for the tested waterproof housings, but consistency throughout the project yielded good results. The paper and its presentation at the OCEANS 2022 conference left unanswered questions about the extended deployment of Sculpt Clear watertight housings and the effect of environmental factors.

3.2 Water Absorption

Water absorption is an industry-standard test, ASTM D570, for the water absorption of plastics [20]. The ASTM standard test gives the option of three different sample sizes for water absorption testing immersed in distilled water at shallow depths. A disc, rod, or tube cross-section should have its mass measured before and during absorption. The water absorption of a sample is investigated by determining the percent weight change in a certain time period. For longer-term immersion, it is recommended that the sample is weighed every two weeks until the difference between measurements is less than 1% of the weight or 5-mg between the time intervals. When this occurs, the samples have reached saturation. The weight measurement of the long-term immersion was obtained by removing the sample from the water, wiping it with a “dry cloth,” and weighing it immediately to the nearest 0.001-g [20]. No clean room was required by the standard to perform this measurement.

From the standard water absorption test, a recommended graph for immersion longer than three weeks is an increase in weight versus the square root of immersion time. Several researchers have performed long-term immersion of composite layups using the graph to make conclusions about saturation [21, 22, 23, 24]. Water absorption investigations for types of 3D printing have also utilized the graph of percent weight versus the square root of immersion time [25, 26]. Another study looked at the effect of pressure on resin versus resin with the reinforcing fibers [27]. They found that the resin without fibers had no significant change in percent increase by weight, but the material properties were not analyzed. However, a study testing the saltwater absorption of a professional-grade resin called Accura ClearVue found that the saturation point of the SLA resin after up to 60 days of immersion was not as clear as the plateau seen in material extrusion methods, including nylon-based filament. However, the resin had less water absorption by percent mass gain than the material extrusion methods [4].

Other types of printing and their water absorption have also gained some traction in research. Several sources have microscopically compared the difference in SLA prints compared to FDM prints after water absorption. While the FDM prints saw increased void sizes, the SLA prints had no noticeable changes [4]. A study using DLP printers created a custom resin formulation and then tested its water absorption when exposed to humidity [28]. MSLA printers have no published water absorption tests reported to the author’s knowledge, but similar results should be expected for the DLP and SLA-printed thermoset resins.

Most resins have datasheets that contain a percentage of water absorption in 24 hours. Sculpt Clear, for example, has a reported water absorption of 0.5% at 24 hours of immersion [29]. However, the datasheets do not show the water absorption's effect on the material properties of the resins or what happens after 24 hours. Limited research further tests extended exposure to vat polymerization printing techniques. One study determined that the SLA-printed Formlabs Clear resin immersed in seawater for three months retains tensile strength within 10% of the non-weathered parts [30]. However, this is not representative of photosensitive resin's compressive properties due to water absorption.

Deeper pressures have also been researched for SLA printers and resins commonly used for composites. In collaboration with the University of Rhode Island, the Naval Undersea Warfare Center (NUWC) Newport tested the saltwater absorption of a commercial-grade resin made by a professional and industrial-grade SLA printer [4]. Their experiment used SLA-printed Accura ClearVue resin, where they compression tested samples with 1) no immersion, 2) 30-day immersion, and 3) 60-day immersion. During water absorption, each sample was placed in a hydrostatic pressure tank to simulate an ocean depth of 3450 m. The water absorption under pressure was not compared to control samples experiencing water immersion without the influence of deep ocean-like pressures. The samples had no visual difference in physical appearance, but the compression test found that the ultimate strength decreased as immersion time increased. A study by Curbell Plastics looked into the effect of deeper ocean pressures on composites that used thermoset resins. The resin least sensitive to the absorption under pressures equivalent to 3500 m of water depth was the epoxy-based composites. At the same time, polyester and vinyl ester saw between 20% and 40% decrease in material strength based on tensile testing [31]. Still, it must be noted that the samples were not compression tested for an accurate comparison to this research. However, it can be theorized from the above sources that Sculpt Clear will absorb saltwater under pressure, which may affect the compressive properties.

3.3 UV Cure

Since post-processing is required to finish curing the resin with UV light, different cure times are expected to affect the material properties of the resins. The same is to be said of the sun when printed parts are exposed outdoors. Some research has been done to see the effects of longer cure-times on SLA resins. The photo-curable resin was tested from zero to 8-hour cure times, and tensile tests showed that the material strength reached its maximum after 4 hours of cure time [32]. The Sculpt Clear resin previously studied in [1] was compression tested at UV cure times of 6, 9, 12, and 15 minutes. The compressive strength gradually increased as time increased until it appeared to plateau at the manufacturer’s recommended cure time of 15 minutes. However, cure time for extended periods was not studied, but similar results to the brief research of SLA long-exposure are expected because both resins are thermosets. Another study found similar trends of a Formlabs Durable SLA resin reaching maximum strength when the manufacturer’s recommended cure time of 60 minutes was reached. This research does not investigate the effect of prolonged exposure well past the manufacturer's recommendations.

The UV cure during post-processing contains an array of UV LEDs. Placement in the UV cure machine could affect the compressive properties if the samples receive differing UV intensities. Formlabs, in their experimental cure machine, determined that the tensile modulus of samples was lower until it reached an ideal radiant power (radiant flux), and then it decreased as radiant power continued increasing [33]. In other words, the tensile modulus was higher when the samples experienced medium-range power from the UV LEDs. This is untested for MSLA and Sculpt Clear resin, but any changes in radiant power throughout sample placement and curing in the machine may result in higher differences in compressive results than a consistent radiant power or irradiance (flux over surface area).

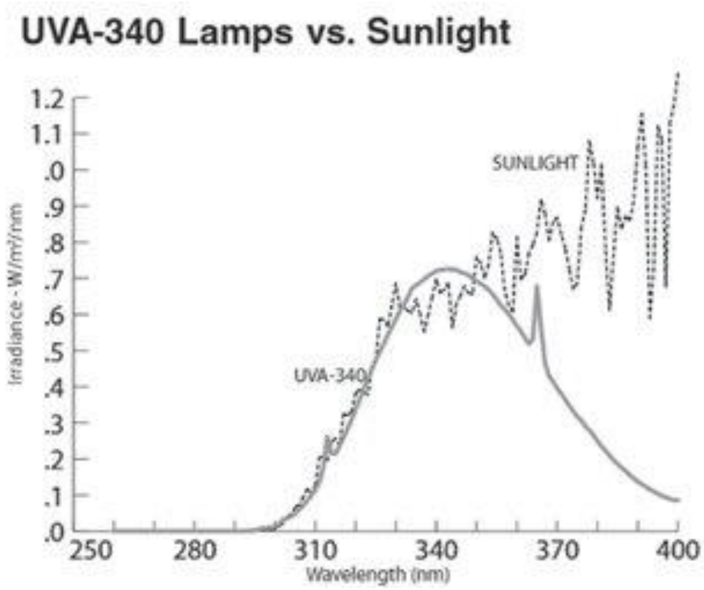


Figure 3: Cure Irradiance for Sunlight and UV Lamp [34]

The graph above highlights the difference in consistent irradiance for a UVA lamp versus sunlight in a day. The sunlight, as wavelength increased, had larger spikes in the irradiance as 400-nm wavelength was approached. While sunlight has a larger range of wavelengths, its variability in irradiance caused by clouds and other factors decreases consistency and reliability for expected material properties.

3.4 Variation and Error in Printing

Limited research is available on post-processing's effect on the compressive properties of MSLA printed objects. In a study from 2021, an Anycubic Photon MSLA printer was used to find optimal wash times and cure times for the best tensile test, shore hardness, and surface roughness [35]. The wash station used was the Anycubic Wash and Cure 2.0, which is the same one used in this research. They found that washing for more than 10 minutes caused a decrease in tensile strength. It is unknown how the wash time may affect the compressive properties of samples. The washing time was kept constant throughout the experiment to prevent bias in the results. In addition, potential errors could result from a change in UV power experienced by the samples being cured in the UV cure machine. The process for this to reduce error was not changed to simplify experiment repeatability. However, a power meter can be used to study how vertical movement on the UV cure machine can cause differences in UV power experienced by the object being cured.

3.5 Statistical Analysis

For a statistical analysis of relationships between variables, the Analysis of Variance (ANOVA) test can be used to analyze means between groups (levels) that are contained within variables. ANOVA determines if the means are significantly different from each other by comparing the means and ranges of their error [36]. One-way ANOVA compares at least three levels and assumes independent data, normally distributed data, and homoscedasticity (constant variance). Since the data in this research is a smaller sample size (5 samples per group) and the data is not normally distributed or homoscedastic, a different test can better quantify the results of this research.

The Kruskal-Wallis test is an alternative to the one-way ANOVA test, which does not assume data follows a certain distribution and creates an ANOVA table as an output [37]. An example of the test results is in Table 1. The sum of squares for all rows is calculated from individual observed y-values compared to the group mean or a fitted value. The total sum of squares is the addition of sum squared error (SSE) and sum squared of the variable.

SSE $$\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$$ **Eqn. 3.1**

SS_variable $$\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2$$ **Eqn. 3.2**

Degrees of Freedom summarizes the independent data groupings by subtracting one from the total number of levels. In this experiment, the levels were variation type or saltwater immersion pressure, and the mean compressive properties were compared. The sum of squares divided by degrees of freedom results in the Mean Squares. Chi-square is a test statistic as a function of ranked means and sample sizes. The ANOVA table contains a p-value, which tests whether the mean values significantly differ between levels of each variable. The null hypothesis that the means are the same can be rejected, and the alternative hypothesis that the means are different can be accepted if the p-value is less than or equal to the significance level, alpha (α). The Bonferroni correction was applied to the significance level to reduce false positives, or Type I error, by dividing an uncorrected 0.05 level by the number of Kruskal-Wallis tests. When only one test is applied, the significance level remains 5%. The null hypothesis rejection in this case occurs with 95% confidence. Otherwise, if the null hypothesis is not rejected because the p-values are greater than 5%, then there are different means between at least two levels of the variable being tested. In the example test results, the P-value is 0.16, which does not reject the null hypothesis, so the means between levels are not different.

Table 1: Example of Kruskal-Wallis Test Results

	Sum of Squares	***DF***	***Mean Squares***	***Chi-sq***	***Prob > Chi-sq (P-values)***
Variable/Factor	179.80	3	59.93	5.14	0.16
Error	485.20	16	30.33		
Total	665	19			

The produced ANOVA table only recognizes surface level the difference between the means exists. A post-hoc test is required to output p-values that proves which two sets of levels have different means. It outputs a boxplot similar to Figure 4 that visually shows the median, 25th to 75th percentile range (interquartile range), minimum values, and maximum values. The data is skewed when the blue outline showing the interquartile range is not centered between the maximum and minimum values. The larger hourglass shapes, or "notches" on the vertical side of the percentile ranges, have a larger deviation from the mean.

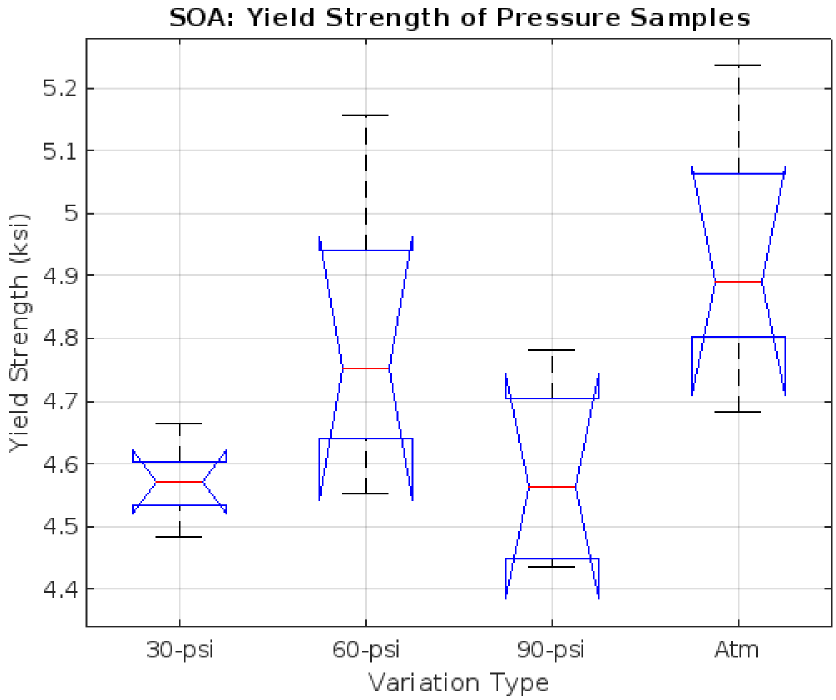


Figure 4: Example Box Plot from Post-Hoc Test

Chapter 4
Variation Possibilities and Potential Errors

4.1 Variation Possibilities and Rationale

Printing process parameters may change the outcome of results for material properties. For example, sculpt clear resin may have different properties if sourced from one manufactured batch versus another or if one batch has been stored on a shelf longer. If a variable is not considered and changed unknowingly, this will increase error of the results. Variables that could impact results include the resin supplier, print settings, printing defects, and post-processing techniques.

Variations in the print settings will affect the material properties of the print. Exposure time per layer, when lengthened, will increase the amount of time that each layer is cured during the printing process. This will affect the material's brittleness based on past research where increasing cure time changes the compressive strength [1].

From previous experience printing with the MSLA printer, some samples printed may contain voids that result from air bubbles. A build plate containing 9 samples only had one sample with obvious voids. To reduce errors from voids affecting the amount of water absorption, any samples with noticeable voids were replaced by samples without voids. The samples with these defects are not created consistently enough to logistically be worth testing. Still, they would warrant a future experiment that investigates the cause and impact of the voids on water absorption.

Variations in post-processing methods may affect the experiment results. Washing method in the alcohol along with UV cure time are major variables that have been proven to change material properties [35]. Washing has the potential to test submersion for a single time period or washing in old, hazy alcohol versus new isopropyl alcohol. The submersion time of the wash could also be tested. Increasing or decreasing UV cure time is known to affect the compressive properties of the resin [1]. Other smaller variables that have the potential to effect error are the time that the prints sit on the build plate before removal and the drying method of the samples after washing but before curing. Drying methods may include drying by sitting in air, having a fan circulating air within an enclosure, using an air compressor, using paper towels, or using microfiber towels.

Knowing that the purpose of the research is to provide an expectation of what the audience should expect from compressive properties of the resin after water absorption and UV cure, the effect of variables that are more difficult to keep consistent is important. The source that the resin is bought from would be a common source of error for applying this research. In addition, the washing process is a variant that may easily be forgotten about but could impact material properties. The drying method before curing is another consideration that could affect results, but accessibility to a compressor, circulating air within an enclosure, or microfiber towels may be limited. So, air drying and paper towels are prioritized. Below, the prioritized variables are represented in a chart.

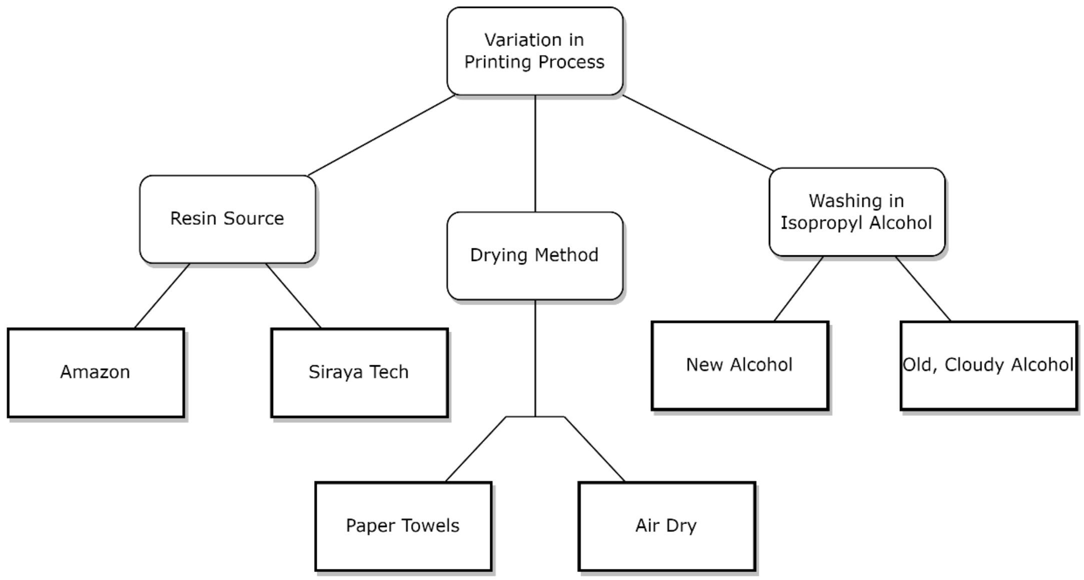


Figure 5: Variables in Printing Process

The theoretical ideal printing conditions include buying resin directly from the manufacturer, Siraya Tech, to limit the time spent sitting on a shelf. When washing, if the alcohol is cloudy, it has particles of old resin in it, and the surface quality of the post-processed part will be affected. If leftover resin particles are in the washing container, the parts will be sticky after curing. New alcohol prevents this. It is unknown if surface quality impacts the compressive properties of the resin. When drying, the optimal method ensures that all alcohol is dry from the part. Otherwise, the weight measurements for water absorption at atmospheric pressure will be skewed.

Of the potential variables that could be changed, a limited number of them must be selected for time management purposes. Testing the effect of one additional variable on the control, water absorption, and UV cure samples would double the number of samples and increase the time to print, post-process, and compression test the samples. Estimated print time varies based on the number of layers being printed. For one build plate with any number of samples on it, the print takes 3 hours. The total time added for one extra variable is estimated to be greater than 39 hours of continuous printing. Since the baseline control method for comparison based on theoretical ideal conditions is resin sourced from Siraya tech, washing solution being new isopropyl alcohol, and complete dryness of the parts after washing. Thus, the resin source and the washing solution quality were selected as the variables in this experiment. The variation in the resin source changes when the resin is bought from Amazon versus Siraya Tech. The washing solution quality was compared when it was new solution directly from a new bottle compared to a cloudy, old alcohol that simulates many washings occurring without the user changing the solution.

After samples have finished absorbing water, errors may arise if the samples expel any water before their weight is measured. However, according to the ATSM D570 standard, drying after long-term immersion with a dry cloth and then immediately weighing the sample is an adequate method. Although the standard does not include testing under hydrostatic pressure, several sources testing water absorption under pressure have been known to place samples post-immersion in a sealed container with water while being transported to the material testing destination [4, 31]. This method will be kept consistent throughout the experiment.

Another consideration is the saltwater mixture in the water absorption containers. Over time, the salinity may change, but if the salinity is set at the beginning of the experiment, then this is a systematic error that would affect all samples the same as long as the same number of samples is placed in each container. This assumption is similar to the water absorption ASTM standard not requiring water changes for long-term immersion in their distilled water.

4.2 Summary of Variation Methods

The resin type was bought from either Amazon or Siraya Tech (the manufacturer). The resin type used to print the current variation type was poured as a 40-mL batch into a washing container filled with 2500-mL of new alcohol. This created a milky color in the washing container. There are 4 combinations of variation with these 2 variables. The figure below represents the combinations explored in this experiment.

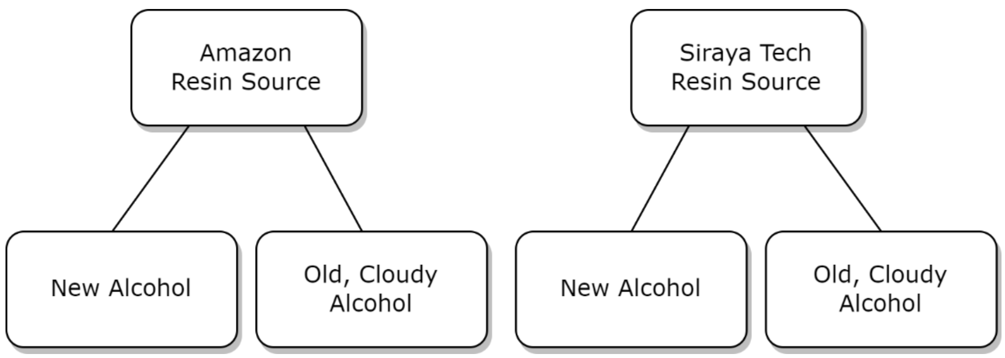


Figure 6: Experiment Variation Summary

Each variation scenario, for example, Amazon Resin washed in new isopropyl alcohol, was applied to all experimental samples. So, each exposure (water absorption, UV cure, and control samples) had 4 sets of samples tested, each with different variations. The variations were also included in the experimental ranges for each phase. Saltwater absorption, for example, at the individual pressure ranges (atmospheric, 30-psi, 60-psi, and 90-psi) had 4 sets of samples per pressure. In UV cure testing, each post-processing cure time contained 4 sample sets.

Chapter 5
Experiment Preparation

5.1 MSLA 3D Printing

Two MSLA 3D printers were available in the Underwater Tech Lab (UTL) at Florida Tech, but only the newest printer was used to keep results consistent and introduce less variables. The printer is the Anycubic Photon Mono X, which has a 192 x 120 x 245-mm print volume. The Siraya Tech Sculpt Clear resin was bought in 1 kg bottles for $40 each [38].

Several potential variables could affect the outcome of the materials testing due to the printing process and environment. To avoid errors from the printing process, the following process was used for printing:

1. Verify print settings in the slicer software and UV power in the machine settings.
2. Print from the same printer for every single print.
3. Use the same bottle of resin per batch of samples in the same printer vat.
4. Print extra samples for each group to replace any samples that have noticeable voids or air bubbles upon inspection.
5. Use the same cure station for all samples with the same number of samples on the rotating plate each time.
    a. Run the cure station for a consistent time throughout the experiment.

Before the experiment samples were printed on the MSA 3D printer, a calibration print ensured the print settings were tuned properly according to the resin manufacturer's suggestions. The goal of the calibration was to adjust the exposure time and observe how it affects printability.

Figure 7: Calibration Test Model [19]

For the calibration test model in Figure 7, the manufacturer suggested beginning analysis with the low-level features on the part such as the raised and recessed crosses and the two triangles' intersection points. If the recessed crosses appear filled with resin, then the UV exposure time per layer is too high. If the extruded crosses did not print, then underexposure occurred. If the intersection of the two triangles is not touching, then the print is underexposed. If the meeting of the triangles shows that they are touching but extra resin is cured where they meet, then the print is overexposed. See Table 2 for a summary of features categorized as underexposed or overexposed, with higher priority features denoted with an asterisk.

Table 2: Calibration Print Exposure

Underexposed	***Overexposed***
Extruded crosses not printing	Recessed crosses filled with resin
*Triangle points not touching (rounded)	Triangle points overlapping with extra resin cured
Extruded pins not printing	Recessed holes not defined
**Cube does not print because supports fail	N/A

The large cube on the upper left in Figure 7 proves the success of printing more complex geometry. The resin manufacturer suggests prioritizing the success of the cube over fine-tuning the other model features [19].

The only print setting changed while calibrating was the exposure time, and Sculpt Clear resin was used beginning with print settings from [1]. Figure 8 compared the calibration prints with exposure times of 9-12 seconds in images a-d respectively.

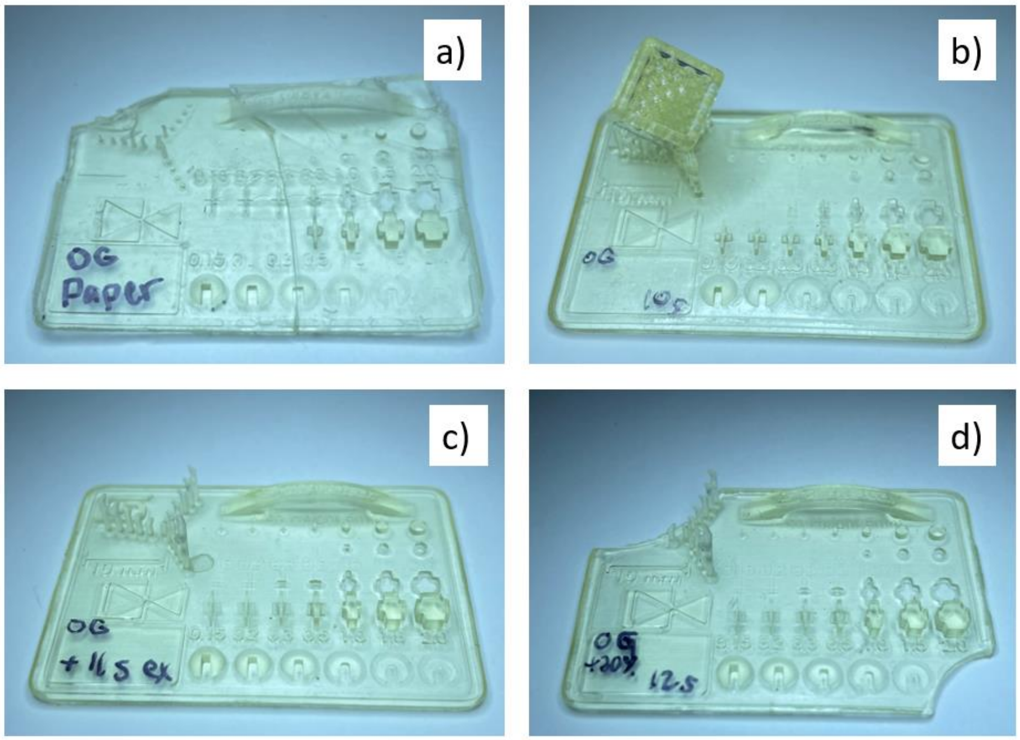


Figure 8: Sculpt Clear Calibration Models

The removal from the printing build plate caused the cracking seen in “a” chipped corners in “d,” and the breaking of cubes from Figure 8, “c,” and “d.” The cube in “a” did not print because the supports failed, but all other cubes were successfully printed with adequate cone supports. The extruded crosses printed on all except the print with a 9-second exposure.

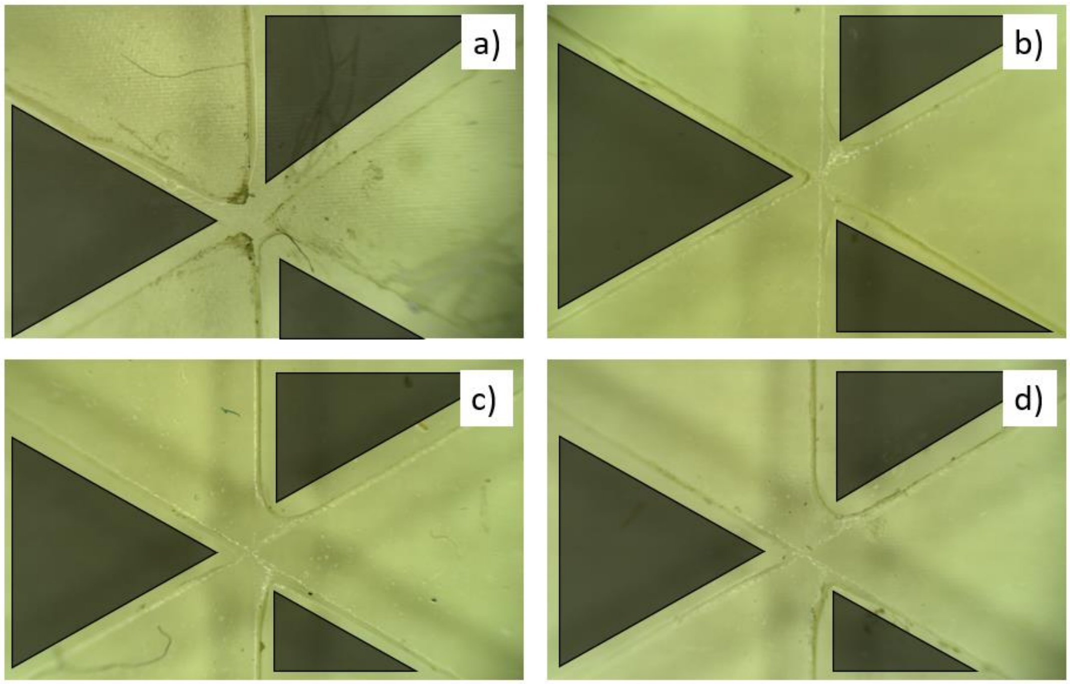


Figure 9: Sculpt Clear Test Model Features (2X zoom)

Figure 9 shows the triangles' intersection with the recessed portions noted by black triangles. The images a-d again correspond to the exposure times 9-12 seconds. The raised triangles in "a" were not completely touching which demonstrates that the print was underexposed. While the triangles in images "c" and "d" appear fused together due to overexposure, image "b" has the most defined triangle intersection with only slight overexposure. Thus, the print settings with the 10 second exposure time in image "b" of Figure 8 and Figure 9 were selected.

Table 3: Print Settings

Print Setting	*Sculpt Clear*
Beginning Number of Layers	6
Beginning Exposure Time (s)	20
Layer Thickness (µm)	50
Light-off Delay (s)	3
Exposure Time (s)	10
Lift After Print (mm)	8
Lowering Speed (mm/s)	5
UV Power (%)	62

Table 3 above shows the final print settings selected for this research.

5.2 MSLA 3D Printing Methods

Lychee Slicer was the slicer software used. After importing the compression sample used in this research, the parts were arranged on the build plate so that the flat side of the cylinder was against the build plate.

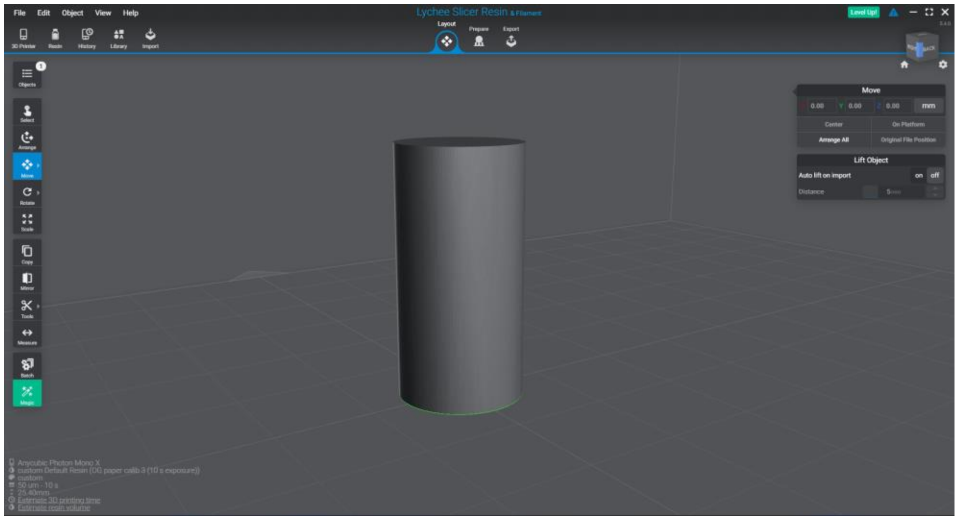


Figure 10: Lychee Slicer ASTM Cylinder Orientation

The sliced files were started on the Photon Mono X machine in Figure 11 after the vat was filled with resin. The printed compression cylinders were washed then cured on the Anycubic Wash and Cure 2.0 machine in Figure 12. The left-most button on the machine was used to toggle between "Wash" and "Cure" mode. The turn knob was used to set the time for washing or curing. All washing of samples occurred for 4-minutes, and curing occurred for 6-minutes.

The UV Cure station emits 405-nm wavelength light in the visible light spectrum. The station has a motor within the base that spins the turntable during curing to evenly expose all sides of the printed object. The tinted enclosure was placed in a proper position for safe curing during operation to prevent user exposure to UV radiation.

Figure 11: Anycubic Photon Mono X [11]

Figure 12: Wash and Cure 2.0 [18]

Chapter 6
Compression Testing

6.1 Materials, Instruments, and Preparation

Before testing occurred, each MSLA sample was labeled specifying which sample set it was part of and its sample number. The sample labels contain 3 or more letters. The first letter signifies whether the sample was printed in resin sourced from Amazon or Siraya Tech with either "A" or "S" respectively. The second letter "O" or "N" refers to the quality of isopropyl alcohol from post processing (old alcohol or new alcohol). The next letter or letters and numbers specify which testing group the sample was in. Water absorption samples were denoted by "A," control samples by "C," and UV cure samples by "UV." The water absorption samples also denote the pressure that they absorbed under (either none, 30, 60, or 90). The UV cure samples have a number after "UV" representing the cure time. The sample number is labeled with an underscore then the sample number. If there is no sample number present, then the label is describing a mean value. See the table below for example labels from testing groups.

Table 4: Sample Labels

Label	*Meaning*
ANA_1	Amazon, New alcohol, Water absorption, Sample 1
AOUV6_1	Amazon, Old alcohol, UV cure of 6-minutes, Sample 1
SNC_1	Siraya Tech, New alcohol, Control sample, Sample 1
SOA60_1	Siraya Tech, Old alcohol, Water absorption, 60 psi, Sample 1

To increase efficiency during testing, each sample diameter and length was measured before testing began. The dimensions were recorded, and the square root of area was calculated. The Tinius Olsen 25ST universal testing machine (UTM) at Structural Composites, Inc. was used for compression testing of the samples. The load cell used for the Tinius Olsen had a maximum load of 5000-lbf that was set up on the machine along with the two compression plates. The position rate during the test was set to 0.03-in/min so that the testing of each sample took between 1 and 3 minutes from when force was applied until the machine was stopped. The Horizon software controlled the machine in the TOVMC application and provided a live data viewer.

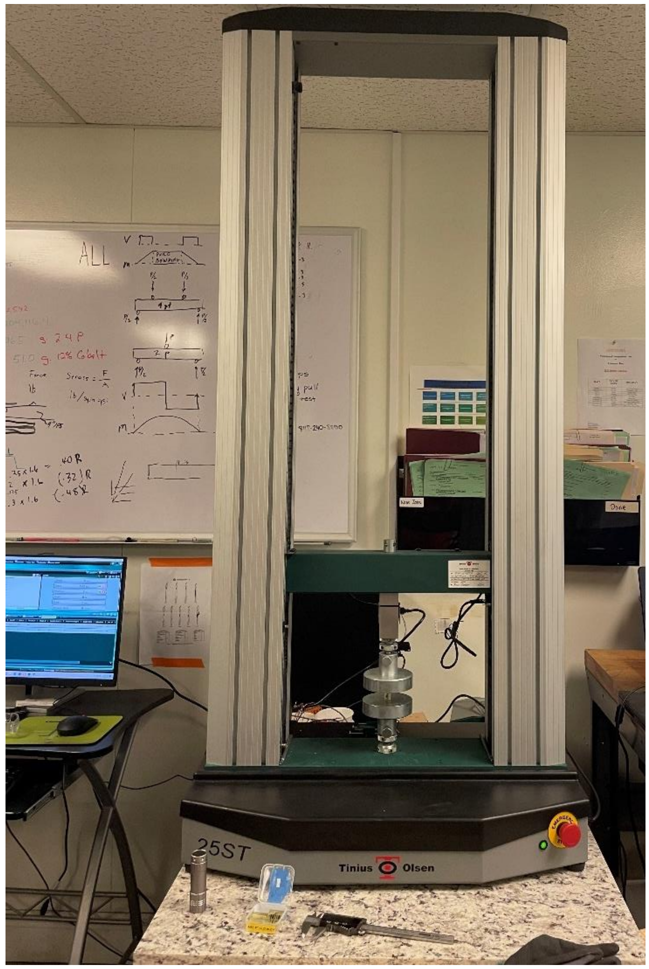
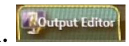


Figure 13: Tinius Olsen 25ST UTM

Machine set-up was required to properly export the raw data produced during compression testing. The file name of each exported file was set to the labeled sample number for these tests by setting the Panel ID in the dynamic path creator. The following steps were used in the Horizon Software on the UTM.

1. Power on the machine and computer.
2. Open the Horizon software.

3. Add a new Testing Tab, select the method under testing options.
4. Select the Output Editor tab on the upper left side of the screen. 

5. Under the Output Editor tab, select Data Exporting. 

6. Click the New Export tab which has an image of paper with a sun logo and a green check mark.
7. If asked for Export Type, select "Points: ACSII" for raw data points then click OK.

Figure 14: Tinius Olsen 25ST UTM

8. In the options file information tab under the primary file, select "Built" from the drop-down menu and hit the build button. 

9. Hit "Add" in the dynamic path creator and add following elements separately. 
    a. Select the element type as "Text" and enter the desired file path ("S:\LAB_Data\Test Results\2023\Suzie Thesis Samples\").
    b. Select the element type as "Result" and enter the result as Panel ID.
    c. Add element 3 with type "Text" and enter ".csv"
10. Once the file path is saved, under the "Data to Export" section, hit "Add" to add a column of raw data to the exported file.
    a. Add force as one column then position as another.

11. Zero the force on the machine control tab before beginning.

Note that after the file output is set up, it will be saved as a “Current Output” with the name given. To test the output and ensure data collection was occurring properly, several test samples were run in the machine until a .csv file was exported to the correct file location with the correct raw data output.

6.2 Samples and Procedures

The selected standard compression sample size was a cylinder with diameter 0.5-in and height 1-in. Overall, 200 samples were compression tested during the experiment. This included 20 control samples, 80 water absorption samples, and 100 UV cure samples. Each sample group contained four levels for variation types. The water absorption also contained samples with 5 different cure times while the water absorption contained samples that were immersed at 4 different pressures.

The following steps outline the compression testing procedure followed during this experiment.

1. Open the Horizon and machine control software and ensure that the proper steps were followed for data exporting.
2. Make sure the correct crosshead is on the UTM and that the software is set for the compression test.
3. In the machine control tab, Jog the upper crosshead to about one inch above the bottom crosshead or until the samples fit between the crossheads.
4. Zero the position of the crosshead and the force gauge on the machine control tab.
5. Enter the required columns into the current test sample’s row on the testing tab.
    a. Operator and Customer as initials of the operator.
    b. Job # and weight as 1.
    c. Failure Mode as Yield.

6. Enter the sample label of the current sample about to be tested into the Panel ID space.
7. Input the square root of the sample's area from the pre-made excel sheet into width and height columns of the Horizon test sample UTM computer software.
8. Place the sample between the center of the crossheads.
9. On the testing tab under the Action/Status section click the green play button to run the test.
10. Continue testing the sample until it reaches the plastic region, and the strain rate slows on the software's real-time stress-strain graph (about 2 minutes after the machine begins reading stress and strain).
11. Click the red "X" on the Action/Status to stop the test.
12. Check that the Panel ID was entered correctly as the sample label.
13. Click the checkmark that exports the data file.
14. Remove the sample.
15. Check the file directory to ensure that the data file was exported.
16. Repeat steps 6-13 until all samples have been tested.
17. Compress the results folder to a .zip then put it onto a flash drive.
18. Shut down the computer and turn off the machine.

Note that the square root of area was entered into the height and width columns so that the software calculates the correct area of each sample. This occurred because there was no option to enter a diameter. In the case that the machine software froze, and no data was saved for that sample, an extra sample was tested.

6.3 Analysis

The test standard for reference is ASTM D695-15, the Standard Test Method for Compressive Properties of Rigid Plastics [5]. The compression test method produces raw data containing Force (F) in lbf and position in inches. From this, stress and strain were calculated. First, stress (σ) in psi was calculated from the Force (F) divided by cross-sectional area (A).

$$\sigma = \frac{F}{A} \qquad \textbf{Eqn. 6.1}$$

Second, strain (ε) was calculated from the change in length (ΔL) from position of the machine crosshead during the experiment over the original sample length which was measured and recorded before the experiment.

$$\varepsilon = \frac{\Delta L}{L} \qquad \textbf{Eqn. 6.2}$$

From the stress and strain data, Young's modulus and yield strength were gathered. Young's modulus is the stress over strain or the slope of the linear portion within the elastic region on the stress-strain graph. A high modulus value corresponds to a more brittle material while a low modulus value corresponds to a more ductile material. In the ocean environment, the yield strength is considered important for pressure housings that may collapse after yielding [39, 1]. The yield strength and Young's modulus were analyzed for each sample. The yield strength is the point where the transition from elastic to plastic region occurs. The material can return to its original state in the elastic region, but the material deformation in the plastic region becomes permanent. For each sample set where $n = 5$, the mean of the yield strength and Young's modulus were calculated along with the standard deviation for each. The below equation shows standard deviation where yield strength or Young's modulus in a vector of 5 samples is represented as "x" and the mean of the vector represented as $\bar{x}$.

$$s = \sqrt{\frac{\sum_{i=1}^{n} |x_i - \bar{x}|^2}{n-1}} \qquad \textbf{Eqn. 6.3}$$

MATLAB was used for data processing of all samples in this experiment (refer to the code located in the Appendix). The data from the UTM was output in an Excel file that contained two columns of data per sample tested. Each Excel sheet was placed in a single file directory categorized by sample type (control, UV cure, or water absorption). The MATLAB code for each file in the directory set created a data structure where the details of one sample of that type were appended to one row of the structure. For example, there were 20 control samples, so that data structure contained 20 rows in total where force and position were cells in separate columns. Calculations occurred in a for loop to apply them to each sample in its row number. For each sample if the force was less than zero, then those force and position indices were removed. The area and length were read into the data structure as columns from a separate Excel sheet. Stress and strain were calculated and appended as new columns as well. Then, they were both filtered to create smooth data by using a Butterworth filter. Figure 15 demonstrates a sample's windowed stress vs strain before and after the data was filtered.

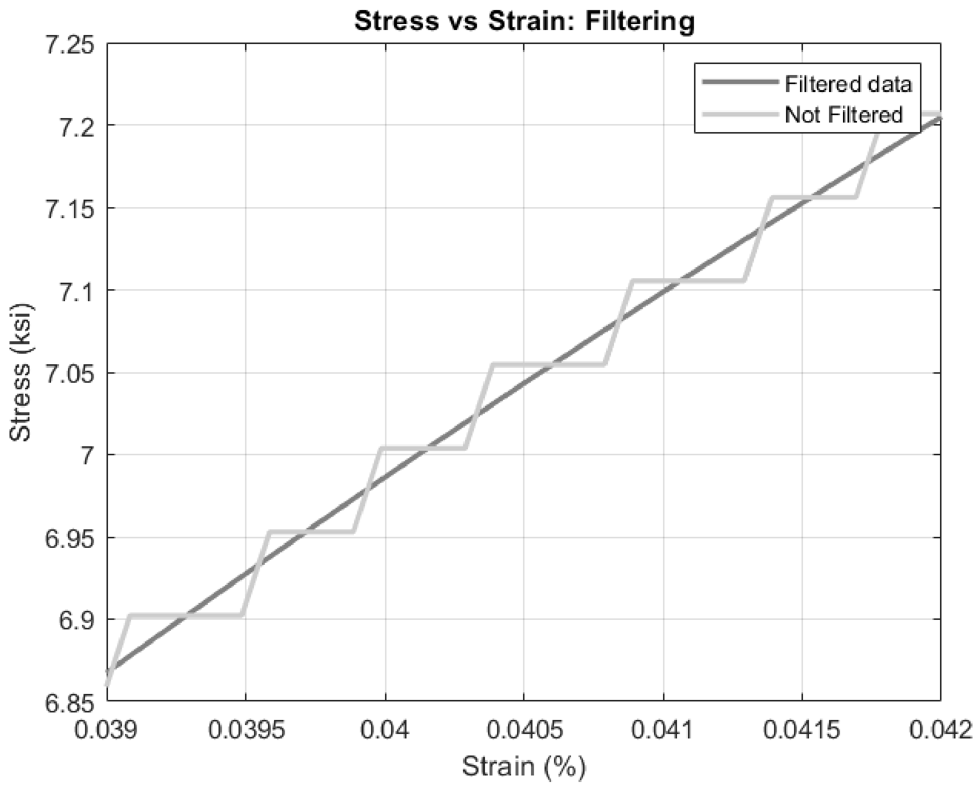


Figure 15: Filtering of Stress-Strain Curves

To automate finding Young's Modulus for the samples, the slope was found between every 2 points on the stress-strain curve. Assuming that the slope did not increase past the linear portion of the curve, the maximum slope was taken as Young's Modulus for each sample. The toe region on the curve exists from the start of the curve until the linear portion is reached. A strain shift was applied to compensate for the toe region as seen in Figure 16. This accounts for the take-up in slack of the UTM in the initial force application region and effectively zeroes the strain. On the original stress-strain curve, the strain was shifted so that the x-intercept of the line created by the slope in the linear portion (Young's modulus) was moved to the origin.

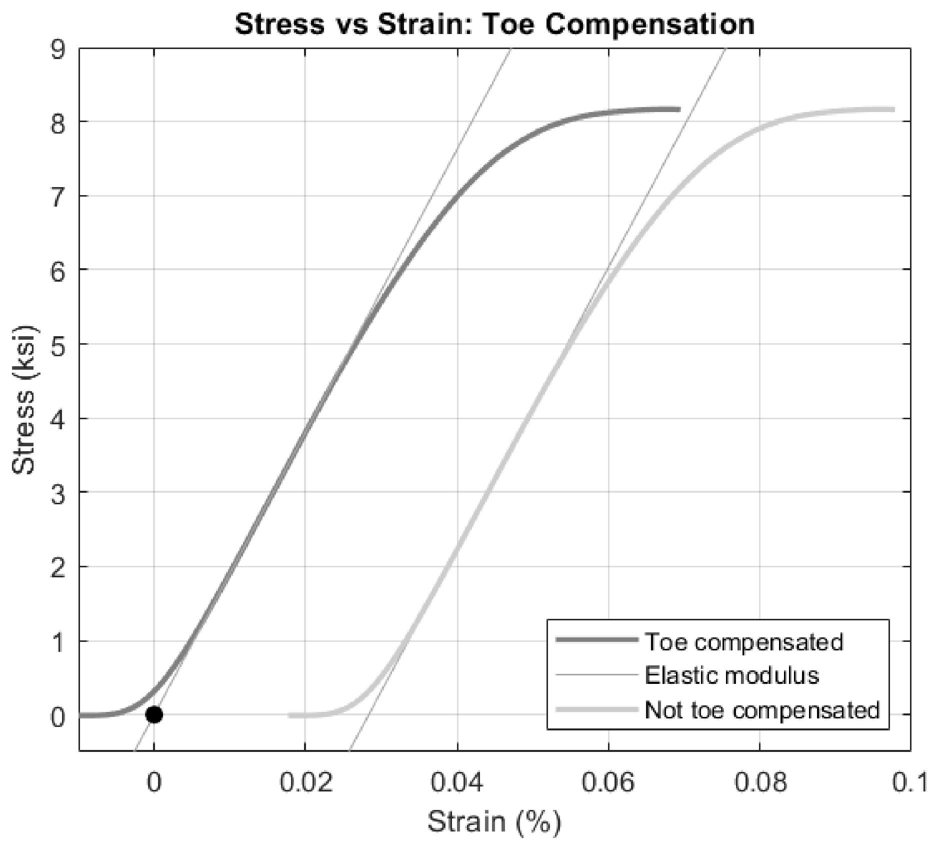


Figure 16: Applying Toe Compensation

The compressive yield strength for each sample was the stress at the point on the curve where the minimum change in slope occurred. Figure 17 summarizes how the modulus and yield stress were obtained from the stress-strain curves by using the first and second derivatives.

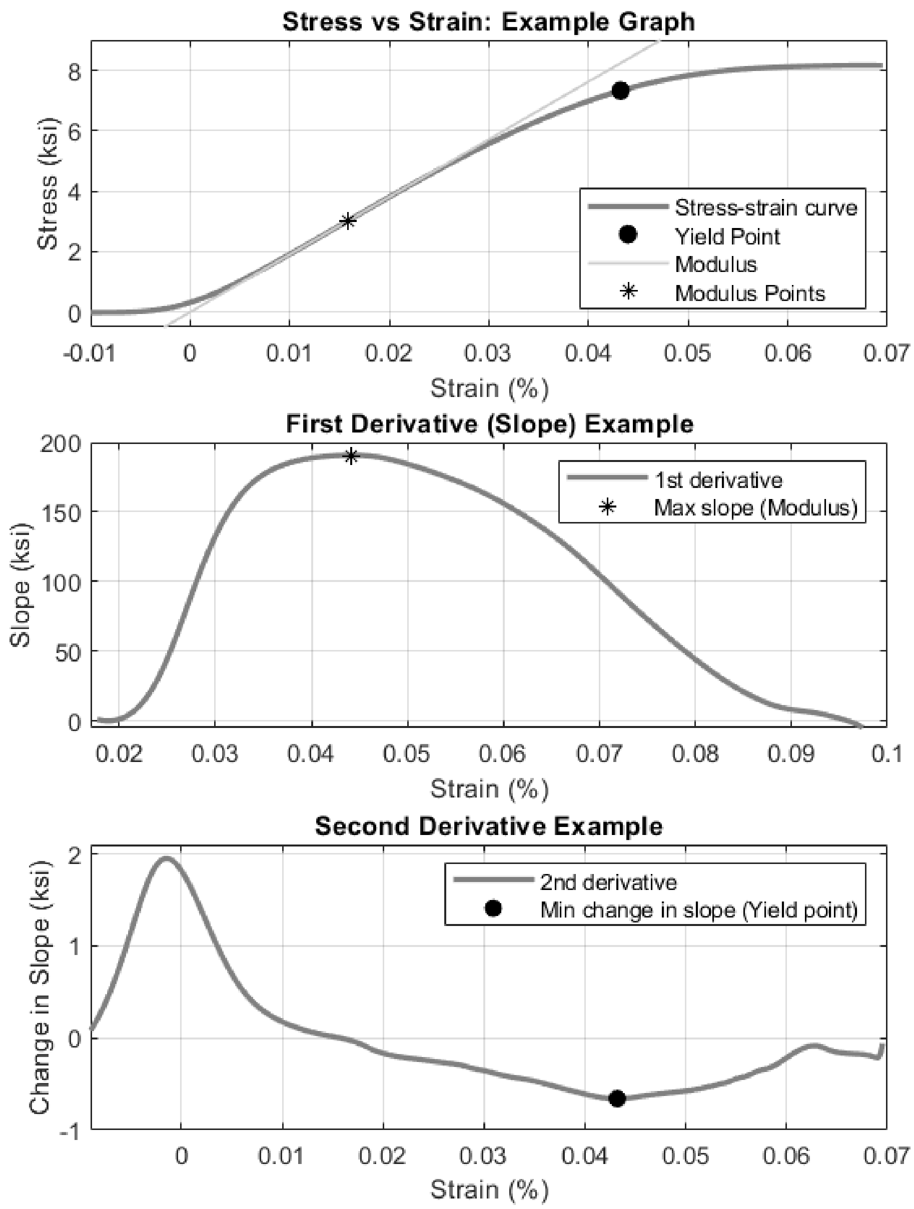


Figure 17: Obtaining Data from Stress-Strain Curve

The control samples tested for the four different variation scenarios consisted of 20 total samples. Once each set of 5 samples was obtained with its moduli and yield strength, the means were taken, and the standard deviation was recorded. Figure 18 shows a bar graph comparing the details of the mean modulus and yield strength for each variation. The standard deviation of each mean is shown on the plot as an error bar.

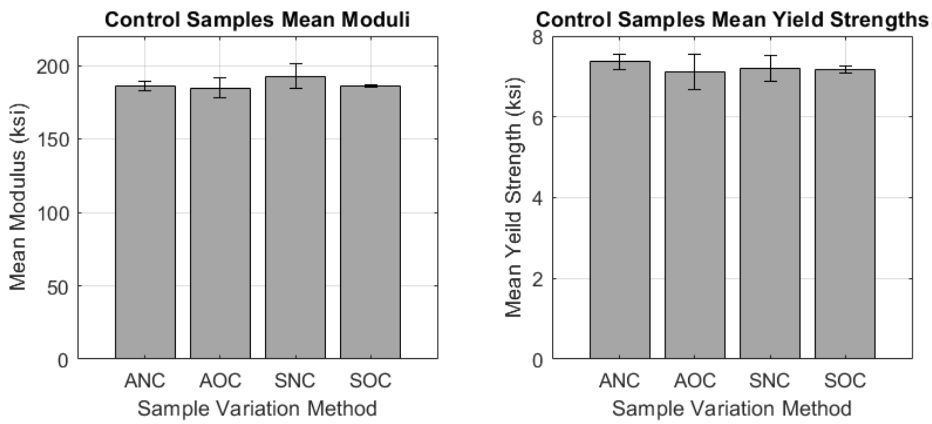


Figure 18: Control Sample Means

The highest modulus was the resin sourced from Siraya Tech, which was washed in old alcohol (SOC), while the highest yield strength was the Amazon resin, which was washed in new alcohol (ANC). The standard deviations were smallest for the SOC samples and larger for the AOC and SNC samples. If these trends are consistent throughout the UV cure and water absorption results, then the variations have a consistent effect on the samples and should be considered when designing printed objects where compressive properties are important.

Table 5: Control Sample Compressive Properties

Variation Type	*Modulus (ksi)*	*Yield Strength (ksi)*
ANC	185.84 $\pm$ 3.44	7.37 $\pm$ 0.19
AOC	184.54 $\pm$ 6.70	7.11 $\pm$ 0.43
SNC	192.78 $\pm$ 8.29	7.20 $\pm$ 0.33
SOC	186.07 $\pm$ 0.95	7.16 $\pm$ 0.09
Overall Mean	188.24 $\pm$ 6.25	7.26 $\pm$ 0.31

The standard deviation for both compressive properties of the SOC samples was much less than the other 3 variation methods. The modulus for SNC samples was higher than the other three methods, but it also had the largest standard deviation, which overlaps with the other three standard deviations and means. Its higher standard deviation results from the larger distance to the mean of certain sample numbers. Out of the five samples tested, SNC sample number 5 had to be re-tested in the machine due to software issues. This sample likely caused the larger standard deviations within the SNC samples because it had the largest distance modulus from the mean. However, the overall mean modulus (188.24 $\pm$ 6.25 -ksi) calculated without separating the 20 total samples into variation categories had a lower standard deviation than the highest two grouped samples (SNC: 192.78 $\pm$ 8.29 -ksi and AOC: 184.54 $\pm$ 6.70 -ksi). This is because the larger sample size of 20 samples, including all variation types, had more results grouped closer to the mean than when the samples were split into variation groups where the sample size was 5. Since the standard deviation formula has sample size in the denominator, it makes sense that the standard deviation would be lower for the overall mean than the means of the variation type. Similar standard deviation trends were seen with the overall mean of yield strength since the $\pm$ 0.31-ksi standard deviation was less than the deviations for AOC and SNC. The greatest difference between any two mean modulus values for variation types was 4.47%. The greatest difference between yield strengths was 3.66%. These low values demonstrate that the variation type does not significantly affect the properties. Rather, the error from individual samples has a greater effect. When observing the 20 samples individually, the greatest percent difference was 15% when the largest modulus was included or 9.8% when the sample with the largest modulus (SNC sample 5) was not included. Thus, the control samples suggest that variation type does not have a significant impact compared to individual sample error, but this can be confirmed by statistical analysis.

The control samples' means between variation type groups produced p-values in Table 6 from the Kruskal-Wallis test. There was only one test for each compressive property, so the significance level remained 0.05 even after the Bonferroni correction was applied.

Table 6: Control Sample Kruskal-Wallis Test P-values

	P-values
Modulus	0.16
Yield Strength	0.18

Neither the compressive modulus nor the yield strength means were affected by variation type since their p-values were greater than the 5% significance level. This does not reject the null hypothesis; the means between groups were not significantly different. The overall means for control samples can subsequently be used to compare with other results.

Chapter 7
Water Absorption

7.1 Materials and Instruments

Water absorption samples were immersed in saltwater for a length of time before removal. Instant Ocean salt was used to create the saltwater, and a YSI conductivity meter from the Center for Corrosion and Biofouling (CCBC) was used to verify the salinity of 35-ppt. The CCBC actively researches coatings used to mitigate biofouling and systems such as cathodic protection used to mitigate corrosion. The lab is led by Dr. Swain, an expert in the field.

Figure 19: YSI Conductivity Meter [40]

The scale in Figure 20 measured the sample mass accurately to 0.001 grams.

Figure 20: Scale [41]

The scale was calibrated before use as recommended by the manufacturer. A sealable container was used for the water absorption samples at atmospheric pressure. A standard CO^2 aluminum tank, seen in Figure 21, provided a portable pressure vessel to keep the samples at a constant pressure. Three tanks were used to reduce the time required to test immersion at multiple pressures. For instance, the three tanks each contained several samples where a different pressure was applied to each tank. Because of this, the samples were able to be removed and compression tested simultaneously. The tank neck is a female ⅝-18 thread size, which the resin printed ½" diameter compression test samples could fit through upon entering and leaving. The tank was pressurized through a regulator adapter with two female ⅛" NPT fittings. A standard paintball fill quick-disconnect fitting was used to fill the tank. A digital pressure gauge attached to the second ⅛" NPT fitting ensures that the tank is filled up to the correct pressure before closing the tank's pin valve.

Throughout the experiment, the pressure was kept at plus or minus 2-psi within the starting pressure.

Figure 21: Pressure Vessel

The air compressor in the UTL had a maximum holding pressure of 125-psi which can fill the pressure vessel up to 100-psi safely before the maximum was reached. Thus, intervals of 30-psi were used from 30- to 90-psi.

7.2 Samples and Procedures

Immersion of MSLA-printed samples occurred until the samples reached saturation. The change in mass of the samples was measured to determine the time until saturation. Second, the samples were compression tested according to ASTM D695-15 [5]. The water absorption occurred at shallow and deeper depths simulated by immersion within a simple container and pressurized container. The pressures tested for this experiment include atmospheric pressure, 206.84 kPa (30-psi), 413.69-kPa (60-psi), and 620.53-kPa (90-psi). These pressures equate to ocean depths of 21.15-m (69.4-ft), 42.31-m (138.81-ft), and 63.46-m (208.21-ft) from re-arranging the formula below where ρ is density of saltwater (1023.6 kg/m^2), g is acceleration due to gravity (9.80665 m/s^2), and Z is water depth.

$$P = \rho g Z \qquad \textbf{Eqn. 7.1}$$

Each container of filtered water was mixed to 35-ppt at the start of immersion. The Instant Ocean mix ratio of 1-tablespoon per 2-cups of water yielded a specific gravity of less than 1.024 (32.1-ppt), so a little more salt was added until the proper salinity was reached [42]. Samples were immersed in groups of 20 containing the labeled samples, with 5 samples in each variation group, and the immersion time at the start timed the removal of all samples so that compression tests occurred in a single sitting to prevent immersion of some samples longer than others. The time immersed was determined by the atmospheric samples' percent increase in weight over time. To check percent weight, the atmospheric samples were removed from their container periodically to measure their weight. Initially, doubling time intervals starting at 6-hrs were used until larger 2-week time intervals were adequate to present smooth data and test change in weight. As recommended by ASTM D570, the samples were immersed until the weight increase between two sample periods was less than 5 mg or less than one percent of the total increase [20]. The time required to reach this point is defined as the saturation time. Once saturation was reached for the atmospheric samples, the saturation of the pressurized samples should also have been reached. Sample removal for all pressures occurred after saturation before compression testing. For every measurement taken with digital calipers and weight measurements, the measurement was taken at least 3 times, and the average was used to minimize measurement error. The procedure for the immersion is listed in steps.

1. Print samples.
2. Label all samples with Sharpie.
3. Weigh each of the samples and record in Excel.
4. Measure diameter and length of the samples and record in Excel.
5. Prepare the containers with enough water to cover the samples with some extra overhead. Measure the proper amount of salt and add it to the containers.
6. Make sure the water is at 35-ppt with the YSI conductivity meter.
7. Begin sample immersion for all pressures with individual groups of 5.
    a. When immersing, make sure the pressure vessel is not pressurized before opening.
8. Check the sample weights of the atmospheric sample sets at doubling time intervals beginning at 6-hrs.
9. Continue immersion until saturation is reached.
10. Remove the samples.
11. Dry the outside of the samples with a "dry cloth" as recommended by the ASTM Standard.
12. Immediately weigh each of the samples post-immersion and record in Excel.
13. Also record the post-immersion diameters, heights, or other physical attributes.
14. Immediately after measurements have been taken, place the samples in a sealed container with salt water until compression testing begins.
15. Briefly dry the outside surface of the samples.
16. Compression test the samples.
17. Organize and analyze the data.

7.3 Analysis and Results

Water absorption of the samples calculates the increase in weight by percent to the nearest 0.01% by Eqn. 7.2 where W_1 was weight after immersion and W_0 was the initial weight before immersion [20].

$$W\% = \frac{W_1 - W_0}{W_0} x100\% \qquad \textbf{Eqn. 7.2}$$

The samples reached saturation during water absorption, during which time the water intake rate slowed down significantly. The ASTM standard recommended analyzing saturation by graphing percent weight versus the square of immersion time in hours. When the % weight plateaus and there is less than 5-mg change between two-week periods, it can be said that saturation has been reached. The graph of percent weight gain versus time at atmospheric pressure is also useful to compare the Sculpt Clear, hobbyist level resin to professional grade resins such as in [4].

Assuming that porosity is open to water absorption, a ratio of void volume to total volume will yield a percentage of void volume, where P is open porosity, V is volume of the samples, ρ_{sw} is density of seawater at 35-ppt, and M is mass. This can be investigated for all samples, even without obvious voids.

$$P = \frac{(M_1 - M_0)/\rho_{sw}}{V} * 100\% \qquad \textbf{Eqn. 7.3}$$

The data analysis for the percent weight of the samples along with compression testing results occurred in MATLAB. Water absorption of percent weight versus time for each variation type created curves where the best fit was a power function with two terms.

$$y = ax^b + c \qquad \textbf{Eqn. 7.4}$$

For each variation, the best fit had goodness of fit parameters and the following terms with their 95% confidence bounds. The R-squared values for each variation type show that the selected power model fit the data with more than 99% of variance explained from the datapoints compared to the fitted equation. Table 7 contains the power functions' coefficients for each variation type.

Table 7: Best Fit Function Parameters for Percent Weight vs Time

Variation Type	***a***	***b***	***c***	R^2
ANA	0.325 ± 0.060	0.391 ± 0.037	-0.158 ± 0.068	0.999
AOA	0.332 ± 0.046	0.396 ± 0.028	-0.169 ± 0.053	0.999
SNA	0.336 ± 0.056	0.393 ± 0.033	-0.113 ± 0.063	0.999
SOA	0.302 ± 0.071	0.414 ± 0.048	-0.093 ± 0.082	0.998

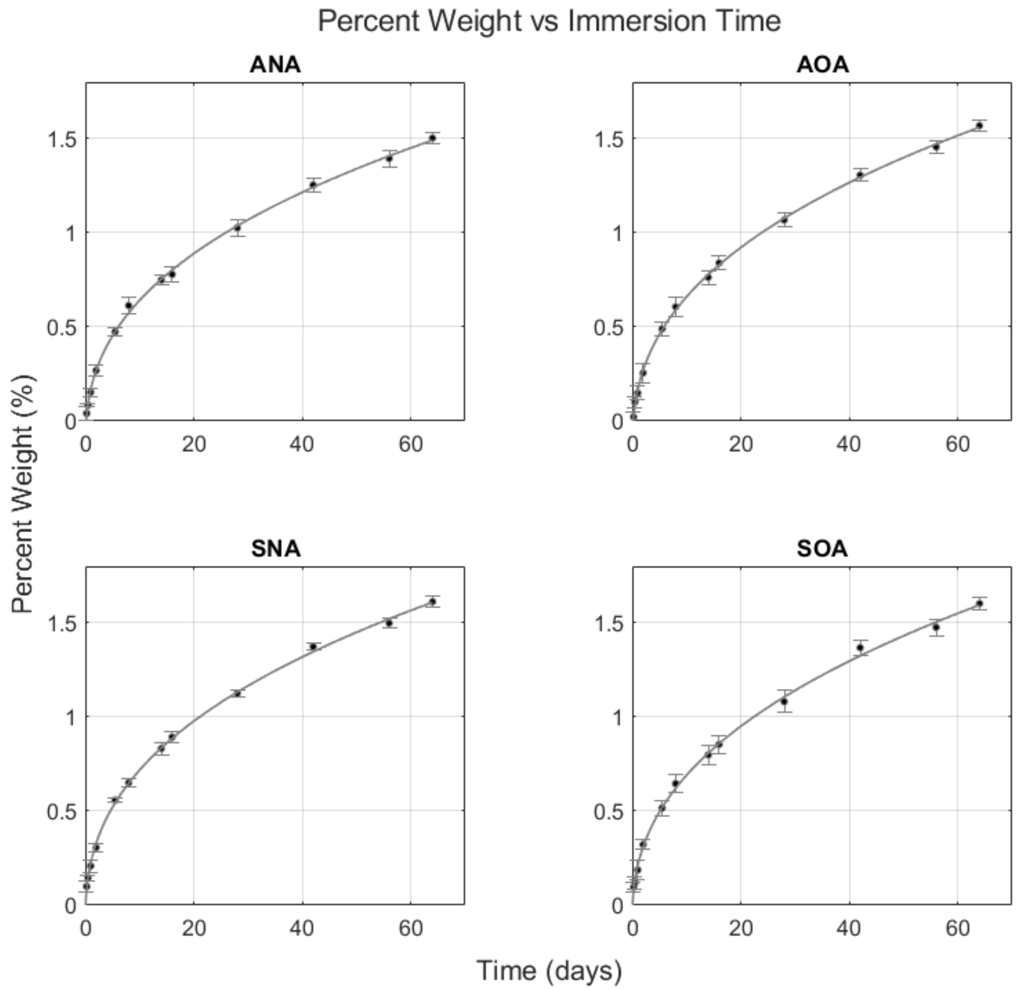


Figure 22: Percent Weight vs Immersion Time

The percent weight at atmospheric pressure for each variation in the plots above continued to increase throughout the immersion time, but at 8 weeks (56 days) of immersion time the change in weight from the previous 2-weeks was less than 5-mg, meaning saturation was reached. No plateau of percent weight was seen after saturation was reached, but water uptake appeared to continue. Because of this and the best fit being a power function, the results were not plotted with the square root of time on the x-axis since this would produce a linear line that does not plateau. So, the difference in percent weight between two-week periods is the determining factor for saturation.

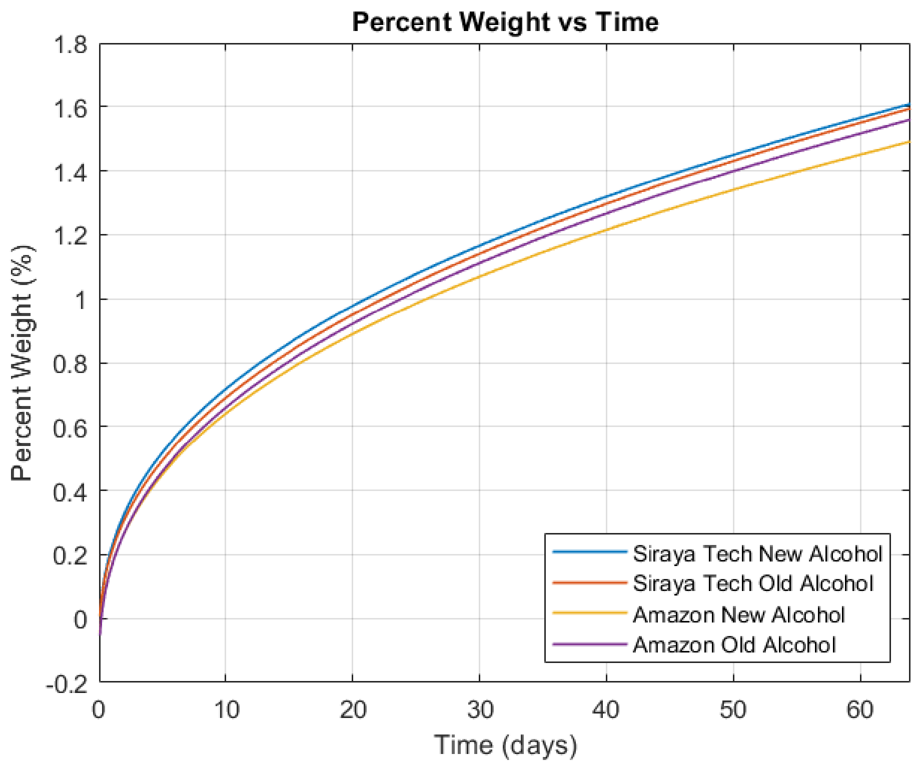


Figure 23: Superimposed Percent Weight vs Immersion Time at Atmospheric Pressure

The superimposed results for the above water absorption samples demonstrate that Siraya Tech resin had higher water absorption by percent weight compared to the Amazon resin. Additionally, the effect of the washing solution quality was greater for the Amazon resin, where the Amazon variation had a greater difference in percent weight between washing solution types. Both Siraya Tech variations do not differ much from each other and have overlapping standard deviations.

Table 8: Atmospheric Percent Weight (%) for Variation Methods during Immersion

Variation Type	*24-hrs*	*14-days*	*28-days*	*42-days*	*56-days*	*64-days*
ANA	0.15 ± 0.02	0.75 ± 0.02	1.03 ± 0.04	1.25 ± 0.03	1.39 ± 0.05	1.50 ± 0.03
AOA	0.14 ± 0.04	0.76 ± 0.04	1.07 ± 0.04	1.31 ± 0.03	1.46 ± 0.03	1.57 ± 0.03
SNA	0.21 ± 0.03	0.83 ± 0.03	1.12 ± 0.02	1.37 ± 0.02	1.49 ± 0.03	1.61 ± 0.03
SOA	0.19 ± 0.05	0.80 ± 0.05	1.08 ± 0.06	1.37 ± 0.04	1.48 ± 0.04	1.60 ± 0.03

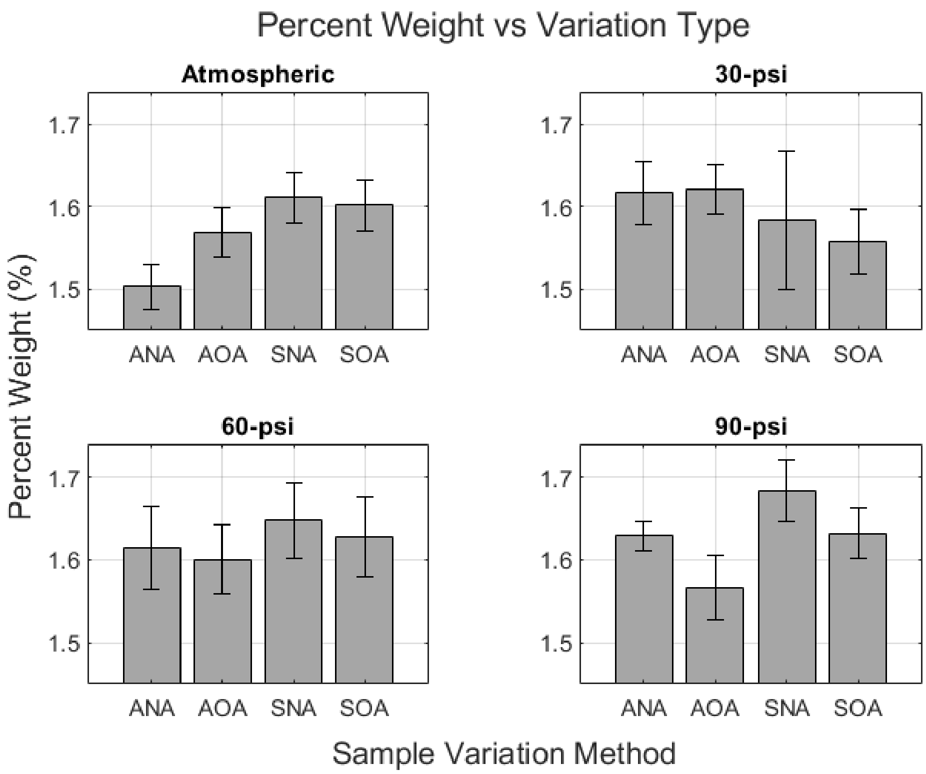


Figure 24: Bar plot of Percent Weight at Different Pressures after 64-days Immersed

At 64-days of immersion, the atmospheric samples in descending percent weight order were SNA, SOA, AOA, and ANA. Those results were mirrored for the 30-psi samples as shown in Figure 24, meaning the conclusion from Figure 23 that Siraya Tech had the higher mean percent weight did not hold valid for the 30-psi samples. The 60-psi and 90-psi variation types both had SNA as the largest water absorption and AOA as the least water absorption. The greatest percent difference between any two mean percent weights of any variation method for atmospheric, 30-, 60-, or 90-psi was only 11.96% between ANA atmospheric samples and SNA at 90-psi.

Table 9: Percent Weight (%) for Variation Methods at Pressure During Immersion after 64-days

Variation Type	*Atmospheric Pressure*	*30-psi*	*60-psi*	*90-psi*
ANA	1.50 ± 0.03	1.62 ± 0.04	1.61 ± 0.05	1.63 ± 0.02
AOA	1.57 ± 0.03	1.62 ± 0.03	1.60 ± 0.04	1.57 ± 0.04
SNA	1.61 ± 0.03	1.58 ± 0.08	1.65 ± 0.05	1.68 ± 0.04
SOA	1.60 ± 0.03	1.56 ± 0.04	1.63 ± 0.05	1.63 ± 0.03

The results from the percent weight graphs and the values in Table 9 do not provide consistent trends when analyzing variation or pressure, suggesting that neither variable significantly impacts the percent weight.

Table 10: Open Porosity (%) of Immersed Samples after 64-day

Variation Type	*Atmospheric Pressure*	*30-psi*	*60-psi*	*90-psi*
ANA	1.82 ± 0.03	1.95 ± 0.05	1.94 ± 0.06	1.96 ± 0.02
AOA	1.88 ± 0.03	1.96 ± 0.03	1.93 ± 0.04	1.88 ± 0.05
SNA	1.94 ± 0.04	1.90 ± 0.10	1.98 ± 0.06	2.04 ± 0.07
SOA	1.92 ± 0.03	1.88 ± 0.04	1.95 ± 0.06	1.95 ± 0.03

The open porosity of samples followed similar trends to the percent weight since both the open porosity and percent weight equations were a function of the sample mass. The values were calculated as a percentage of sample volume.

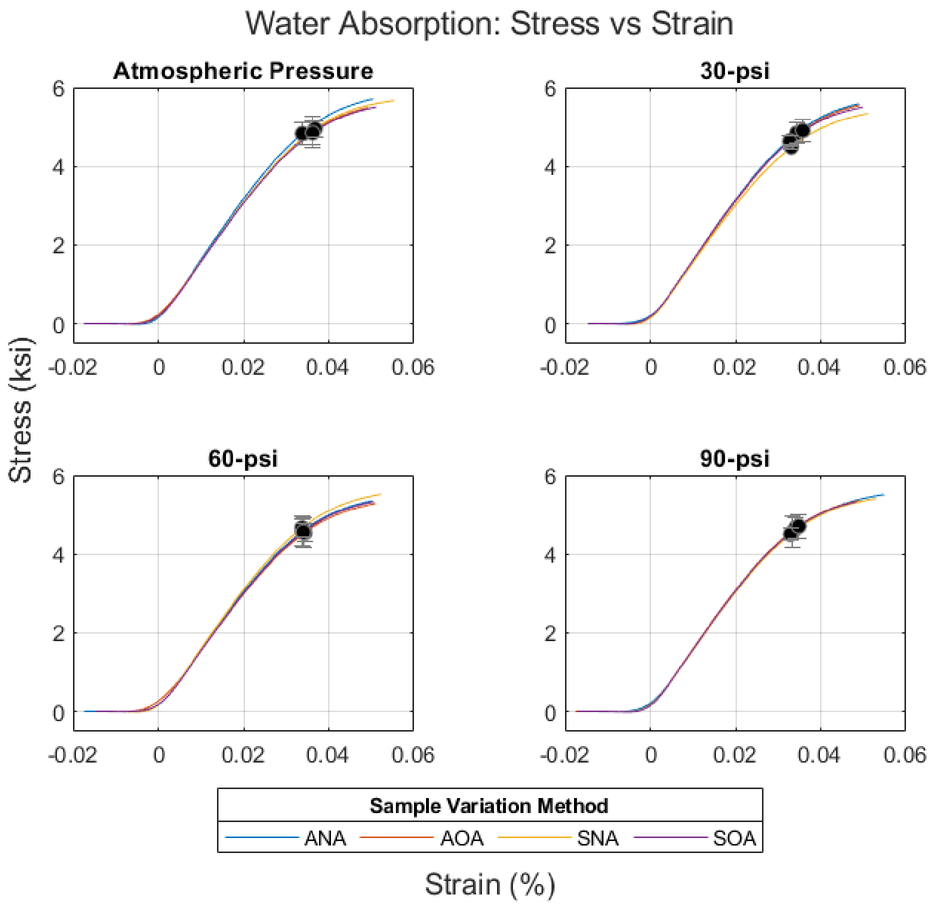


Figure 25: Water Absorption Stress-Strain Curves

Figure 25 contains the mean stress-strain curve for each variation type at all tested immersion pressures. The standard deviations of the yield strengths are shown as grey error bars, none of which appear excessively large. The curves are grouped closer together for the 90-psi samples than the atmospheric and 30-psi samples. There doesn't appear to be a larger change in yield stress or initial slope for the modulus when pressure is increased.

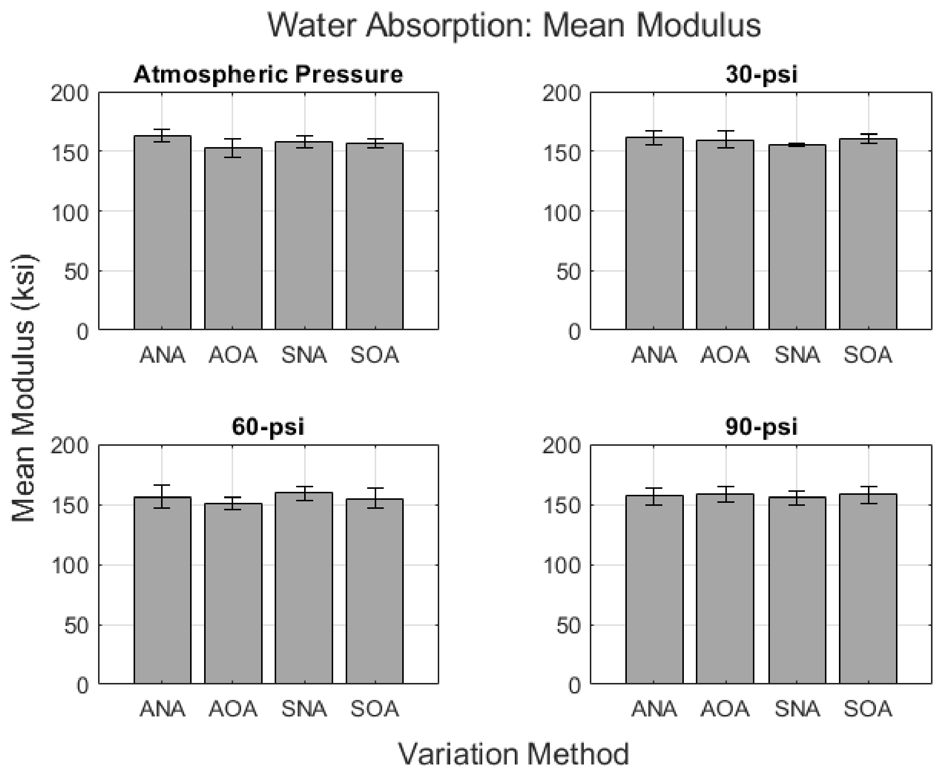


Figure 26: Mean Modulus (ksi) - Variation Methods per Pressure (64-days Immersed)

Comparing variation types shows little difference between means of variation type groups. The means that appear different from the plots are ANA modulus being higher for atmospheric pressure and SNA compressive properties being different from the rest of the 30-psi variation types. This can be confirmed by statistical analysis.

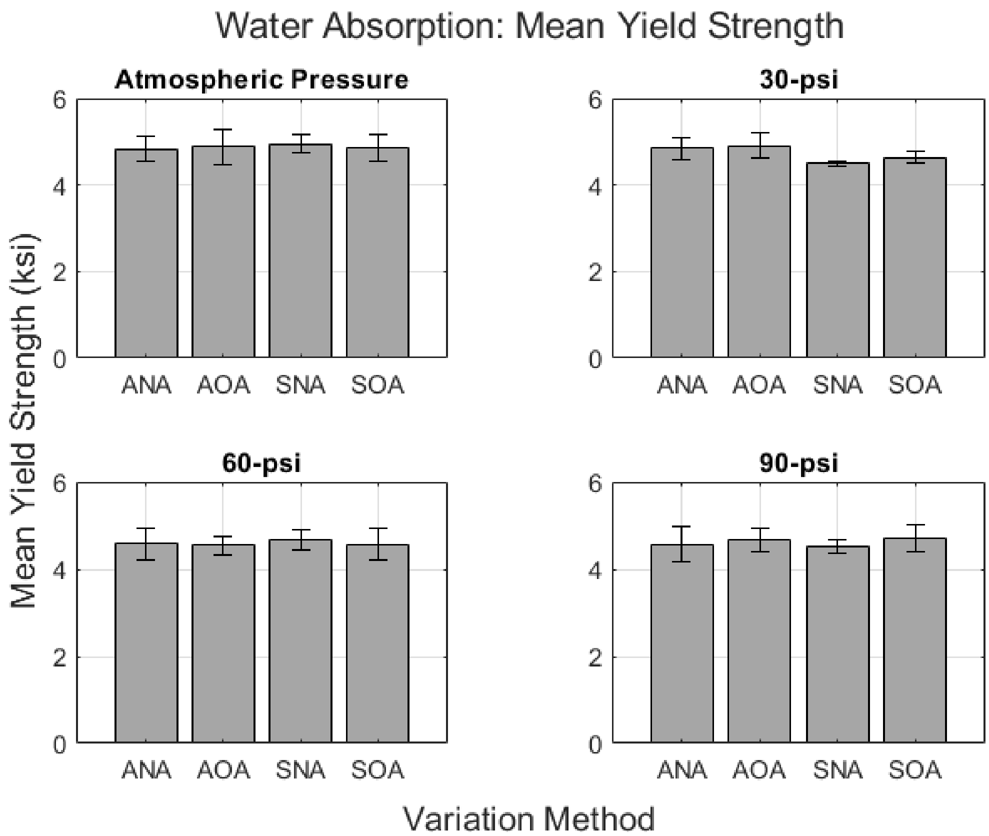


Figure 27: Mean Yield Strength (ksi) - Variation Methods per Pressure (64-days Immersed)

Statistically testing the water absorption samples determined whether the variation types or immersion pressures had a significant effect on the results. The p-values testing the effect of variation type for each pressure ascertained that the variation type did not notably change the means within each pressure group. So, overall means across variation types are accurate for comparisons. The overall means in Table 12 and Table 13 have a lower standard deviation than the highest standard deviation of the individual variation methods. Similar to the control samples, the larger sample size for the overall means increases the denominator of the standard deviation equation, making the value smaller.

Table 11: Water Absorption Kruskal-Wallis Test P-values Comparing Variation Types Within Pressures

P-values	*Atmospheric Pressure*	*30-psi*	*60-psi*	*90-psi*
Modulus	0.30	0.05	0.63	0.91
Yield Strength	0.73	0.06	0.85	0.16

Table 12: Mean Modulus (ksi) for Variation Methods after 64-day Immersion

Variation Type	*Atmospheric Pressure*	*30-psi*	*60-psi*	*90-psi*
ANA	163.24 ± 5.24	161.73 ± 5.65	156.32 ± 9.51	156.54 ± 7.04
AOA	153.28 ± 7.55	159.94 ± 7.04	150.14 ± 5.23	158.26 ± 6.86
SNA	157.94 ± 4.95	155.32 ± 1.48	159.21 ± 5.40	155.40 ± 5.50
SOA	156.93 ± 3.81	160.75 ± 3.88	154.84 ± 8.63	158.01 ± 7.32
Overall Means	159.80 ± 5.63	160.08 ± 5.30	157.01 ± 7.14	158.26 ± 6.35

Table 13: Mean Yield Strength (ksi) for Variation Methods after 64-day Immersion

Variation Type	*Atmospheric Pressure*	*30-psi*	*60-psi*	*90-psi*
ANA	4.84 ± 0.30	4.85 ± 0.25	4.58 ± 0.37	4.57 ± 0.40
AOA	4.88 ± 0.39	4.91 ± 0.28	4.55 ± 0.21	4.67 ± 0.26
SNA	4.95 ± 0.21	4.49 ± 0.06	4.67 ± 0.23	4.51 ± 0.15
SOA	4.85 ± 0.31	4.64 ± 0.14	4.56 ± 0.37	4.71 ± 0.29
Overall Means	4.90 ± 0.31	4.82 ± 0.26	4.65 ± 0.30	4.72 ± 0.28

When viewed as rows, Table 12 and Table 13 confirm that change in pressure does not cause a consistent linear increase or decrease in the Modulus or Yield Strength. For example, the mean modulus of AOA and SOA samples along the rows of Table 12 increases then decreases before increasing again. SNA samples follow the opposite pattern when the modulus decreases and then increases before decreasing again. ANA results did not follow either pattern and were not linear since the modulus increased at 30-psi and continued decreasing. The yield strength also did not exhibit linear behavior for each variation method. The maximum and minimum for each variation method did not remain consistent. The lack of consistency and the overlapping standard deviations per pressure suggest that the pressure during immersion does not affect the compressive properties significantly.

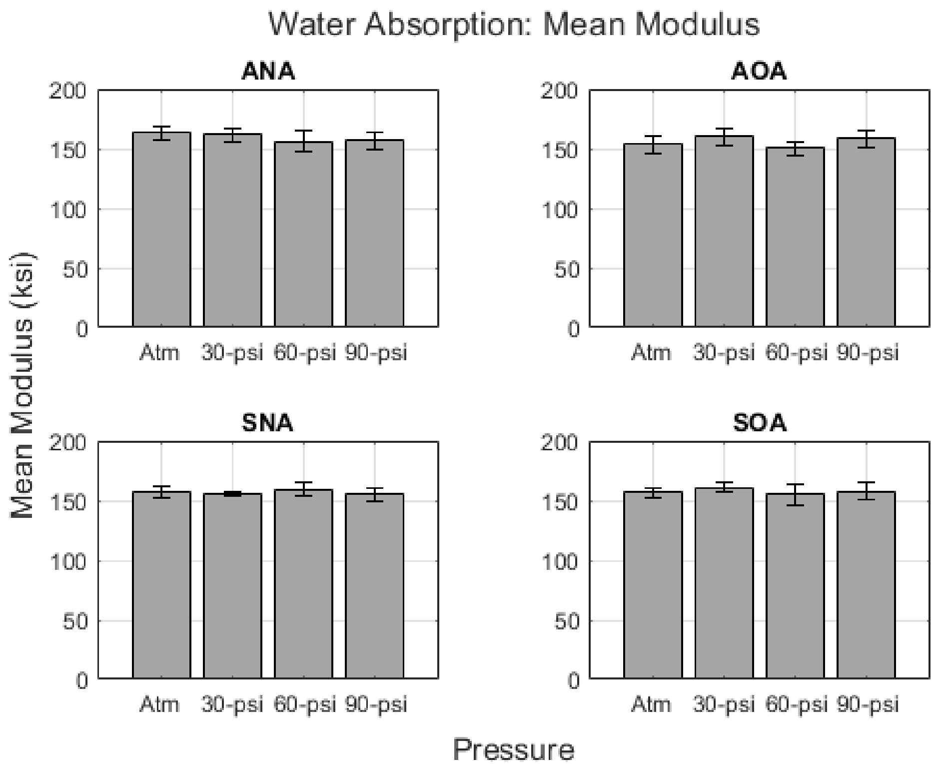


Figure 28: Mean Modulus (ksi) - Pressures per Variation Method (64-days Immersed)

The modulus and yield strength results were rearranged and grouped by variation method in each subplot. It is still clear that the standard deviations between pressure groups mostly overlap, even though the mean modulus for some pressures may be higher than the others of that variation type. For example, the mean modulus at atmospheric pressure (163.24-ksi) and at 30-psi (161.73-ksi) was larger than the modulus at 60-psi (156.32-ksi) and at 90-psi (156.54-ksi). Still, the standard deviations for the latter two pressures were larger than those for the former. These overlapping standard deviations agree with previous results from the table that the change in pressure had a low impact on yield strength and modulus, but statistical analysis can confirm this.

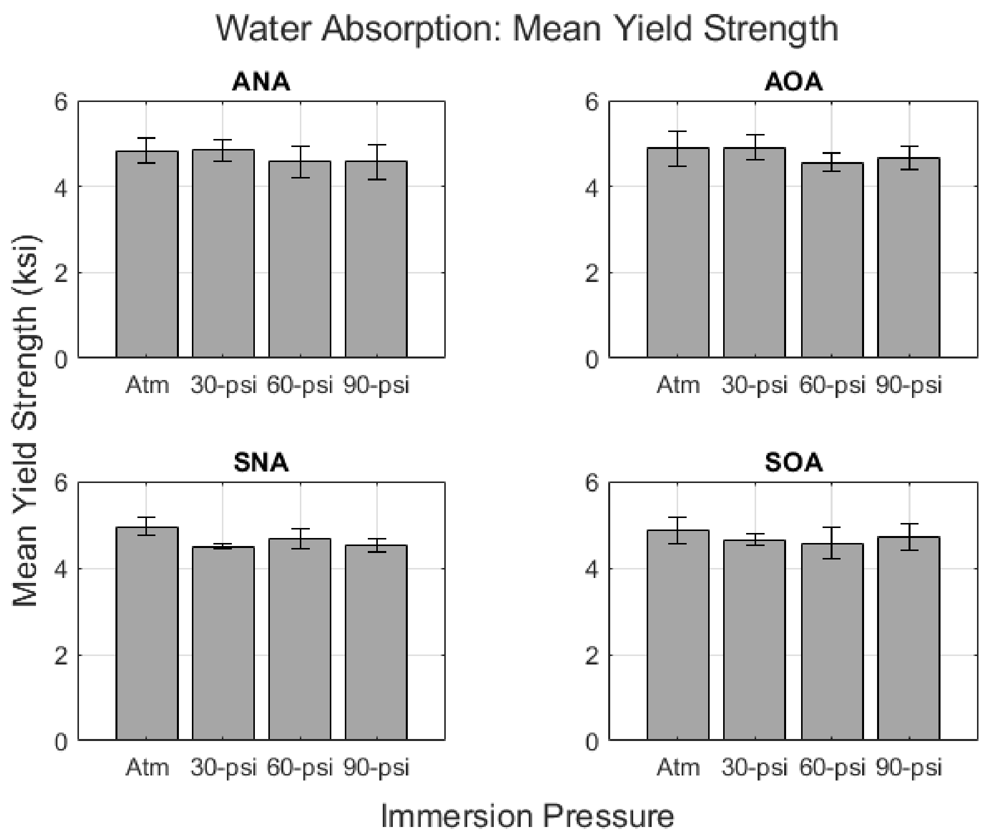


Figure 29: Mean Yield Strength (ksi) - Pressures per Variation Method after 64-days Immersed

The number of Kruskal-Wallis tests per compressive property was four, so the significance level was corrected to α = 0.0125. The p-values in Table 14 show that the pressure within each variation type had no significant impact on the compressive properties. The group closest to the significance level was located within SOA's yield strength.

Table 14: Water Absorption Kruskal-Wallis Test P-values Comparing Pressure Within Variation Types

P-values	*ANA*	*AOA*	*SNA*	*SOA*
Modulus	0.54	0.63	0.41	0.46
Yield Strength	0.30	0.10	0.95	0.02

The post-hoc test for the SOA yield strength group provided p-values between the individual pressure groups. The percent difference between the mean yield strengths of the atmospheric and 30-psi groups was only 4.53%.

Table 15: Pairwise comparison of SOA Yield Strength Groups

Group 1	*Group 2*	*P-values*
30-psi	60-psi	0.32
30-psi	90-psi	0.99
30-psi	Atmospheric Pressure	0.03
60-psi	90-psi	0.41
60-psi	Atmospheric Pressure	0.74
90-psi	Atmospheric Pressure	0.05

The plot in Figure 30 visually shows the difference in the means for the SOA yield strengths. Note that the blue shapes represent 25^{th}- 75^{th} percentile data, and the overlapping hourglass shapes, such as those in the lower 25th percentile of the atmospheric samples, signify higher variability.

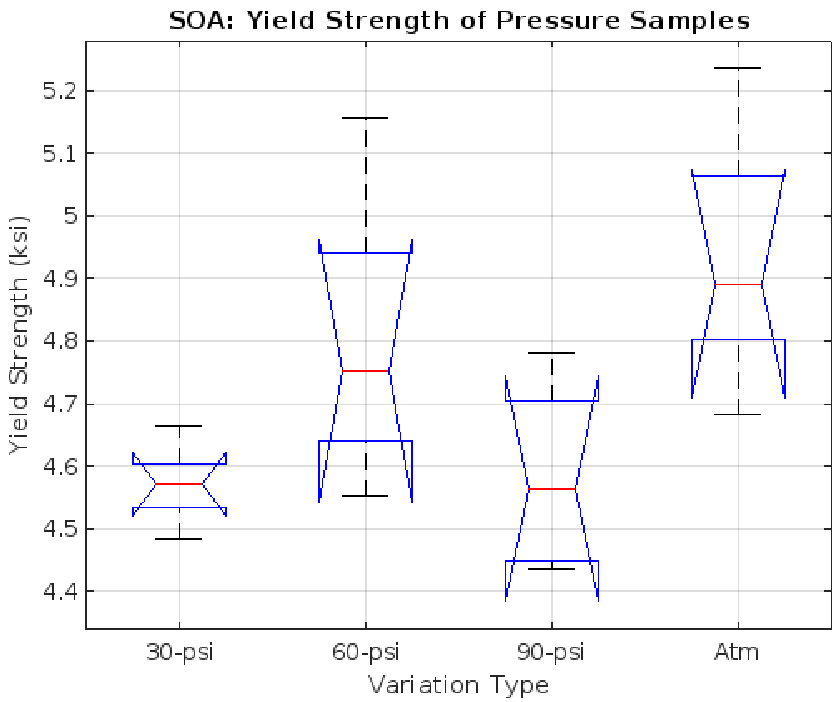


Figure 30: Water Absorption SOA Yield Strength Means

Chapter 8
UV Cure

8.1 Materials and Instruments

The Wash and Cure 2.0 machine was used to cure the samples. The time knob was adjusted to extend the cure time, and samples were cured in time periods of 60-mins. The UV power that the samples experience during curing potentially causes a difference in the compressive property results per sample. A power meter was used to measure power in mW and then convert it to irradiance in mW/cm^2 by dividing the area of the sensor. Pictured in Figure 31, the Gentec-eo Uno Laser Power Meter paired with the UPK19-15S-H5-D0 sensor [43,44].

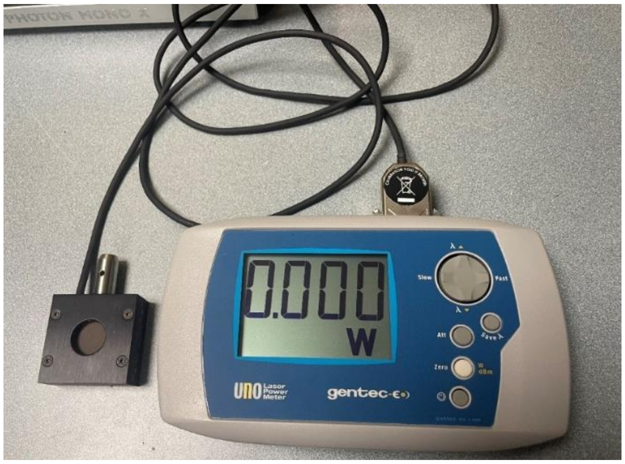


Figure 31: Laser Power Meter

8.2 Samples and Procedures

Production processes for the UV cure samples were the same as all other experimental samples except for UV post-cure time. This included the printing process; before the samples were cured, they had to be washed with isopropyl alcohol. The turntable was removed from the cure station, and the washing container circulated alcohol around the printed parts to remove excess resin. All samples were dried with paper towels. The selected cure times were 6-min, 15-min, 60-min, 120-min, and 240-min. The highest cure time is equivalent to 4-hours on the machine. There were 100 samples in this portion of the experiment, 5 samples per cure time.

The Anycubic cure station limits continuous use of the station to 60-minutes per session, so for time over that cutoff, the station was re-started. No warnings against curing for longer than 60 minutes were present in the operator manual [45]. During curing, the samples were stacked vertically at the center of the turntable.

To investigate the power absorbed by the samples, the power meter's sensor was placed in the UV cure machine. The wavelength output by the UV cure station was input into the power meter before use. Also, the sensor was zeroed in darkness and placed so that the face of the sensor was parallel to the face of the UV LEDs before use. The average value during one minute was taken at each height and compared to each other. In addition, the power was converted to irradiance by dividing the area of the sensor. The irradiance results from the UV cure machine may also be compared to the irradiance from the sun to understand better how printed parts may react when used outdoors for longer periods of time.

8.3 Analysis and Results

Compression testing of the UV cure samples occurred to compare the variation method and UV cure time. The UV cure sample set means per cure time resulted in the following stress-strain curves where the yield strength and elastic modulus increase as cure time increases. The yield strength is marked in black on the curves.

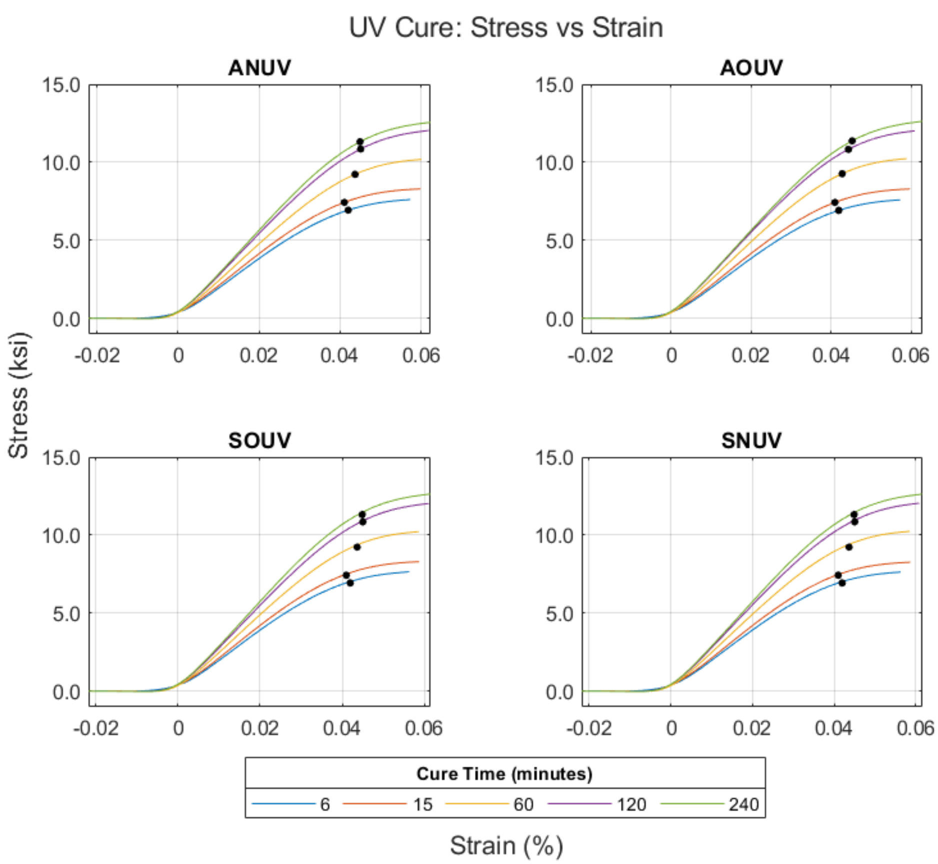


Figure 32: Stress-Strain Curves by Variation

For the 6-min and 15-min cure times, their yield strengths and moduli are within 8% of each other for all variations even though the cure time was only 9-min different. The highest percent difference between cure times was 25% between 15-min and 60-min times. The highest 2 cure times, which have a difference of 2 hours between them, have a maximum percent difference of 5%. This shows that even though the cure time was increasing by a larger amount for the 240-min samples, the time past the 120-min cure has less effect on the properties than the shorter, initial cure times.

A plot of time versus the means in Figure 33 and Figure 34 better shows as a function of time the effect on the compressive properties. The standard deviations of the means are represented as error bars. Note that the curves were fitted to the data, and all variation types had an R-squared value larger than 0.99 for the modulus and yield strength. The yield strength and modulus plateau as the higher cure times are reached, visually showing that the initial curing has more of an effect on the sample's compressive properties.

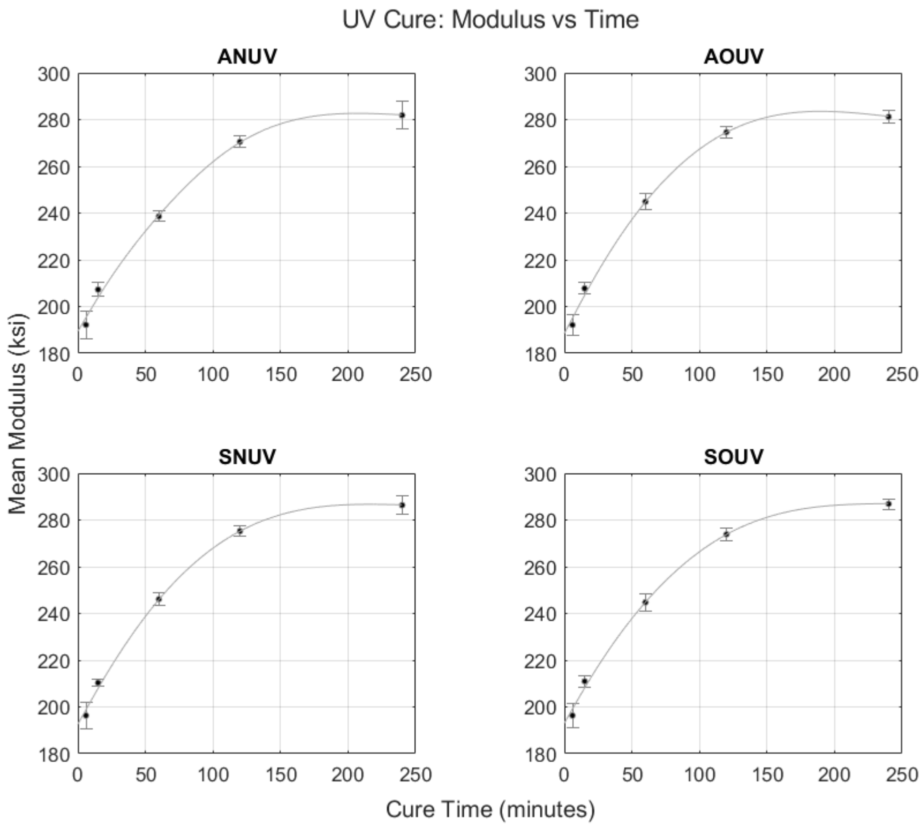


Figure 33: UV Cure Modulus vs Time per Variation

The decrease in rate of change as cure time increases suggests that cure past the 240-mins (4-hrs) in this experiment would not cause a large increase in the modulus or yield strength. Table 16 and Table 17 contain the overall means used for the slope calculations and individual means per variation. The slope between the overall mean modulus of the 60-min and 6-min samples was 0.91-ksi/min and the slope between 240-min and 120-min samples was 0.07-ksi/min. For the overall yield strength, the slopes were 0.046-ksi/min and 0.003-ksi/min between the 60-min and 6-min along with the 240-min and 120-min samples respectively. The higher slope values for initial cure times prove that there is a higher rate of change in the properties for initial cure times. Within each cure time category, the mean yield strength did not differ much from one variation type to another. These trends can be confirmed by statistical analysis.

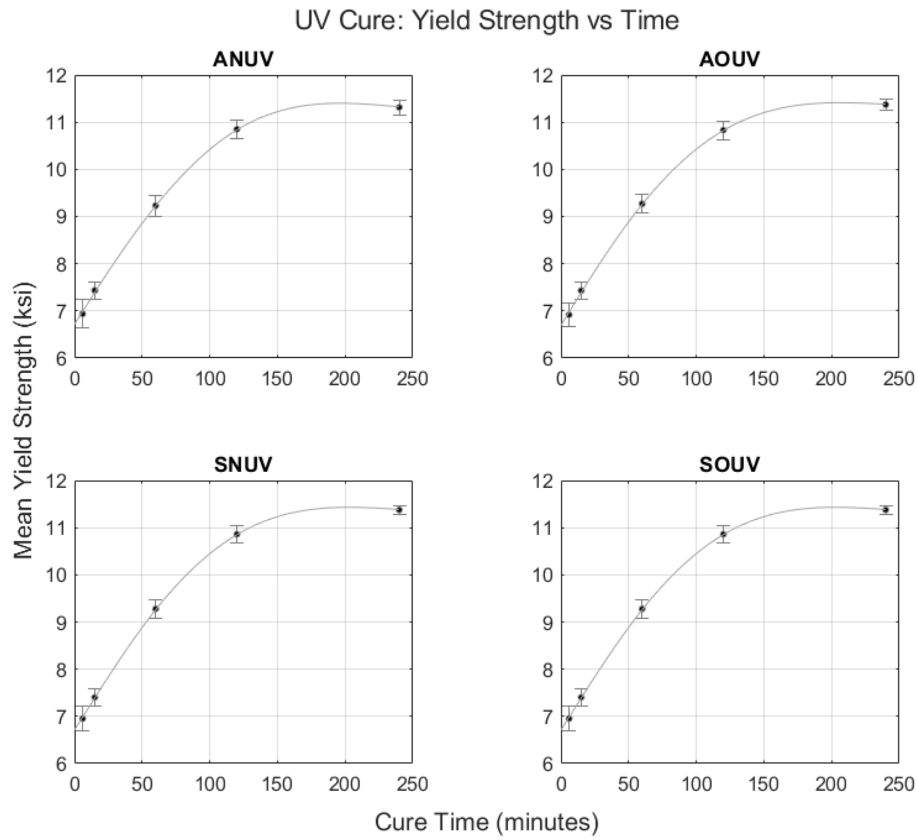


Figure 34: UV Cure Yield Strength vs Time per Variation

The trends also prove that there is more capacity to cure the parts past the resin manufacturer's cure time recommendation of 15-mins since the properties continue to increase over time past 15-mins. The higher yield strengths and moduli as time increases cause the materials to become more brittle and reach permanent deformation at a higher pressure.

Table 16: Mean Modulus (ksi) for Variation Methods and UV Cure Times

Variation Type	*6-min*	*15-min*	*60-min*	*120-min (2-hrs)*	*240-min (4-hrs)*
ANUV	192.16 ± 6.11	207.28 ± 3.02	238.59 ± 2.20	270.52 ± 2.48	281.87 ± 5.80
AOUV	192.12 ± 4.39	207.76 ± 2.51	244.84 ± 3.33	274.64 ± 2.44	281.22 ± 2.57
SNUV	196.32 ± 5.64	210.35 ± 1.39	246.10 ± 2.74	275.25 ± 2.23	286.36 ± 3.89
SOUV	196.33 ± 5.30	210.98 ± 2.45	244.77 ± 3.86	273.87 ± 2.58	286.89 ± 2.24
Overall Mean	196.31 ± 5.40	211.09 ± 2.77	245.21 ± 4.15	276.25 ± 2.93	285.17 ± 4.44

Table 17: Mean Yield Strength (ksi) for Variation Methods and UV Cure Times

Variation Type	*6-min*	*15-min*	*60-min*	*120-min (2-hrs)*	*240-min (4-hrs)*
ANUV	6.94 ± 0.30	7.43 ± 0.18	9.23 ± 0.22	10.85 ± 0.19	11.32 ± 0.16
AOUV	6.92 ± 0.24	7.43 ± 0.19	9.27 ± 0.19	10.83 ± 0.20	11.37 ± 0.13
SNUV	6.95 ± 0.27	7.40 ± 0.18	9.28 ± 0.19	10.86 ± 0.19	11.38 ± 0.09
SOUV	6.97 ± 0.26	7.44 ± 0.18	9.26 ± 0.16	10.84 ± 0.20	11.38 ± 0.09
Overall Mean	6.93 ± 0.25	7.55 ± 0.17	9.43 ± 0.18	10.98 ± 0.18	11.35 ± 0.11

Statistical analysis can confirm or deny the difference in means between groups. If the samples had instead compared groups of cure time with variation type as the main variable, the mean compressive properties would be different between cure times. For UV cure, the means between groups were tested only for the variation types within each cure time category to obtain meaningful results. The significance level was reduced from 0.05 to 0.01 since the statistical test was completed 5 times for each compressive property. Table 18 displaying the result for the p-values show that the variation type does not significantly impact results because the p-values were greater than the significance level. The two groups closest to the significance level were the 60-min and 240-min samples.

Table 18: UV Cure Kruskal-Wallis Test for Variation Type Within Cure Times

P-values	*6-min*	*15-min*	*60-min*	*120-min*	*240-min*
Modulus	0.27	0.12	0.02	0.09	0.03
Yield Strength	0.99	0.99	0.94	0.97	0.83

Table 19: Pairwise Comparison of 60-min Modulus Groups

Group 1	*Group 2*	*P-values*
ANUV	AOUV	0.10
ANUV	SNUV	0.03
ANUV	SOUV	0.10
AOUV	SNUV	0.96
AOUV	SOUV	1.0
SNUV	SOUV	0.96

Figure 35 shows the analyzed means for the modulus of the 60-min sample. ANUV samples have a lower mean modulus and range of values than the rest of the variation types, but their mean modulus values were less than 10% different. While the maximim values of ANUV overlap with the minimum values for SNUV and SOUV, they do not overlap with the SNUV minimum modulus values. In addition, the mean modulus for SNUV was slightly higher than the other means, and it had a larger variance on the lower 25th percentile since its bottom blue line is folded over while the AOUV and SOUV samples 25th percentiles were not.

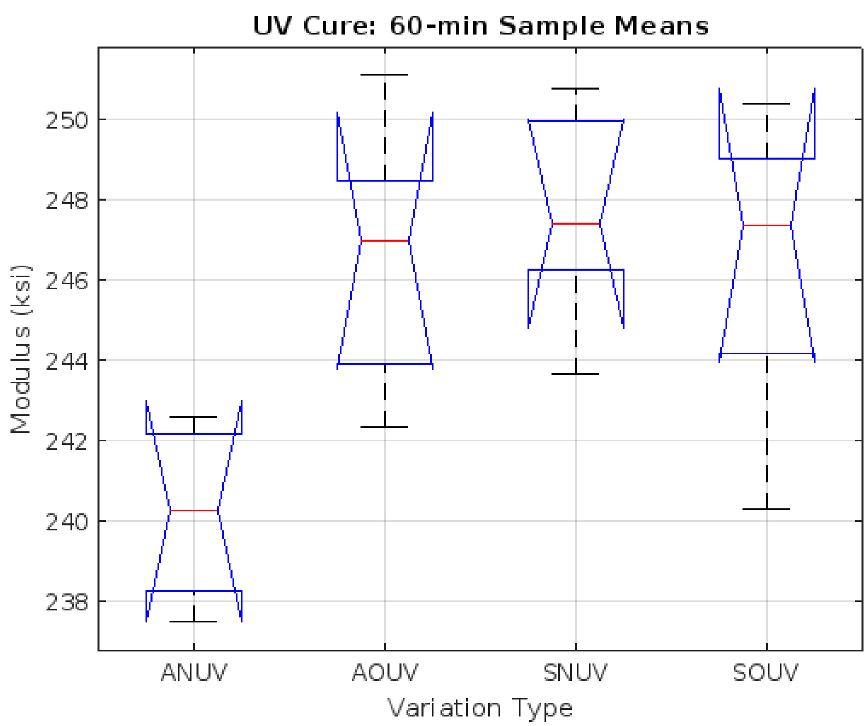


Figure 35: UV Cure 60-min Sample Groups' Mean Modulus Comparison

The post-hoc test for the 240-min samples show that variation types with means most different from each other were AOUV and SOUV. However, these are still not considered significantly different because their p-value was greater than $\alpha = 0.01$.

Table 20: Pairwise Comparison of 240-min Modulus Groups

Group 1	*Group 2*	*P-values*
ANUV	AOUV	0.90
ANUV	SNUV	0.44
ANUV	SOUV	0.24
AOUV	SNUV	0.13
AOUV	SOUV	0.05
SNUV	SOUV	0.98

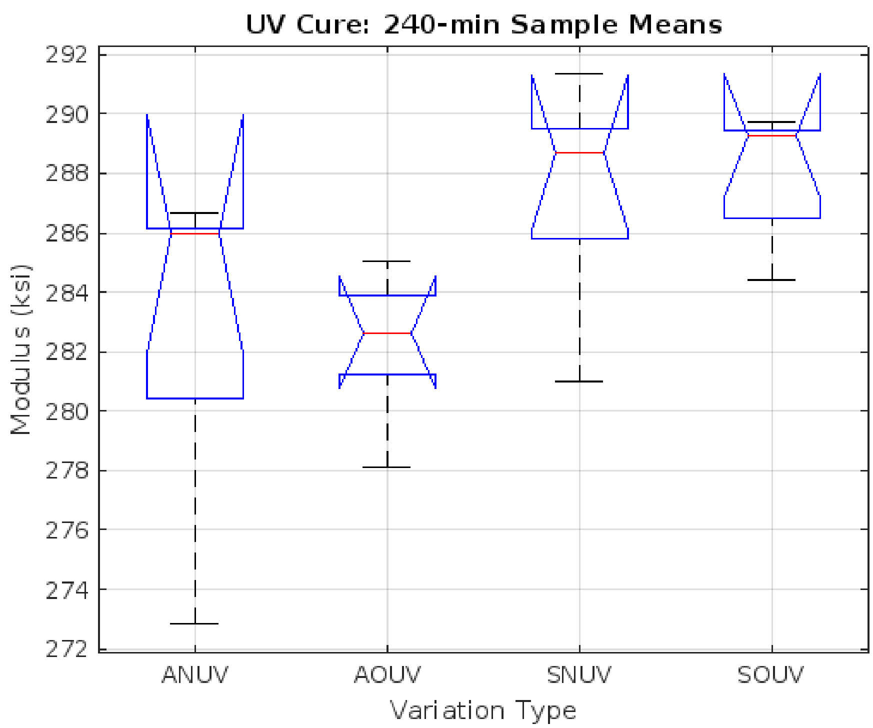


Figure 36: UV Cure 240-min Sample Groups' Mean Modulus Comparison

Chapter 9
Experimental Error

9.1 Printing and Post-Processing Methods

Standard deviations of the results may be partially explained by the UV power the samples experienced during curing. When the power meter was placed at different heights in the cure station, the irradiance in mW/cm^2 was greatest at the center of the machine where the beams from surrounding areas overlap from above and below the sample. The below image represents the cure machine and beam angles for each LED of 42.3 degrees. The beam angle was determined by measuring the power at centerline of one LED. At the centerline of the two columns of LEDs, the irradiance was highest. When the sensor was moved away from the centerline, and the irradiance was half of what it was at centerline, the angle between the centerline and half irradiance is half of the total beam angle [46]. This concept provides an understanding of the variation source in compressive properties even though there is light spilled outside of the beam angle [46]. In addition, it gives a baseline comparison for irradiation from the sun versus irradiation from the UV cure machine.

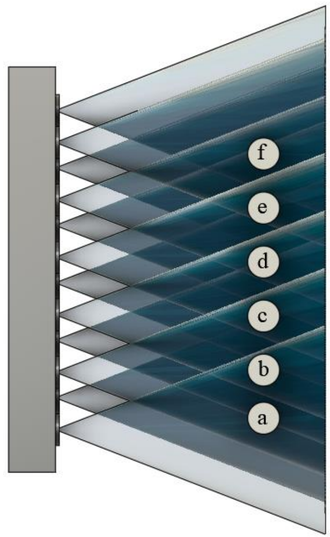


Figure 37: UV LED Side Profile and Beam Angles

The irradiance was highest at locations "c" and "d" where more beams from the LEDs were overlapping.

Table 21: Irradiance Measured Vertically in UV Cure Machine

Image Location	*Height Above Platform Base (in)*	*Irradiance (mW/cm²)*
a	1	24.15
b	1.89	29.45
c	2.89	34.16
d	3.89	34.16
e	4.89	31.21
f	5.89	28.27

The average Irradiance including all locations in the UV cure machine was 30.23-mW/cm^2. The average Irradiance in February of 2023 during the month of this experiment from the University of Florida was 87.28-mW/cm^2 [47]. Comparing the irradiance under the UV cure machine versus the sun on an average February day at the time of this experiment, the irradiance ratio was 1/3. This gives a comparison value for the irradiance, but more detailed experimentation would be required to correlate time of cure in the sun versus the cure machine. Due to the amount of variability involved with the sun's irradiance and time limitations, this correlation was not investigated further in this research.

Additional errors in this experiment stemming from the printing process include temperature. While the printing room was kept at room temperature, prints experienced fluctuation in temperature due to the machine heating up as the prints were started. For prints started in succession, the printer was already warm from the previous print. The temperature of the resin during printing was not listed in the technical data sheet for the Sculpt Clear resin [29].

9.2 Experimental Methods

The water absorption portion of the experiment could contain error due to lack of immediate testing. Logistically, too many samples were in the CO2 tanks to remove them on-site. The 30-, 60-, and 90-psi samples were removed from their pressurized tanks 12-hours before compression testing occurred. If the samples did not reach the plastic region where deformation was permanent, then they could have returned to a condition resembling the atmospheric samples. To help determine this, the compressive properties and their relation to the water absorption also need to be analyzed.

Chapter 10
Comparative Analysis

Individually, the results for control samples, water absorption, and UV cure have been analyzed. Additional comparisons are necessary between control samples and each exposure group. Since the UV cure samples and control samples were both 6-min cure times, but the resin was from a different bottle number, the comparison of their compressive properties is useful. Below is a representation of which resin bottle each portion of the experiment was printed from. Note that images “a”, “b”, “c”, and “d” represent Amazon resin control samples, Amazon resin UV cure samples, Siraya Tech resin control samples, and Siraya Tech resin UV cure samples. The same resin bottles that were used to create the control samples were also used for the water absorption samples. Note that the Amazon resin for UV cure samples in “b” does not have the 8K on the upper right of the label. In addition, bottles “a” and “d” share the same printed date on the warning label which is the production date batch from May, 2023. So, even though bottle “a” was bought from Amazon and bottle “d” was bought from the manufacturer, Siraya Tech, the bottles of resin were from the same batch. Because of this, it may be less helpful to compare “Amazon” vs “Siraya Tech” bottles and more useful to compare control samples and UV cure samples of equal cure times. This will help determine if different batches of resin have a significant difference in their compressive properties.

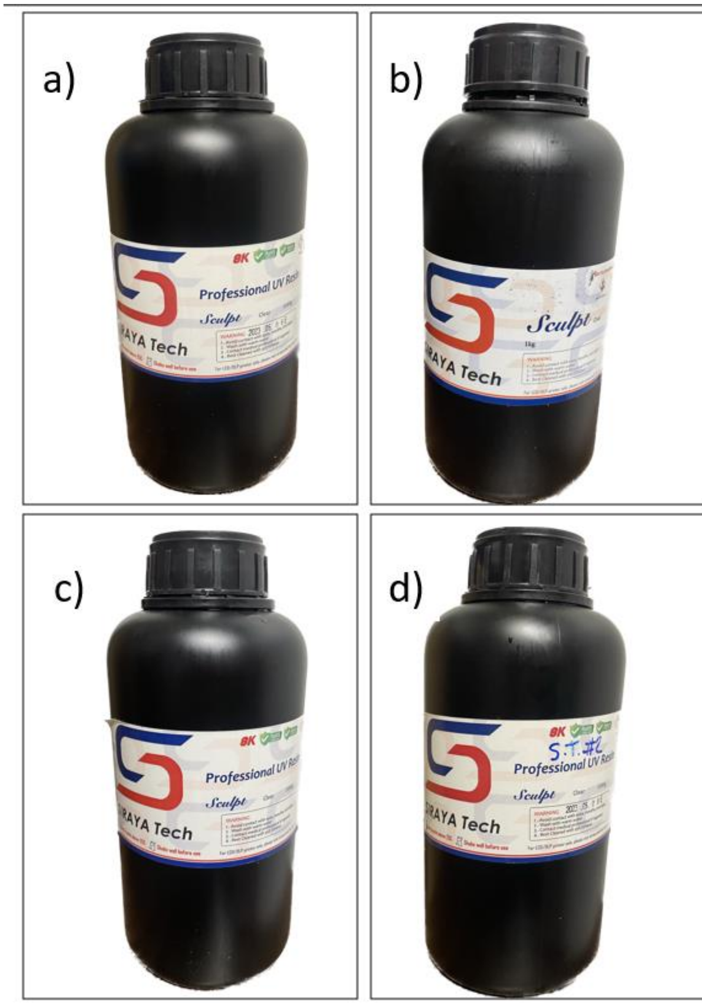


Figure 38: Resin Bottles Used for Printing

Figure 38 contains the following images with the resin supplier and printed sample types:

a) Amazon Resin Control and Water Absorption Samples

b) Amazon Resin UV Cure Samples

c) Siraya Tech Resin Control and Water Absorption Samples

d) Siraya Tech Resin UV Cure Samples

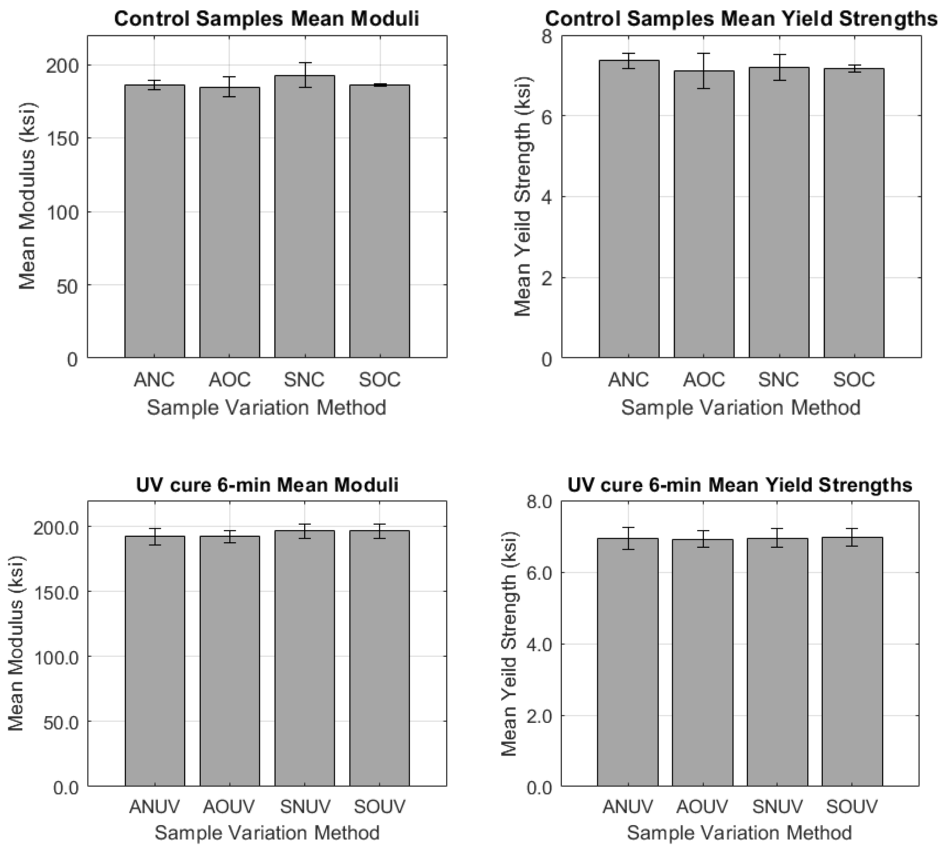


Figure 39: Control Samples vs UV 6-min Samples

The results in Figure 39 for the control samples differ more between sample variation types than the UV cure samples. Since Amazon resin control samples and Siraya Tech resin UV cure samples are of the same batch date, their values can be compared. From Table 22, the Amazon control sample moduli of 185.84-ksi and 184.54-ksi were less similar to the Siraya Tech resin UV cure moduli of 196.32-ksi and 196.33-ksi than the rest of their respective control or UV cure 6-min samples.

Table 22: Control Samples vs UV Cure (6-min)

	Control Samples		***UV Cure 6-min***	
Variation Type	**Modulus (ksi)**	**Yield Strength (ksi)**	**Modulus (ksi)**	**Yield Strength (ksi)**
AN	185.84 ± 3.44	7.37 ± 0.19	192.16 ± 6.11	6.94 ± 0.30
AO	184.54 ± 6.70	7.11 ± 0.43	192.12 ± 4.39	6.92 ± 0.24
SN	192.78 ± 8.29	7.20 ± 0.33	196.32 ± 5.64	6.95 ± 0.27
SO	186.07 ± 0.95	7.16 ± 0.09	196.33 ± 5.30	6.97 ± 0.26
Overall Mean	188.24 ± 6.25	7.26 ± 0.31	196.31 ± 5.40	6.93 ± 0.25

From the UV samples cured for 6-min, the difference between the variation method results was less significant than the differences between variations for the control samples. In other words, the UV cure 6-min samples had a lower standard deviation for modulus and yield strength than the control samples. The control samples had a mean modulus for SNC and a yield strength for ANC that were higher than the other variation types by a more significant amount than any outliers in the UV cure 6-min samples.

Table 23: Control Samples vs Water Absorption Means

	Modulus (ksi)	***Yield Strength (ksi)***
Control Samples	188.24 ± 6.25	7.26 ± 0.31
Water Absorption	158.83 ± 6.30	4.77 ± 0.30
Percent Difference	18.52%	52.20%

The control sample mean moduli comparing control samples to water absorption samples was 18.52% difference. The yield strength decreased by 52.2% after the samples had been immersed for 64-days. This is a significant degradation in material properties, and long-term immersion applications should consider this before deployment. From [4], the effect of saltwater absorption for 60-days on the Accura ClearVue resin decreased the compressive modulus by 8.3%. Because the ClearVue resin is professional-grade resin printed on an SLA printer upwards of $400,000, it is not surprising that the ClearVue resin is impacted less by water absorption than Sculpt Clear resin printed on a MSLA machine less than $600 [48, 11].

Table 24: SLA resins and Acrylic Data [1, 4, 49, 50]

Description	***Young's Modulus (ksi)***	***Yield Strength (ksi)***
Sculpt Clear (9-second exposure)[1]	69.80	2.19
Accura ClearVue: No immersion[4]	377.10	N/A
Accura ClearVue: 60-days immersion[4]	348.09	N/A
Formlabs CLEAR[49]	220.48	5.74
Acrylic[50]	16.0-18.0	400-440

Sculpt Clear when printed with the 9-second exposure had a compressive modulus of 69.80-ksi and yield strength of 2.19-ksi. These are lower than the average compressive properties (of control and UV cure overall means) from this research by 178% and 224% respectively for modulus and yield strength due to the adjustment of exposure time per layer to 10-minutes. This significant increase in the properties is reasonable. A study in 2018 found that an increase from 1.6-s to 2-s exposure time caused the elastic modulus to increase 214% [51]. Formlabs CLEAR resin printed with the Formlabs Form 2 SLA machine had comparable compressive modulus and yield strength to the present research, 24% difference for yield strength and less than 15% difference for compressive modulus.

Chapter 11
Conclusion and Suggestions

11.1 Conclusion

The photosensitive resin printed with an MSLA printer experiences water absorption and UV light from marine and outdoor use. This research created the foundation that could be used to connect material properties and marine deployment of an MSLA-printed object. Sculpt Clear resin was compression tested to compare samples that experienced UV cure time, and water absorption, and resin plus post-processing variations.

An increase in UV cure time caused the modulus and yield strengths to plateau as the cure time approached 4-hrs. The overall means between cure times increased at a quicker rate for lower cure times up to 60-min than the cure times past that. Between 120- and 240-min UV cure times, the increase in modulus and yield strength was negligible. These results prove the hypothesis that UV cure time caused an increase in the properties, but 4-hrs was not long enough exposure to cause the properties to decrease again as originally theorized.

The samples after being immersed in saltwater reached saturation after 56-days and were compression tested at 64-days. Analysis determined that the pressure at which the samples were immersed did not have a significant impact on samples' compressive property means. The average sample water absorption of 1.61% and open porosity of 1.93% by volume. In addition, the samples' average modulus decreased 18%, and the yield strength decreased 52% after immersion. Engineers and scientists should consider the environmental conditions of deployment and account for this in their design, especially if the design is acting as a structural member or a point of failure for any given project.

Variation type did not have a significant impact on the mean of all experimental exposure types as determined by trends in bar plots and statistical analysis. The Kruskal-Wallis test accepted the alternative hypothesis that all the means are not different. Thus, all sample means were not affected significantly by the variation types. The original theorization of ideal variation conditions was proven inconsequential.

11.2 Future Research

With the MSLA technology being relatively new, technology continues to advance. An example of this is the Anycubic Wash and Cure Max designed to increase post-processing efficiency. The printed part can be placed into the station where it is rinsed with alcohol then cured without removal from the container. Testing the differences between the Wash and Cure Max versus the Wash and Cure 2.0 was not within the scope of this project because the technology was still in the pre-order phase. As technology continues to develop and new materials or machines are created, the potential use of these materials and research to use them properly in the ocean environment broadens.

The UV cure time during water absorption for this experiment was 6-minutes to limit the sample numbers. The cure time could be varied during water absorption to determine how this impacts compressive properties.

In addition, the different effects of sunlight on the material properties could be further explored. The irradiance ratio between the UV cure machine and the sun gives a theoretical relationship between sunlight-cured parts versus the UV LEDs in the cure machine. The correlation of the UV cure machine's irradiance to the sun's irradiance was determined as a ratio of 1/3 when the sun's irradiance was gathered for the month during the time of the experiment in Florida. Proving this relationship and determining an average cure time in the sun to reach the same material properties from samples that were cured in the UV cure machine would provide further correlation to outdoor exposure.

Since ocean-going parts are often deployed, retrieved, and deployed again, another interesting research topic could explore cyclic exposure. Sun and water experienced in succession repetitively have an unknown impact on resin-printed parts. For repetitive use with limited cost and maintenance, these effects on the material properties should be investigated.

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Appendix A: Expenses

Table 25: Expenses to Date

Part	***Cost***
¼” MNPT quick disconnect	2.99
Air hose	18.74
¼” to 1/8” FNPT adapter	8.99
Tank fill adapter male	9.29
Quick disconnect fill adapter female	15.59
CO2 tank fill station adapter	11.39
¼” female to 1/8” male NPT adapter	7.99
Pressure gauge	12.97
Precise measuring scale	18.99
Organizer for compression samples	5.99
CO2 tanks (x3)	79.95
Resin	80.00
Isopropyl Alcohol	67.00
Total	**339.88**

Appendix B: MATLAB Code Functions

The core MATLAB Functions are contained within this appendix where the following tree shows the functions being called within each script.

- Function of Functions
    - Calculations
    - Set Length
    - Summary Data
    - Mean of 5

```
function [mean_modulus,mean_YS_strain, mean_YS_stress, std_mod, std_YS_stress,S, ↙
ANA_mean_strain, ANA_mean_stress,AOA_mean_strain, AOA_mean_stress,SNA_mean_strain, ↙
SNA_mean_stress,SOA_mean_strain, SOA_mean_stress,overall_mean_modulus, ↙
overall_mean_YS,overall_mod_std, overall_YS_std] = FunctionOfFunctions(T,P,S,fc,fs)
%function that reads data and contains other functions for calculation
% used in code titled: Water_absorption_analysis
% outputs: mean modulus and mean yield strength (YS_stress), error for each variation ↙
method
    % where resin sources are amazon or siraya tech
    % where post-process washing is in new or old isypropyl alcohol
    % overall_mean_modulus,overall_mean_YS,overall_mod_std, overall_YS_std

names = ["ANA" "AOA" "SNA" "SOA"]; % sample names

[S] = calculations(S, P, T, fc, fs); % call function for data calculations within↙
data structure

% resize data for to the minimum length of the sample set
[~,S] = set_length(1,S);
[~,S] = set_length(6,S);
[~,S] = set_length(11,S);
[start,S] = set_length(16,S);

% summary data - call function for summary calculations
[std_YS_stress, std_mod, overall_mean_modulus, overall_mean_YS, overall_mean_strain, ↙
overall_mod_std, overall_YS_std] = SummaryData(S);

% individual data summaries
% name empty arrays then call function to calculate mean per variation
[ANA_mean_strain, ANA_mean_stress, ANA_stress, ANA_strain, ANA_mean_modulus, ↙
ANA_YS_stress, ANA_YS_strain] = mean_of_5(S,1,5); % call function to calc mean of 5↙
samples
[AOA_mean_strain, AOA_mean_stress, AOA_stress, AOA_strain, AOA_mean_modulus, ↙
AOA_YS_stress, AOA_YS_strain] = mean_of_5(S,6,10);
[SNA_mean_strain, SNA_mean_stress, SNA_stress, SNA_strain, SNA_mean_modulus, ↙
SNA_YS_stress, SNA_YS_strain] = mean_of_5(S,11,15);
[SOA_mean_strain, SOA_mean_stress, SOA_stress, SOA_strain, SOA_mean_modulus, ↙
SOA_YS_stress, SOA_YS_strain] = mean_of_5(S,16,20);

% condense data to be plotted
mean_YS_strain = [ANA_YS_strain,AOA_YS_strain,SNA_YS_strain,SOA_YS_strain];
mean_YS_stress = [ANA_YS_stress,AOA_YS_stress,SNA_YS_stress,SOA_YS_stress];
mean_modulus = [ANA_mean_modulus, AOA_mean_modulus, SNA_mean_modulus, ↙
SOA_mean_modulus];
overall_mean_YS_stress = mean(mean_YS_stress);
overall_mean_modulus_2 = mean(mean_modulus);
overall_mod_std_2 = std(mean_modulus);
overall_YS_std2 = std(mean_YS_stress);
```

```
% plot all control samples superimposed
for n = 1:length(S)
    plot(S(n).strain_comped,S(n).filtered_Stress, S(n).YS_strain, S(n).YS_stress, '-↙
ok','MarkerFaceColor','k')
    xlabel('Strain (%)')
    ylabel('Stress (psi)')
    title('Stress vs Strain')
    %legend(S_WA_Atm(n).name, 'Location', 'SouthOutside') % fix
    hold on
    if mod(n,5)==0 % start a new figure every 5th sample
        figure
    end
end

end
```

```
%% function - import data, filter data, and perform calculations per sample

%  import file data
function [S] = calculations(S, P, T, fc, fs)
for k = 1:numel(S)
    F = fullfile(P,S(k).name);      % full file path
    S(k).data = csvread(F,1,0);     % read file at path and save data
    S(k).force = (S(k).data(:,1));    % create force column
    S(k).position = S(k).data(:,2); % create position column
    S(k).indices = find(S(k).force<0); % find where force <0
    S(k).force(S(k).indices) = [];  % remove indices where force<0
    S(k).position(S(k).indices) = [];% remove indices of position where force<0
    S(k).area = T.A(k);             % append area per sample
    S(k).stress = (S(k).force/S(k).area)./1000; % for each .data, calculate stress =
F/A
    S(k).length = T.Length(k);      % pull length value from table and put into
structure
    S(k).strain = (S(k).position/S(k).length); % strain = change in length/length

    % get elastic modulus - find slope (not toe comped)
    S(k).filtered_Strain = Butterworth(fc,fs, S(k).strain, 'low'); % low pass filter
    S(k).filtered_Stress = Butterworth(fc,fs, S(k).stress, 'low'); % low pass filter
    S(k).m = diff(S(k).filtered_Stress) ./ diff(S(k).filtered_Strain); % find slope m
(1st derivative)
    [S(k).max_m, S(k).maxm_index] = max(S(k).m); % where max slope is youngs modulus
in psi

    S(k).YM_stress = S(k).filtered_Stress(S(k).maxm_index); % find stress at modulus
index
    S(k).YM_strain = S(k).filtered_Strain(S(k).maxm_index); % find strain at modulus
index
    % line equation of modulus
    S(k).b = S(k).YM_stress - (S(k).max_m*S(k).YM_strain); % need - stress and strn
from line only
    S(k).line = S(k).max_m*S(k).filtered_Strain + S(k).b; % line equation
    % toe compensation using line equation
    S(k).strain_shift = S(k).b/S(k).max_m;
    S(k).strain_comped = S(k).filtered_Strain + S(k).strain_shift;

    % get yield strength - from change in slope
    S(k).change_in_m = diff(S(k).m);
    [S(k).min_change_in_m, S(k).min_change_in_m_index] =  min(S(k).change_in_m); %
find point of min change
    S(k).YS_stress = S(k).filtered_Stress(S(k).min_change_in_m_index);    % pull YS
from min change in slope
    S(k).YS_strain = S(k).strain_comped(S(k).min_change_in_m_index);      % strain at
YS

    S(k).set_length_strain = S(k).strain_comped;
```

```
    S(k).set_length_stress = S(k).filtered_Stress;

    S(k).stress_strain_length = length(S(k).strain_comped);

    % find percent offset
    S(k).mod_strain_at_YS_stress = (S(k).YS_stress - S(k).b)/S(k).max_m;
    S(k).offset = S(k).mod_strain_at_YS_stress - S(k).YS_strain; % strain on modulus
line at same stress as YS minus strain at YS

end
end

%butterworth filter high or low
% param: condition = type of butterworth filter (e.g. 'high', 'low', etc.)
function [filtered_data] = Butterworth(fc,fs, data_in_Ax, condition)
[b,a] = butter(2,fc/(fs/2),condition);
% figure
% freqz(b,a,[],fs) % plot frequency response
% title('Filter Frequency Response:',condition)
% xlim([0 1])
filtered_data = filtfilt(b, a, data_in_Ax);
end
```

```
function [start,S] = set_length(start,S)
    for c = start:start+4
    min_length = min(cell2mat({(S(start:(start+4)).stress_strain_length)}')); % grab
min length
        if length(S(c).strain_comped) >= min_length
        S(c).set_length_strain((min_length+1):end) = [];
        S(c).set_length_stress((min_length+1):end) = [];
        end

        if mod(c,5)==0 && c~=start % break if ii divisible by 5
            break
        end

    end
end
```

```
function [Control_std_YS, Control_std_modulus, overall_mean_modulus, overall_mean_YS, ↙
overall_mean_strain, overall_mod_std, overall_YS_std] = SummaryData(S)
modulus = {S(:).max_m}';
modulus2 = cell2mat(reshape(modulus,[5,length(S)/5])); % reshape to 5x4
%mean_modulus = mean(modulus2); % take avg of columns to get mean modulus per ↙
variation

% find avg YS stress
YS = {S(:).YS_stress}';
YS2 = cell2mat(reshape(YS,[5,length(S)/5]));

% find avg YS strain
strain = {S(:).YS_strain}';

% standard deviation for mean modulus and YS of ALL control samples
overall_mean_modulus = mean(cell2mat(modulus));
overall_mean_YS = mean(cell2mat(YS));
overall_mean_strain = mean(cell2mat(strain));
overall_mod_std = std(cell2mat(modulus));
overall_YS_std = std(cell2mat(YS));

Control_std_YS = std(YS2);
Control_std_modulus = std(modulus2);
end
```

```
function [control_mean_strain, control_mean_stress, control_stress, ...
    control_strain, mean_modulus,YS_stress, YS_strain] = mean_of_5(S, start, stop)

ii = start;
control_strain = [];
control_stress = [];
for i = 1:5 % append each set of variation to a row then take mean
    control_strain(i,:) = S(ii).set_length_strain';
    control_stress(i,:) = S(ii).set_length_stress';

    if mod(ii,5)==0 % break if ii divisible by 5
        break
    end
    ii = ii + 1;
end
control_mean_strain = mean(control_strain)';
control_mean_stress = mean(control_stress)';

m = diff(control_mean_stress) ./ diff(control_mean_strain); % find slope
    [mean_modulus, mean_mod_idx] =  max(m); % mean modulus per 5 samples
change_in_m = diff(m); % 2nd derivative of stress strain curve
    [min_change_in_m, min_change_in_m_index] =  min(change_in_m); % find point of min
change
    YS_stress = control_mean_stress(min_change_in_m_index);     % pull YS from min
change in slope
    YS_strain = control_mean_strain(min_change_in_m_index);       % strain at YS

end
```

Appendix C: MATLAB Code

This Appendix contains the following Codes where results were gathered from the functions and plotted.

- WA_analysis (Water Absorption Analysis)
- Percent_Weight
    - Pwr2_curve_fit
- AOUV_analysis (main code for all UV cure samples)
    - Plot UV
- UV Cure 6-min
- Stats_analysis_kwTest (statistical analysis code)
    - KW_test (Kruskal-Wallis test function)

```
% Suzie Dixon - Thesis results analysis
% Code for Water absorption samples
% where WA_Atm stands for water absorption at atmospheric pressure, 30 is
% 30 psi, 60 = 60 psi, 90 = 90 psi
clear all
clc
close all

%% constants for all data
fc = 0.1;  % cutoff frequency (for data filter)
fs = 16;   % sample frequency: 16 Hz _ Nyquist freq of 8 _> about 4 hz cutoff freq
names = ["ANA" "AOA" "SNA" "SOA" ];
%% Analysis - control samples
T = readtable('Sample_dimensions_pretest_control.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true);
P = 'C:\Users\thist\Desktop\Thesis\Compression Testing\Control Samples';
S = dir(fullfile(P,'*.csv')); % only .csv files
[control_mean_modulus,control_mean_YS_strain,control_mean_YS_stress, ↙
Control_std_modulus, Control_std_YS,S] = FunctionOfFunctions(T,P,S,fc,fs);

%% Analysis: Water absorption samples - ATMOSPHERIC
T_WA_Atm = readtable('Sample_dimensions_WA_atmospheric.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_WA_Atm = 'C:\Users\thist\Desktop\Thesis\Compression Testing\Water Absorption\ANA';↙
% file directory
S_WA_Atm = dir(fullfile(P_WA_Atm,'*.csv')); % read csv files and in structure
[WA_Atm_mean_modulus,WA_Atm_mean_YS_strain,WA_Atm_mean_YS_stress, WA_Atm_std_modulus, ↙
WA_Atm_std_YS,S_WA_Atm,ANA_mean_strain, ANA_mean_stress,AOA_mean_strain, ↙
AOA_mean_stress,SNA_mean_strain, SNA_mean_stress,SOA_mean_strain, SOA_mean_stress, ↙
WA_atm_overall_mean_modulus,WA_atm_overall_mean_YS,WA_atm_overall_mod_std, ↙
WA_atm_overall_YS_std] = FunctionOfFunctions(T_WA_Atm,P_WA_Atm,S_WA_Atm,fc,fs);

%% Analysis: Water absorption samples - 30 psi
T_WA_30 = readtable('Sample_dimensions_WA_atmospheric.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_WA_30 = 'C:\Users\thist\Desktop\Thesis\Compression Testing\Water↙
Absorption\pressure_30'; % file directory
S_WA_30 = dir(fullfile(P_WA_30,'*.csv')); % only .csv files
[WA_30_mean_modulus,WA_30_mean_YS_strain,WA_30_mean_YS_stress, WA_30_std_modulus, ↙
WA_30_std_YS,S_WA_30,ANA30_mean_strain, ANA30_mean_stress,AOA30_mean_strain, ↙
AOA30_mean_stress,SNA30_mean_strain, SNA30_mean_stress,SOA30_mean_strain, ↙
SOA30_mean_stress,WA_30_overall_mean_modulus,WA_30_overall_mean_YS, ↙
WA_30_overall_mod_std, WA_30_overall_YS_std] = FunctionOfFunctions(T_WA_30,P_WA_30, ↙
S_WA_30,fc,fs);

%% Analysis: Water absorption samples - 60 psi
T_WA_60 = readtable('Sample_dimensions_WA_atmospheric.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_WA_60 = 'C:\Users\thist\Desktop\Thesis\Compression Testing\Water↙
```

```
Absorption\pressure_60'; % file directory
S_WA_60 = dir(fullfile(P_WA_60,'*.csv')); % only .csv files
[WA_60_mean_modulus,WA_60_mean_YS_strain,WA_60_mean_YS_stress, WA_60_std_modulus, ↙
WA_60_std_YS,S_WA_60,ANA60_mean_strain, ANA60_mean_stress,AOA60_mean_strain, ↙
AOA60_mean_stress,SNA60_mean_strain, SNA60_mean_stress,SOA60_mean_strain, ↙
SOA60_mean_stress,WA_60_overall_mean_modulus,WA_60_overall_mean_YS, ↙
WA_60_overall_mod_std, WA_60_overall_YS_std] = FunctionOfFunctions(T_WA_60,P_WA_60, ↙
S_WA_60,fc,fs);

%% Analysis: Water absorption samples - 90 psi
T_WA_90 = readtable('Sample_dimensions_WA_atmospheric.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_WA_90 = 'C:\Users\thist\Desktop\Thesis\Compression Testing\Water ↙
Absorption\pressure_90'; % file directory
S_WA_90 = dir(fullfile(P_WA_90,'*.csv')); % only .csv files
[WA_90_mean_modulus,WA_90_mean_YS_strain,WA_90_mean_YS_stress, WA_90_std_modulus, ↙
WA_90_std_YS,S_WA_90,ANA90_mean_strain, ANA90_mean_stress,AOA90_mean_strain, ↙
AOA90_mean_stress,SNA90_mean_strain, SNA90_mean_stress,SOA90_mean_strain, ↙
SOA90_mean_stress,WA_90_overall_mean_modulus,WA_90_overall_mean_YS, ↙
WA_90_overall_mod_std, WA_90_overall_YS_std] = FunctionOfFunctions(T_WA_90,P_WA_90, ↙
S_WA_90,fc,fs);

%% Summary Data - plots
figure
t = tiledlayout(2,2);
nexttile
plot(ANA_mean_strain, ANA_mean_stress)
hold on
plot(AOA_mean_strain, AOA_mean_stress)
plot(SNA_mean_strain, SNA_mean_stress)
plot(SOA_mean_strain, SOA_mean_stress)
errorbar(WA_Atm_mean_YS_strain, WA_Atm_mean_YS_stress, WA_Atm_std_YS, "o",'Color', [.↙
5 .5 .5], 'MarkerFaceColor','k')
title('Atmospheric Pressure')
grid on
ylim([-0.5 6])

nexttile
plot(ANA30_mean_strain, ANA30_mean_stress)
hold on
plot(AOA30_mean_strain, AOA30_mean_stress)
plot(SNA30_mean_strain, SNA30_mean_stress)
plot(SOA30_mean_strain, SOA30_mean_stress)
errorbar(WA_30_mean_YS_strain, WA_30_mean_YS_stress, WA_30_std_YS, "o",'Color', [.5 .↙
5 .5], 'MarkerFaceColor','k')
title('30-psi')
grid on
ylim([-0.5 6])
```

```
nexttile
plot(ANA60_mean_strain, ANA60_mean_stress)
hold on
plot(AOA60_mean_strain, AOA60_mean_stress)
plot(SNA60_mean_strain, SNA60_mean_stress)
plot(SOA60_mean_strain, SOA60_mean_stress)
errorbar(WA_60_mean_YS_strain, WA_60_mean_YS_stress, WA_60_std_YS, "o",'Color', [.5 .↙
5 .5], 'MarkerFaceColor','k')
title('60-psi')
grid on
ylim([-0.5 6])

nexttile
plot(ANA90_mean_strain, ANA90_mean_stress)
hold on
plot(AOA90_mean_strain, AOA90_mean_stress)
plot(SNA90_mean_strain, SNA90_mean_stress)
plot(SOA90_mean_strain, SOA90_mean_stress)
errorbar(WA_90_mean_YS_strain, WA_90_mean_YS_stress, WA_90_std_YS, "o",'Color', [.5 .↙
5 .5], 'MarkerFaceColor','k')
title('90-psi')
grid on
ylim([-0.5 6])

lgd = legend('ANA', 'AOA', 'SNA', 'SOA', 'location','southoutside',↙
'Orientation','horizontal');
lgd.Title.String = 'Sample Variation Method';
lgd.Layout.Tile = 'south';
title(t,'Water Absorption: Stress vs Strain')
xlabel(t,'Strain (%)')
ylabel(t,'Stress (ksi)')

%% Summary data - barplots
Bar3D_Modulus = cat(1,control_mean_modulus,WA_Atm_mean_modulus,WA_30_mean_modulus, ↙
WA_60_mean_modulus,WA_90_mean_modulus)';
Bar3D_YS = cat(1,control_mean_YS_stress,WA_Atm_mean_YS_stress,WA_30_mean_YS_stress, ↙
WA_60_mean_YS_stress,WA_90_mean_YS_stress)';

figure
bar3(Bar3D_Modulus)
hold on
xlabel('Pressure')
ylabel('Sample Variation Method')
zlabel('Mean Modulus (psi)')
title('Sample Variation vs Mean Modulus')
lgd = legend('N/A','Atmospheric', '30 psi', '60 psi', '90 psi','location',↙
'southoutside','Orientation','horizontal','Position',[0.2215 0.02 0.566 0.08]);
title(lgd,'UV Cure Time(minutes)')
set(gca, 'YTickLabel',{'ANA','AOA','SNA','SOA'}, 'XTickLabel',↙
```

```
{'Control','Atmospheric', '30 psi', '60 psi', '90 psi'} )
view(-90,0)

figure
bar3(Bar3D_YS)
hold on
xlabel('Cure Time (minutes)')
ylabel('Sample Variation Method')
zlabel('Mean Yield Strength (psi)')
title('Sample Variation vs Mean Yield Strength')
lgd = legend('N/A','Atmospheric', '30 psi', '60 psi', '90 psi','location',↙
'southoutside','Orientation','horizontal','Position',[0.2215 0.02 0.566 0.08]);
title(lgd,'UV Cure Time (minutes)')
set(gca, 'YTickLabel',{'ANA','AOA','SNA','SOA'}, 'XTickLabel',↙
{'Control','Atmospheric', '30 psi', '60 psi', '90 psi'} )
view(-90,0)
%% 4 SUBPLOTS WITH ERROR BAR with all variations on one plot.
% grab column of matrix for all variations of one
figure
t1 = tiledlayout(2,2);
title(t1,'Water Absorption: Mean Modulus')
xlabel(t1,'Variation Method')
ylabel(t1,'Mean Modulus (ksi)')

nexttile
bar(categorical(names),WA_Atm_mean_modulus)
hold on
errorbar(categorical(names),WA_Atm_mean_modulus,↙
WA_Atm_std_modulus,'Color','k','LineStyle','none')
title('Atmospheric Pressure')
ylim([0 200])
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

nexttile
bar(categorical(names),WA_30_mean_modulus)
hold on
errorbar(categorical(names),WA_30_mean_modulus,↙
WA_30_std_modulus,'Color','k','LineStyle','none')
title('30-psi')
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

nexttile
bar(categorical(names),WA_60_mean_modulus)
hold on
errorbar(categorical(names),WA_60_mean_modulus,↙
```

```
WA_60_std_modulus,'Color','k','LineStyle','none')
title('60-psi')
ylim([0 200])
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

nexttile
bar(categorical(names),WA_90_mean_modulus)
hold on
errorbar(categorical(names),WA_90_mean_modulus, ↙
WA_90_std_modulus,'Color','k','LineStyle','none')
title('90-psi')
ylim([0 200])
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on


%% mean YS 2D barplot
figure
t1 = tiledlayout(2,2);
title(t1,'Water Absorption: Mean Yield Strength')
xlabel(t1,'Variation Method')
ylabel(t1,'Mean Yield Strength (ksi)')

nexttile
bar(categorical(names),WA_Atm_mean_YS_stress)
hold on
errorbar(categorical(names),WA_Atm_mean_YS_stress, ↙
WA_Atm_std_YS,'Color','k','LineStyle','none')
title('Atmospheric Pressure')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

nexttile
bar(categorical(names),WA_30_mean_YS_stress)
hold on
errorbar(categorical(names),WA_30_mean_YS_stress, ↙
WA_30_std_YS,'Color','k','LineStyle','none')
title('30-psi')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

nexttile
bar(categorical(names),WA_60_mean_YS_stress)
hold on
errorbar(categorical(names),WA_60_mean_YS_stress, ↙
WA_60_std_YS,'Color','k','LineStyle','none')
```

```
title('60-psi')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

nexttile
bar(categorical(names),WA_90_mean_YS_stress)
hold on
errorbar(categorical(names),WA_90_mean_YS_stress, ↙
WA_90_std_YS,'Color','k','LineStyle','none')
title('90-psi')
set(gca, 'XTickLabel',{'ANA','AOA','SNA','SOA'})
grid on

%% barplots comparing pressure
mat_mod = cat(1,WA_Atm_mean_modulus, WA_30_mean_modulus,WA_60_mean_modulus, ↙
WA_90_mean_modulus);
mat_YS = cat(1,WA_Atm_mean_YS_stress, WA_30_mean_YS_stress,WA_60_mean_YS_stress, ↙
WA_90_mean_YS_stress);
Pressure = categorical({'Atm','30-psi','60-psi','90-psi'});
press_ord = reordercats(Pressure, {'Atm','30-psi','60-psi','90-psi'});
mat_mod_std = cat(1,WA_Atm_std_modulus,WA_30_std_modulus,WA_60_std_modulus, ↙
WA_90_std_modulus);
mat_YS_std = cat(1,WA_Atm_std_YS,WA_30_std_YS,WA_60_std_YS,WA_90_std_YS);

figure
t2 = tiledlayout(2,2);
title(t2,'Water Absorption: Mean Yield Strength')
xlabel(t2,'Immersion Pressure')
ylabel(t2,'Mean Yield Strength (ksi)')

nexttile
bar(press_ord,mat_YS(:,1))
hold on
errorbar(press_ord,mat_YS(:,1),mat_YS_std(:,1),'Color','k','LineStyle','none')
title('ANA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

nexttile
bar(press_ord,mat_YS(:,2))
hold on
errorbar(press_ord,mat_YS(:,2),mat_YS_std(:,2),'Color','k','LineStyle','none')
title('AOA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

nexttile
bar(press_ord,mat_YS(:,3))
hold on
```

```
errorbar(press_ord,mat_YS(:,3),mat_YS_std(:,3),'Color','k','LineStyle','none')
title('SNA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

nexttile
bar(press_ord,mat_YS(:,4))
hold on
errorbar(press_ord,mat_YS(:,4),mat_YS_std(:,4),'Color','k','LineStyle','none')
title('SOA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on
%% mod

figure
t3 = tiledlayout(2,2);
title(t3,'Water Absorption: Mean Modulus')
xlabel(t3,'Pressure')
ylabel(t3,'Mean Modulus (ksi)')

nexttile
bar(press_ord,mat_mod(:,1))
hold on
errorbar(press_ord,mat_mod(:,1),mat_mod_std(:,1),'Color','k','LineStyle','none')
title('ANA')
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

nexttile
bar(press_ord,mat_mod(:,2))
hold on
errorbar(press_ord,mat_mod(:,2),mat_mod_std(:,2),'Color','k','LineStyle','none')
title('AOA')
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

nexttile
bar(press_ord,mat_mod(:,3))
hold on
errorbar(press_ord,mat_mod(:,3),mat_mod_std(:,3),'Color','k','LineStyle','none')
title('SNA')
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

nexttile
bar(press_ord,mat_mod(:,4))
```

```
hold on
errorbar(press_ord,mat_mod(:,4),mat_mod_std(:,4),'Color','k','LineStyle','none')
title('SOA')
%ytickformat('%1.1f')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
grid on

%% compile summary data
mean_modulus_matrix = mat_mod'./1000; % mean modulus (ksi) for each variation method
mean_modulus_std = mat_mod_std'./1000; % standard deviation (ksi)
mean_YS_matrix = mat_YS'./1000; % mean modulus (ksi) for each variation method
mean_YS_std = mat_YS_std'./1000; % standard deviation (ksi)

% means of all variation methods per pressure immersed
Overall_mean_modulus = [WA_atm_overall_mean_modulus,WA_30_overall_mean_modulus, ↙
WA_60_overall_mean_modulus,WA_90_overall_mean_modulus]./1000;
Overall_mean_YS = [WA_atm_overall_mean_YS,WA_30_overall_mean_YS, ↙
WA_60_overall_mean_YS,WA_90_overall_mean_YS]./1000;
Overall_mean_mod_std = [WA_atm_overall_mod_std, WA_30_overall_mod_std, ↙
WA_60_overall_mod_std,WA_90_overall_mod_std]./1000;
Overall_mean_YS_std = [WA_atm_overall_YS_std, WA_30_overall_YS_std, ↙
WA_60_overall_YS_std,WA_90_overall_YS_std]./1000;
```

```
% Percent weight code
% Suzie Dixon - Thesis results analysis
% ToDo: move graphs with error bar into function and update
clear all
clc
close all
%%
time = [6; 12; 24; 48; 132; 192; 336; 384; 672; 1008; 1344; 1536];
days = [0.25;0.5; 1; 2; 5.5; 8; 14; 16; 28; 42; 56; 64];
V = (3.14*0.5^2)/4; % sample volume inches^3
S = 16.77; % salinity in g/in^3
%% atmospheric samples data process
[Pct_wt_SNA,pct_wt_std_SNA,Pct_wt_SNA_allData, P_SNA, P_std_SNA] = data_process ↙
('SNA', time, S, V); % to get wt vs time
[fitresult_SNA, gof_SNA] = pwr2_curve_fit(days, Pct_wt_SNA);
[Pct_wt_SOA,pct_wt_std_SOA,Pct_wt_SOA_allData,P_SOA, P_std_SOA] = data_process('SOA',↙
time, S, V);
[fitresult_SOA, gof_SOA] = pwr2_curve_fit(days, Pct_wt_SOA);
[Pct_wt_ANA,pct_wt_std_ANA,Pct_wt_ANA_allData, P_ANA, P_std_ANA] = data_process ↙
('ANA', time, S, V);
[fitresult_ANA, gof_ANA] = pwr2_curve_fit(days, Pct_wt_ANA);
[Pct_wt_AOA,pct_wt_std_AOA,Pct_wt_AOA_allData,P_AOA, P_std_AOA] = data_process('AOA',↙
time, S, V);
[fitresult_AOA, gof_AOA] = pwr2_curve_fit(days, Pct_wt_AOA);

%% pressure samples - 64 days
[Pct_wt_SNA30, pct_wt_std_SNA30, P_SNA30, P_std_SNA30] = data_process2('SNA30',S,V);↙
% function get pct wt for 30-psi
[Pct_wt_SOA30, pct_wt_std_SOA30, P_SOA30, P_std_SOA30] = data_process2('SOA30',S,V);
[Pct_wt_ANA30, pct_wt_std_ANA30, P_ANA30, P_std_ANA30] = data_process2('ANA30',S,V);
[Pct_wt_AOA30, pct_wt_std_AOA30, P_AOA30, P_std_AOA30] = data_process2('AOA30',S,V);

[Pct_wt_SNA60, pct_wt_std_SNA60, P_SNA60, P_std_SNA60] = data_process2('SNA60',S,V);↙
% get pct wt for 60-psi
[Pct_wt_SOA60, pct_wt_std_SOA60, P_SOA60, P_std_SOA60] = data_process2('SOA60',S,V);
[Pct_wt_ANA60, pct_wt_std_ANA60, P_ANA60, P_std_ANA60] = data_process2('ANA60',S,V);
[Pct_wt_AOA60, pct_wt_std_AOA60, P_AOA60, P_std_AOA60] = data_process2('AOA60',S,V);

[Pct_wt_SNA90, pct_wt_std_SNA90, P_SNA90, P_std_SNA90] = data_process2('SNA90',S,V);↙
% get pct wt for 90-psi
[Pct_wt_SOA90, pct_wt_std_SOA90, P_SOA90, P_std_SOA90] = data_process2('SOA90',S,V);
[Pct_wt_ANA90, pct_wt_std_ANA90, P_ANA90, P_std_ANA90] = data_process2('ANA90',S,V);
[Pct_wt_AOA90, pct_wt_std_AOA90, P_AOA90, P_std_AOA90] = data_process2('AOA90',S,V);

% compile the results for each pressure
mean_64_pctwt30 = [Pct_wt_ANA30,Pct_wt_AOA30,Pct_wt_SNA30,Pct_wt_SOA30];
mean_64_pctwt60 = [Pct_wt_ANA60,Pct_wt_AOA60,Pct_wt_SNA60,Pct_wt_SOA60];
mean_64_pctwt90 = [Pct_wt_ANA90,Pct_wt_AOA90,Pct_wt_SNA90,Pct_wt_SOA90];
stdev_64_pctwt30 = [pct_wt_std_ANA30,pct_wt_std_AOA30,pct_wt_std_SNA30, ↙
```

```
pct_wt_std_SOA30];
stdev_64_pctwt60 = [pct_wt_std_ANA60,pct_wt_std_AOA60,pct_wt_std_SNA60, ↙
pct_wt_std_SOA60];
stdev_64_pctwt90 = [pct_wt_std_ANA90,pct_wt_std_AOA90,pct_wt_std_SNA90, ↙
pct_wt_std_SOA90];
P_Atm = cat(1,P_ANA,P_AOA,P_SNA,P_SOA);
P_30 = cat(1,P_ANA30,P_AOA30,P_SNA30,P_SOA30);
P_60 = cat(1,P_ANA60,P_AOA60,P_SNA60,P_SOA60);
P_90 = cat(1,P_ANA90,P_AOA90,P_SNA90,P_SOA90);
P = table(round(P_Atm,2),round(P_30,2),round(P_60,2),round(P_90,2))
P_mean = mean((table2array(P)))

P_std_Atm = cat(1,P_std_ANA,P_std_AOA,P_std_SNA,P_std_SOA);
P_std_30 = cat(1,P_std_ANA30,P_std_AOA30,P_std_SNA30,P_std_SOA30);
P_std_60 = cat(1,P_std_ANA60,P_std_AOA60,P_std_SNA60,P_std_SOA60);
P_std_90 = cat(1,P_std_ANA90,P_std_AOA90,P_std_SNA90,P_std_SOA90);
P_std = table(round(P_std_Atm,2),round(P_std_30,2),round(P_std_60,2),round(P_std_90, ↙
2))
%% plots - individ
figure
t = tiledlayout(2,2);
title(t,'Percent Weight vs Immersion Time')
xlabel(t,'Time (days)')
ylabel(t,'Percent Weight (%)')

nexttile
errorbar(days, Pct_wt_ANA, pct_wt_std_ANA ,"o",'Color', [.5 .5 .5],↙
'MarkerFaceColor','k','MarkerSize',3) % Pct_wt_err_neg, Pct_wt_err_pos
hold on
grid on
p = plot(fitresult_ANA);
title('ANA')
legend('hide')
xlim([0 70])
ylim([0 1.8])
%ytickformat('%1.1f')
set(p,'Color',[0.5 0.5 0.5], 'LineWidth',1)

nexttile
errorbar(days, Pct_wt_AOA, pct_wt_std_AOA ,"o",'Color', [.5 .5 .5],↙
'MarkerFaceColor','k','MarkerSize',3) % Pct_wt_err_neg, Pct_wt_err_pos
hold on
grid on
p1 = plot(fitresult_AOA);
title('AOA')
legend('hide')
xlim([0 70])
ylim([0 1.8])
%ytickformat('%1.1f')
```

```
set(p1,'Color',[0.5 0.5 0.5], 'LineWidth',1)

nexttile
errorbar(days, Pct_wt_SNA, pct_wt_std_SNA ,"o",'Color', [.5 .5 .5],↙
'MarkerFaceColor','k','MarkerSize',3) % Pct_wt_err_neg, Pct_wt_err_pos
hold on
grid on
p2 = plot(fitresult_SNA);
title('SNA')
legend('hide')
xlim([0 70])
ylim([0 1.8])
%ytickformat('%1.1f')
set(p2,'Color',[0.5 0.5 0.5], 'LineWidth',1)

nexttile
errorbar(days, Pct_wt_SOA, pct_wt_std_SOA ,"o",'Color', [.5 .5 .5],↙
'MarkerFaceColor','k','MarkerSize',3) % Pct_wt_err_neg, Pct_wt_err_pos
hold on
grid on
p3 = plot(fitresult_SOA);
title('SOA')
legend('hide')
xlim([0 70])
ylim([0 1.8])
%ytickformat('%1.1f')
set(p3,'Color',[0.5 0.5 0.5], 'LineWidth',1)

%% plots - summary
% pct wt vs time - superimposed


figure
pl1 = plot(fitresult_SNA);
hold on
pl2 = plot(fitresult_SOA);
pl3 = plot(fitresult_ANA);
pl4 = plot(fitresult_AOA);
legend("Siraya Tech New Alcohol", "Siraya Tech Old Alcohol", "Amazon New Alcohol",↙
"Amazon Old Alcohol",'Location', 'southeast')
xlabel("Time (days)")
ylabel("Percent Weight (%)")
title("Percent Weight vs Time")
xlim([0 64])
%ytickformat('%1.1f')
grid on
set(pl1,'Color',[0.00 0.45 0.74], 'LineWidth',1) % set plot line colors and widths
set(pl2,'Color',[0.85 0.33 0.10], 'LineWidth',1)
set(pl3,'Color',[0.93 0.69 0.13], 'LineWidth',1)
```

```
set(pl4,'Color',[0.49 0.18 0.56], 'LineWidth',1)
%%
% pct wt vs sqrt(time) - superimposed
t_squared = sqrt(time);
days_squared = sqrt(days);
figure
plot(days_squared,Pct_wt_SNA,days_squared,Pct_wt_SOA, days_squared,Pct_wt_ANA, ↙
days_squared, Pct_wt_AOA)
legend("Siraya Tech New Alcohol", "Siraya Tech Old Alcohol", "Amazon New Alcohol",↙
"Amazon Old Alcohol",'Location', 'southeast')
xlabel("t^{1/2}")
ylabel("Percent Weight (%)")
title("Percent Weight vs Square Root of Time")
grid on

%% bar plot of pct wt at 64 days
variation = ["ANA" "AOA" "SNA" "SOA"]'; % sample names
mean_64_pctwt = [Pct_wt_ANA(1,12),Pct_wt_AOA(1,12),Pct_wt_SNA(1,12),Pct_wt_SOA ↙
(1,12)];
stdev_64_pctwt = [pct_wt_std_ANA(1,12),pct_wt_std_AOA(1,12),pct_wt_std_SNA(1,12), ↙
pct_wt_std_SOA(1,12)];

figure
bar(categorical(variation), mean_64_pctwt)
hold on
errorbar(categorical(variation),mean_64_pctwt, ↙
stdev_64_pctwt,'Color','k','LineStyle','none')
xlabel('Sample Variation Method')
ylabel('Percent Weight (%)')
title('Percent Weight at 64 days')
ylim([1.46 1.65])
grid on
ytickformat('%1.2f')

%% tiled layout comparing 64 days at all pressures
figure
tile = tiledlayout(2,2);
title(tile,'Percent Weight vs Variation Type')
xlabel(tile,'Sample Variation Method')
ylabel(tile,'Percent Weight (%)')

nexttile
bar(categorical(variation), mean_64_pctwt)
hold on
errorbar(categorical(variation),mean_64_pctwt, ↙
stdev_64_pctwt,'Color','k','LineStyle','none')
grid on
title('Atmospheric')
ytickformat('%1.1f')
```

```
ylim([1.45 1.74])

nexttile
bar(categorical(variation), mean_64_pctwt30)
hold on
errorbar(categorical(variation),mean_64_pctwt30, ↙
stdev_64_pctwt30,'Color','k','LineStyle','none')
grid on
title('30-psi')
ytickformat('%1.1f')
ylim([1.45 1.74])

nexttile
bar(categorical(variation), mean_64_pctwt60)
hold on
errorbar(categorical(variation),mean_64_pctwt60, ↙
stdev_64_pctwt60,'Color','k','LineStyle','none')
grid on
title('60-psi')
ytickformat('%1.1f')
ylim([1.45 1.74])

nexttile
bar(categorical(variation), mean_64_pctwt90)
hold on
errorbar(categorical(variation),mean_64_pctwt90, ↙
stdev_64_pctwt90,'Color','k','LineStyle','none')
grid on
title('90-psi')
ytickformat('%1.1f')
ylim([1.45 1.74])

%% assemble pct wt of pressures in matrix
ANA = cat(1,Pct_wt_ANA(1,12),Pct_wt_ANA30,Pct_wt_ANA60,Pct_wt_ANA90);
AOA = cat(1,Pct_wt_AOA(1,12),Pct_wt_AOA30,Pct_wt_AOA60,Pct_wt_AOA90);
SNA = cat(1,Pct_wt_SNA(1,12),Pct_wt_SNA30,Pct_wt_SNA60,Pct_wt_SNA90);
SOA = cat(1,Pct_wt_SOA(1,12),Pct_wt_SOA30,Pct_wt_SOA60,Pct_wt_SOA90);
ANA_std = cat(1,pct_wt_std_ANA(1,12),pct_wt_std_ANA30,pct_wt_std_ANA60, ↙
pct_wt_std_ANA90);
AOA_std = cat(1,pct_wt_std_AOA(1,12),pct_wt_std_AOA30,pct_wt_std_AOA60, ↙
pct_wt_std_AOA90);
SNA_std = cat(1,pct_wt_std_SNA(1,12),pct_wt_std_SNA30,pct_wt_std_SNA60, ↙
pct_wt_std_SNA90);
SOA_std = cat(1,pct_wt_std_SOA(1,12),pct_wt_std_SOA30,pct_wt_std_SOA60, ↙
pct_wt_std_SOA90);
water_abs_pct_wt_mat = cat(1,ANA',AOA',SNA',SOA');

%% tiled layout comparing variations by of all pressures
Pressure = categorical({'Atm','30-psi','60-psi','90-psi'});
```

```
press_ord = reordercats(Pressure, {'Atm','30-psi','60-psi','90-psi'});
figure
tile2 = tiledlayout(2,2);
title(tile2,'Percent Weight vs Pressure')
xlabel(tile2,'Pressure')
ylabel(tile2,'Percent Weight (%)')

nexttile
bar(press_ord, ANA)
hold on
errorbar(press_ord,ANA,ANA_std,'Color','k','LineStyle','none')
grid on
title('ANA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
ytickformat('%1.2f')
ylim([1.45 1.74])

nexttile
bar(press_ord, AOA)
hold on
errorbar(press_ord,AOA,AOA_std,'Color','k','LineStyle','none')
grid on
title('AOA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
ytickformat('%1.2f')
ylim([1.45 1.74])

nexttile
bar(press_ord, SNA)
hold on
errorbar(press_ord,SNA,SNA_std,'Color','k','LineStyle','none')
grid on
title('SNA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
ytickformat('%1.2f')
ylim([1.45 1.74])

nexttile
bar(press_ord, SOA)
hold on
errorbar(press_ord,SOA,SOA_std,'Color','k','LineStyle','none')
grid on
title('SOA')
set(gca, 'XTickLabel',{'Atm','30-psi','60-psi','90-psi'})
ytickformat('%1.2f')
ylim([1.45 1.74])

%% summary data compilation - NEED ALL OF THEM NOT JUST MEANS FOR EACH VAR
Pct_wt_matrix = cat(1,Pct_wt_ANA, Pct_wt_AOA, Pct_wt_SNA, Pct_wt_SOA); % assemble all↙
```

```
data at atmospheric
Pct_wt_atm_24hr = Pct_wt_matrix(:,3); % 24 hr data
Pct_wt_atm_14days = Pct_wt_matrix(:,7); % 14 days
Pct_wt_atm_28days = Pct_wt_matrix(:,9); % 28 days
Pct_wt_atm_42days = Pct_wt_matrix(:,10); % 42 days
Pct_wt_atm_56days = Pct_wt_matrix(:,11); % 56 days
Pct_wt_atm_64days = Pct_wt_matrix(:,12); % 64 days

pct_wt_std_matrix = cat(1,pct_wt_std_ANA, pct_wt_std_AOA, pct_wt_std_SNA, ↙
pct_wt_std_SOA); % assemble all data at atmospheric
Pct_wt_std_atm_24hr = pct_wt_std_matrix(:,3); % 24 hr data
Pct_wt_std_atm_14days = pct_wt_std_matrix(:,7); % 14 days
Pct_wt_std_atm_28days = pct_wt_std_matrix(:,9); % 28 days
Pct_wt_std_atm_42days = pct_wt_std_matrix(:,10); % 42 days
Pct_wt_std_atm_56days = pct_wt_std_matrix(:,11); % 56 days
Pct_wt_std_atm_64days = pct_wt_std_matrix(:,12); % 64 days

%% calculations

function [Pct_wt_avg, Pct_wt_stdev,Pct_wt, P, P_std] = data_process(sheet_name, t, S, ↙
V)

T = readtable('PercentWeight.xlsx','sheet', sheet_name,'PreserveVariableNames',true);

Sample = T.Sample;
W0 = T.("Initial weight");
W6 = T.("6 hr");
W12 = T.("12 hr");
W24 = T.("24 hr");
W48 = T.("48 hr");
W132 = T.("132 hr (5.5 days)");
W192 = T.("8 days");
W336 = T.("2 weeks");
W384 = T.("16 days");
W672 = T.("4 weeks");
W1008 = T.("6 weeks");
W1344 = T.("8 weeks");
W1536 = T.("64 days");
wt_avg = mean(T{:,2:end});

time = [0,6,12,24,48,132,192,336,384,672,1008,1344,1536];
W0_std_matrix = [W0,W6,W12,W24,W48,W132,W192,W336,W384,W672,W1008,W1344, W1536];

Pct_Wt_6 = ((W6-W0)./W0)*100; % Calculate percent weights
Pct_Wt_12 = ((W12-W0)./W0)*100;
Pct_Wt_24 = ((W24-W0)./W0)*100;
Pct_Wt_48 = ((W48-W0)./W0)*100;
Pct_Wt_132 = ((W132-W0)./W0)*100;
Pct_Wt_192 = ((W192-W0)./W0)*100;
```

```
Pct_Wt_336 = ((W336-W0)./W0)*100;
Pct_Wt_384 = ((W384-W0)./W0)*100;
Pct_Wt_672 = ((W672-W0)./W0)*100;
Pct_Wt_1008 = ((W1008-W0)./W0)*100;
Pct_Wt_1344 = ((W1344-W0)./W0)*100;
Pct_Wt_1536 = ((W1536-W0)./W0)*100;

Pct_wt = [Pct_Wt_6,Pct_Wt_12, Pct_Wt_24, Pct_Wt_48, Pct_Wt_132,Pct_Wt_192,Pct_Wt_336, ↙
Pct_Wt_384,Pct_Wt_672,Pct_Wt_1008,Pct_Wt_1344,Pct_Wt_1536];
Pct_wt_avg = mean(Pct_wt);

Pct_wt_stdev = std(Pct_wt); % stdev of percent weight
P = (((W1536-W0)/S)/V)*100; % Open porosity (theoretically)
P_std = std(P);
P = mean(P);
end


function [Pct_wt_avg, Pct_wt_stdev,P, P_std] = data_process2(sheet_name,S,V)  %↙
function just for 64 days

T = readtable('PercentWeight.xlsx','sheet', sheet_name,'PreserveVariableNames',true);
W0 = T.("Initial weight");
W1536 = T.("64 days");
Pct_Wt_1536 = ((W1536-W0)./W0)*100; % calculate pct wt for each sample
Pct_wt_avg = mean(Pct_Wt_1536); % average
Pct_wt_stdev = std(Pct_Wt_1536); % stdev
P = (((W1536-W0)/S)/V)*100; % Open porosity (theoretically)
P_std = std(P);
P = mean(P);
end
```

```
function [fitresult, gof] = pwr2_curve_fit(days, Pct_wt_SNA)
%CREATEFIT(DAYS,PCT_WT_SNA)
%  Create a fit.
%
%  Data for 'SNA_fit' fit:
%      X Input : days
%      Y Output: Pct_wt_SNA
%  Output:
%      fitresult : a fit object representing the fit.
%      gof : structure with goodness-of fit info.
%
%  See also FIT, CFIT, SFIT.

%  Auto-generated by MATLAB on 25-Feb-2024 14:07:09
% Author's note: Curve Fitting Tool was used to create code

%% Fit: 'SNA_fit'.
[xData, yData] = prepareCurveData( days, Pct_wt_SNA );

% Set up fittype and options.
ft = fittype( 'power2' );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Display = 'Off';
opts.StartPoint = [0.202950935299434 0.52773775194623 -0.0330321539071522];

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

end
```

```
% Suzie Dixon - Thesis results analysis
% Code for UV Cure samples

clear all
clc
close all
%% Analysis: AOUV samples
T_AOUV = readtable('Sample_dimensions_AOUV.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_AOUV = 'C:\Users\thist\Desktop\Thesis\Compression Testing\UV cure samples\Amazon ↙
Old'; % file directory
S_AOUV = dir(fullfile(P_AOUV,'*.csv')); % only .csv files
names = ["AOUV6" "AOUV15" "AOUV60" "AOUV120" "AOUV240"]; % sample names
fc = 0.1;  % cutoff frequency (for data filter)
fs = 16;   % sample frequency: 16 Hz _ Nyquist freq of 8 _> about 4 hz cutoff freq

[S_AOUV] = calculations(S_AOUV, P_AOUV, T_AOUV, fc, fs); % call function for data↙
calculations within data structure

% resize data for to the minimum length of the sample set
[~,S_AOUV] = set_length(1,S_AOUV);
[~,S_AOUV] = set_length(6,S_AOUV);
[~,S_AOUV] = set_length(11,S_AOUV);
[~,S_AOUV] = set_length(16,S_AOUV);
[start,S_AOUV] = set_length(21,S_AOUV);

% summary data - call function for summary calculations
[AOUV_std_YS, AOUV_std_modulus, overall_mean_modulus, overall_mean_YS, ↙
overall_mean_strain, overall_mod_std, overall_YS_std] = SummaryData(S_AOUV);

% individual data summaries
% name empty arrays then call function to calculate mean per variation
[AOUV6_mean_strain, AOUV6_mean_stress, AOUV6_stress, AOUV6_strain, ↙
AOUV6_mean_modulus, AOUV6_YS_stress, AOUV6_YS_strain] = mean_of_5(S_AOUV,1,5); % call↙
function to calc mean of 5 samples
[AOUV15_mean_strain, AOUV15_mean_stress, AOUV15_stress, AOUV15_strain, ↙
AOUV15_mean_modulus,AOUV15_YS_stress, AOUV15_YS_strain] = mean_of_5(S_AOUV,6,10);
[AOUV60_mean_strain, AOUV60_mean_stress, AOUV60_stress, AOUV60_strain, ↙
AOUV60_mean_modulus,AOUV60_YS_stress, AOUV60_YS_strain] = mean_of_5(S_AOUV,11,15);
[AOUV120_mean_strain, AOUV120_mean_stress, AOUV120_stress, AOUV120_strain, ↙
AOUV120_mean_modulus,AOUV120_YS_stress, AOUV120_YS_strain] = mean_of_5(S_AOUV,16,20);
[AOUV240_mean_strain, AOUV240_mean_stress, AOUV240_stress, AOUV240_strain, ↙
AOUV240_mean_modulus,AOUV240_YS_stress, AOUV240_YS_strain] = mean_of_5(S_AOUV,21,25);
% condense data to be plotted
AOUV_mean_YS_strain = [AOUV6_YS_strain,AOUV15_YS_strain,AOUV60_YS_strain, ↙
AOUV120_YS_strain,AOUV240_YS_strain];
AOUV_mean_YS_stress = [AOUV6_YS_stress,AOUV15_YS_stress,AOUV60_YS_stress, ↙
AOUV120_YS_stress,AOUV240_YS_stress];
AOUV_mean_modulus = [AOUV6_mean_modulus, AOUV15_mean_modulus, AOUV60_mean_modulus, ↙
```

```
AOUV120_mean_modulus,AOUV240_mean_modulus];
AOUV_overall_mean_YS_stress = mean(AOUV_mean_YS_stress);
AOUV_overall_mean_modulus_2 = mean(AOUV_mean_modulus);
AOUV_overall_mod_std_2 = std(AOUV_mean_modulus);
AOUV_overall_YS_std2 = std(AOUV_mean_YS_stress);

%plot all control samples superimposed
for n = 1:length(S_AOUV)
    plot(S_AOUV(n).strain_comped,S_AOUV(n).filtered_Stress, S_AOUV(n).YS_strain, ↙
S_AOUV(n).YS_stress, '-o')
    xlabel('Strain (%)')
    ylabel('Stress (psi)')
    title('Stress vs Strain')
    %legend(S_AOUV(n).name, 'Location', 'SouthOutside') % fix
    hold on
    if mod(n,5)==0 % start a new figure every 5th sample
        figure
    end
end
hold off
close(6)

minutes = [6 15 60 120 240];


%% Analysis: ANUV samples
T_ANUV = readtable('Sample_dimensions_ANUV.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_ANUV = 'C:\Users\thist\Desktop\Thesis\Compression Testing\UV cure samples\Amazon ↙
Old'; % file directory
S_ANUV = dir(fullfile(P_ANUV,'*.csv')); % only .csv files
names = ["ANUV6" "ANUV15" "ANUV60" "ANUV120" "ANUV240"]; % sample names
fc = 0.1;  % cutoff frequency (for data filter)
fs = 16;   % sample frequency: 16 Hz _ Nyquist freq of 8 _> about 4 hz cutoff freq

[S_ANUV] = calculations(S_ANUV, P_ANUV, T_ANUV, fc, fs); % call function for data↙
calculations within data structure

% resize data for to the minimum length of the sample set
[~,S_ANUV] = set_length(1,S_ANUV);
[~,S_ANUV] = set_length(6,S_ANUV);
[~,S_ANUV] = set_length(11,S_ANUV);
[~,S_ANUV] = set_length(16,S_ANUV);
[start,S_ANUV] = set_length(21,S_ANUV);

% summary data - call function for summary calculations
[ANUV_std_YS, ANUV_std_modulus, overall_mean_modulus, overall_mean_YS, ↙
overall_mean_strain, overall_mod_std, overall_YS_std] = SummaryData(S_ANUV);
```

```
% individual data summaries
% name empty arrays then call function to calculate mean per variation
[ANUV6_mean_strain, ANUV6_mean_stress, ANUV6_stress, ANUV6_strain, ↙
ANUV6_mean_modulus, ANUV6_YS_stress, ANUV6_YS_strain] = mean_of_5(S_ANUV,1,5); % call↙
function to calc mean of 5 samples
[ANUV15_mean_strain, ANUV15_mean_stress, ANUV15_stress, ANUV15_strain, ↙
ANUV15_mean_modulus,ANUV15_YS_stress, ANUV15_YS_strain] = mean_of_5(S_ANUV,6,10);
[ANUV60_mean_strain, ANUV60_mean_stress, ANUV60_stress, ANUV60_strain, ↙
ANUV60_mean_modulus,ANUV60_YS_stress, ANUV60_YS_strain] = mean_of_5(S_ANUV,11,15);
[ANUV120_mean_strain, ANUV120_mean_stress, ANUV120_stress, ANUV120_strain, ↙
ANUV120_mean_modulus,ANUV120_YS_stress, ANUV120_YS_strain] = mean_of_5(S_ANUV,16,20);
[ANUV240_mean_strain, ANUV240_mean_stress, ANUV240_stress, ANUV240_strain, ↙
ANUV240_mean_modulus,ANUV240_YS_stress, ANUV240_YS_strain] = mean_of_5(S_ANUV,21,25);
% condense data to be plotted
ANUV_mean_YS_strain = [ANUV6_YS_strain,ANUV15_YS_strain,ANUV60_YS_strain, ↙
ANUV120_YS_strain,ANUV240_YS_strain];
ANUV_mean_YS_stress = [ANUV6_YS_stress,ANUV15_YS_stress,ANUV60_YS_stress, ↙
ANUV120_YS_stress,ANUV240_YS_stress];
ANUV_mean_modulus = [ANUV6_mean_modulus, ANUV15_mean_modulus, ANUV60_mean_modulus, ↙
ANUV120_mean_modulus,ANUV240_mean_modulus];
ANUV_overall_mean_YS_stress = mean(ANUV_mean_YS_stress);
ANUV_overall_mean_modulus_2 = mean(ANUV_mean_modulus);
ANUV_overall_mod_std_2 = std(ANUV_mean_modulus);
ANUV_overall_YS_std2 = std(ANUV_mean_YS_stress);

%plot all control samples superimposed
for n = 1:length(S_ANUV)
    plot(S_ANUV(n).strain_comped,S_ANUV(n).filtered_Stress, S_ANUV(n).YS_strain, ↙
S_ANUV(n).YS_stress, '-o')
    xlabel('Strain (%)')
    ylabel('Stress (psi)')
    title('Stress vs Strain')
    %legend(S_ANUV(n).name, 'Location', 'SouthOutside') % fix
    hold on
    if mod(n,5)==0 % start a new figure every 5th sample
        figure
    end
end
hold off
close(6)

%% Analysis: SOUV samples
T_SOUV = readtable('Sample_dimensions_SOUV.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_SOUV = 'C:\Users\thist\Desktop\Thesis\Compression Testing\UV cure samples\Amazon↙
Old'; % file directory
S_SOUV = dir(fullfile(P_SOUV,'*.csv')); % only .csv files
names = ["SOUV6" "SOUV15" "SOUV60" "SOUV120" "SOUV240"]; % sample names
fc = 0.1;  % cutoff frequency (for data filter)
```

```
fs = 16;   % sample frequency: 16 Hz _ Nyquist freq of 8 _> about 4 hz cutoff freq

[S_SOUV] = calculations(S_SOUV, P_SOUV, T_SOUV, fc, fs); % call function for data↙
calculations within data structure

% resize data for to the minimum length of the sample set
[~,S_SOUV] = set_length(1,S_SOUV);
[~,S_SOUV] = set_length(6,S_SOUV);
[~,S_SOUV] = set_length(11,S_SOUV);
[~,S_SOUV] = set_length(16,S_SOUV);
[start,S_SOUV] = set_length(21,S_SOUV);

% summary data - call function for summary calculations
[SOUV_std_YS, SOUV_std_modulus, overall_mean_modulus, overall_mean_YS, ↙
overall_mean_strain, overall_mod_std, overall_YS_std] = SummaryData(S_SOUV);

% individual data summaries
% name empty arrays then call function to calculate mean per variation
[SOUV6_mean_strain, SOUV6_mean_stress, SOUV6_stress, SOUV6_strain, ↙
SOUV6_mean_modulus, SOUV6_YS_stress, SOUV6_YS_strain] = mean_of_5(S_SOUV,1,5);  % call↙
function to calc mean of 5 samples
[SOUV15_mean_strain, SOUV15_mean_stress, SOUV15_stress, SOUV15_strain, ↙
SOUV15_mean_modulus,SOUV15_YS_stress, SOUV15_YS_strain] = mean_of_5(S_SOUV,6,10);
[SOUV60_mean_strain, SOUV60_mean_stress, SOUV60_stress, SOUV60_strain, ↙
SOUV60_mean_modulus,SOUV60_YS_stress, SOUV60_YS_strain] = mean_of_5(S_SOUV,11,15);
[SOUV120_mean_strain, SOUV120_mean_stress, SOUV120_stress, SOUV120_strain, ↙
SOUV120_mean_modulus,SOUV120_YS_stress, SOUV120_YS_strain] = mean_of_5(S_SOUV,16,20);
[SOUV240_mean_strain, SOUV240_mean_stress, SOUV240_stress, SOUV240_strain, ↙
SOUV240_mean_modulus,SOUV240_YS_stress, SOUV240_YS_strain] = mean_of_5(S_SOUV,21,25);
% condense data to be plotted
SOUV_mean_YS_strain = [SOUV6_YS_strain,SOUV15_YS_strain,SOUV60_YS_strain, ↙
SOUV120_YS_strain,SOUV240_YS_strain];
SOUV_mean_YS_stress = [SOUV6_YS_stress,SOUV15_YS_stress,SOUV60_YS_stress, ↙
SOUV120_YS_stress,SOUV240_YS_stress];
SOUV_mean_modulus = [SOUV6_mean_modulus, SOUV15_mean_modulus, SOUV60_mean_modulus, ↙
SOUV120_mean_modulus,SOUV240_mean_modulus];
SOUV_overall_mean_YS_stress = mean(SOUV_mean_YS_stress);
SOUV_overall_mean_modulus_2 = mean(SOUV_mean_modulus);
SOUV_overall_mod_std_2 = std(SOUV_mean_modulus);
SOUV_overall_YS_std2 = std(SOUV_mean_YS_stress);

%plot all control samples superimposed
for n = 1:length(S_SOUV)
    plot(S_SOUV(n).strain_comped,S_SOUV(n).filtered_Stress, S_SOUV(n).YS_strain, ↙
S_SOUV(n).YS_stress, '-o')
    xlabel('Strain (%)')
    ylabel('Stress (psi)')
    title('Stress vs Strain')
    %legend(S_SOUV(n).name, 'Location', 'SouthOutside') % fix
```

```
    hold on
    if mod(n,5)==0 % start a new figure every 5th sample
        figure
    end
end
hold off
close(6)

%% Analysis: SNUV samples
T_SNUV = readtable('Sample_dimensions_SNUV.xlsx','sheet',↙
'Sheet1','PreserveVariableNames',true); % read sample dimensions
P_SNUV = 'C:\Users\thist\Desktop\Thesis\Compression Testing\UV cure samples\Amazon↙
Old'; % file directory
S_SNUV = dir(fullfile(P_SNUV,'*.csv')); % only .csv files
names = ["SNUV6" "SNUV15" "SNUV60" "SNUV120" "SNUV240"]; % sample names
fc = 0.1;  % cutoff frequency (for data filter)
fs = 16;   % sample frequency: 16 Hz _ Nyquist freq of 8 _> about 4 hz cutoff freq

[S_SNUV] = calculations(S_SNUV, P_SNUV, T_SNUV, fc, fs); % call function for data↙
calculations within data structure

% resize data for to the minimum length of the sample set
[~,S_SNUV] = set_length(1,S_SNUV);
[~,S_SNUV] = set_length(6,S_SNUV);
[~,S_SNUV] = set_length(11,S_SNUV);
[~,S_SNUV] = set_length(16,S_SNUV);
[start,S_SNUV] = set_length(21,S_SNUV);

% summary data - call function for summary calculations
[SNUV_std_YS, SNUV_std_modulus, overall_mean_modulus, overall_mean_YS, ↙
overall_mean_strain, overall_mod_std, overall_YS_std] = SummaryData(S_SNUV);

% individual data summaries
% name empty arrays then call function to calculate mean per variation
[SNUV6_mean_strain, SNUV6_mean_stress, SNUV6_stress, SNUV6_strain, ↙
SNUV6_mean_modulus, SNUV6_YS_stress, SNUV6_YS_strain] = mean_of_5(S_SNUV,1,5); % call↙
function to calc mean of 5 samples
[SNUV15_mean_strain, SNUV15_mean_stress, SNUV15_stress, SNUV15_strain, ↙
SNUV15_mean_modulus,SNUV15_YS_stress, SNUV15_YS_strain] = mean_of_5(S_SNUV,6,10);
[SNUV60_mean_strain, SNUV60_mean_stress, SNUV60_stress, SNUV60_strain, ↙
SNUV60_mean_modulus,SNUV60_YS_stress, SNUV60_YS_strain] = mean_of_5(S_SNUV,11,15);
[SNUV120_mean_strain, SNUV120_mean_stress, SNUV120_stress, SNUV120_strain, ↙
SNUV120_mean_modulus,SNUV120_YS_stress, SNUV120_YS_strain] = mean_of_5(S_SNUV,16,20);
[SNUV240_mean_strain, SNUV240_mean_stress, SNUV240_stress, SNUV240_strain, ↙
SNUV240_mean_modulus,SNUV240_YS_stress, SNUV240_YS_strain] = mean_of_5(S_SNUV,21,25);
% condense data to be plotted
SNUV_mean_YS_strain = [SNUV6_YS_strain,SNUV15_YS_strain,SNUV60_YS_strain, ↙
SNUV120_YS_strain,SNUV240_YS_strain];
SNUV_mean_YS_stress = [SNUV6_YS_stress,SNUV15_YS_stress,SNUV60_YS_stress, ↙
```

```
SNUV120_YS_stress,SNUV240_YS_stress];
SNUV_mean_modulus = [SNUV6_mean_modulus, SNUV15_mean_modulus, SNUV60_mean_modulus, ↙
SNUV120_mean_modulus,SNUV240_mean_modulus];
SNUV_overall_mean_YS_stress = mean(SNUV_mean_YS_stress);
SNUV_overall_mean_modulus_2 = mean(SNUV_mean_modulus);
SNUV_overall_mod_std_2 = std(SNUV_mean_modulus);
SNUV_overall_YS_std2 = std(SNUV_mean_YS_stress);

% plot all control samples superimposed
for n = 1:length(S_SNUV)
    plot(S_SNUV(n).strain_comped,S_SNUV(n).filtered_Stress, S_SNUV(n).YS_strain, ↙
S_SNUV(n).YS_stress, '-o')
    xlabel('Strain (%)')
    ylabel('Stress (psi)')
    title('Stress vs Strain')
    %legend(S_SNUV(n).name, 'Location', 'SouthOutside') % fix
    hold on
    if mod(n,5)==0 % start a new figure every 5th sample
        figure
    end
end
hold off
close(6)
%% plot superimposed means

figure
t = tiledlayout(2,2);
nexttile
plot(ANUV6_mean_strain, ANUV6_mean_stress)
hold on
plot(ANUV15_mean_strain, ANUV15_mean_stress)
plot(ANUV60_mean_strain, ANUV60_mean_stress)
plot(ANUV120_mean_strain, ANUV120_mean_stress)
plot(ANUV240_mean_strain, ANUV240_mean_stress)
plot(ANUV_mean_YS_strain, ANUV_mean_YS_stress,"o",'Color', [0.0 0.0↙
0.0],'MarkerSize',3,'MarkerFaceColor','k')
title('ANUV')
grid on
ytickformat('%1.1f')
ylim([-1 15])

nexttile
plot(AOUV6_mean_strain, AOUV6_mean_stress)
hold on
plot(AOUV15_mean_strain, AOUV15_mean_stress)
plot(AOUV60_mean_strain, AOUV60_mean_stress)
plot(AOUV120_mean_strain, AOUV120_mean_stress)
plot(AOUV240_mean_strain, AOUV240_mean_stress)
plot(AOUV_mean_YS_strain, AOUV_mean_YS_stress,"o",'Color', [0.0 0.0↙
```

```
0.0],'MarkerSize',3,'MarkerFaceColor','k')
title('AOUV')
grid on
ytickformat('%1.1f')
ylim([-1 15])

nexttile
plot(SOUV6_mean_strain, SOUV6_mean_stress)
hold on
plot(SOUV15_mean_strain, SOUV15_mean_stress)
plot(SOUV60_mean_strain, SOUV60_mean_stress)
plot(SOUV120_mean_strain, SOUV120_mean_stress)
plot(SOUV240_mean_strain, SOUV240_mean_stress)
plot(ANUV_mean_YS_strain, ANUV_mean_YS_stress,"o",'Color', [0.0 0.0↙
0.0],'MarkerSize',3,'MarkerFaceColor','k')
title('SOUV')
grid on
ytickformat('%1.1f')
ylim([-1 15])

nexttile
plot(SNUV6_mean_strain, SNUV6_mean_stress)
hold on
plot(SNUV15_mean_strain, SNUV15_mean_stress)
plot(SNUV60_mean_strain, SNUV60_mean_stress)
plot(SNUV120_mean_strain, SNUV120_mean_stress)
plot(SNUV240_mean_strain, SNUV240_mean_stress)
plot(ANUV_mean_YS_strain, ANUV_mean_YS_stress,"o",'Color', [0.0 0.0↙
0.0],'MarkerSize',3,'MarkerFaceColor','k')
title('SNUV')
grid on
ytickformat('%1.1f')
ylim([-1 15])

lgd = legend('6', '15', '60', '120', '240', 'location', 'southoutside',↙
'Orientation','horizontal');
lgd.Title.String = 'Cure Time (minutes)';
lgd.Layout.Tile = 'south';
title(t,'UV Cure: Stress vs Strain')
xlabel(t,'Strain (%)')
ylabel(t,'Stress (ksi)')

%% tiled plots for means vs time - modulus
hours = [0.1 0.25 1.00 2 4];
figure
t2 = tiledlayout(2,2);
[ANUV_fitresult,ANUV_fit_stats] = plotUV(minutes, ANUV_mean_modulus, ↙
ANUV_std_modulus);
title('ANUV')
```

```
[AOUV_fitresult,AOUV_fit_stats] = plotUV(minutes,AOUV_mean_modulus, ↙
AOUV_std_modulus);
title('AOUV')
[SNUV_fitresult,SNUV_fit_stats] = plotUV(minutes, SNUV_mean_modulus, ↙
SNUV_std_modulus);
title('SNUV')
[SOUV_fitresult,SOUV_fit_stats] = plotUV(minutes, SOUV_mean_modulus, ↙
SOUV_std_modulus);
title('SOUV')
title(t2,'UV Cure: Modulus vs Time')
xlabel(t2,'Cure Time (minutes)')
ylabel(t2,'Mean Modulus (ksi)')

%% tiled plots for means vs time - Yield Strength

figure
t3 = tiledlayout(2,2);
[ANUV_fitresult2,ANUV_fit_stats2] = plotUV(minutes, ANUV_mean_YS_stress, ↙
ANUV_std_YS);
title('ANUV')
[AOUV_fitresult2,AOUV_fit_stats2] = plotUV(minutes,AOUV_mean_YS_stress, AOUV_std_YS);
title('AOUV')
[SNUV_fitresult2,SNUV_fit_stats2] = plotUV(minutes, SNUV_mean_YS_stress, ↙
SNUV_std_YS);
title('SNUV')
[SOUV_fitresult2,SOUV_fit_stats2] = plotUV(minutes, SNUV_mean_YS_stress, ↙
SNUV_std_YS);
title('SOUV')
title(t3,'UV Cure: Yield Strength vs Time')
xlabel(t3,'Cure Time (minutes)')
ylabel(t3,'Mean Yield Strength (ksi)')

%% - PLOT ALL UV MEANS SUPERIMPOSED on line plot
figure
ANUV_p = plot(ANUV_fitresult);
hold on
set(ANUV_p,'color',[0 0.4470 0.7410])
AOUV_p =plot(AOUV_fitresult);
set(AOUV_p,'color',[0.8500 0.3250 0.0980])
SNUV_p = plot(SNUV_fitresult);
set(SNUV_p,'color',[0.9290 0.6940 0.1250])
SOUV_p = plot(SOUV_fitresult);
set(SOUV_p,'color',[0.4940 0.1840 0.5560])
 errorbar(minutes, ANUV_mean_modulus, ANUV_std_modulus, "o",'Color', [0 0.4470↙
0.7410], 'MarkerFaceColor','k')
 errorbar(minutes, SNUV_mean_modulus, SNUV_std_modulus, "o",'Color', [0.8500 0.3250↙
0.0980], 'MarkerFaceColor','k')
 errorbar(minutes, AOUV_mean_modulus, ANUV_std_modulus, "o",'Color', [0.9290 0.6940↙
0.1250], 'MarkerFaceColor','k')
```

```
 errorbar(minutes, SOUV_mean_modulus, SNUV_std_modulus, "o",'Color', [0.4940 0.1840↙
0.5560], 'MarkerFaceColor','k')
xlabel('SNUV Cure time (minutes)')
ylabel('Mean Modulus (psi)')
title('Mean Modulus vs UV Cure time')
legend('ANUV', 'AOUV', 'SNUV', 'SOUV','Location','southeast')
grid on
%% summary data
Bar3D_Modulus = (cat(1,ANUV_mean_modulus,AOUV_mean_modulus,SNUV_mean_modulus, ↙
SOUV_mean_modulus))./1000; % combine to get matrix of values
Bar3D_YS = (cat(1,ANUV_mean_YS_stress,AOUV_mean_YS_stress,SNUV_mean_YS_stress, ↙
SOUV_mean_YS_stress))./1000;
Bar3D_Modulus_std = (cat(1,ANUV_std_modulus,AOUV_std_modulus,SNUV_std_modulus, ↙
SOUV_std_modulus))./1000;
Bar3D_YS_std = (cat(1,ANUV_std_YS,AOUV_std_YS,SNUV_std_YS,SOUV_std_YS))./1000;

%% 3D barplot
figure
bar3(Bar3D_Modulus)
hold on
xlabel('Cure Time (minutes)')
ylabel('Sample Variation Method')
zlabel('Mean Modulus (psi)')
title('Sample Variation vs Mean Modulus')
lgd = legend('6', '15', '60', '120', '240','location',↙
'southoutside','Orientation','horizontal','Position',[0.2215 0.02 0.566 0.08]);
title(lgd,'UV Cure Time (minutes)')
set(gca, 'YTickLabel',{'ANUV','AOUV','SNUV','SOUV'}, 'XTickLabel',↙
{'6','15','60','120','240'} )
view(-90,0)

figure
bar3(Bar3D_YS)
hold on
xlabel('Cure Time (minutes)')
ylabel('Sample Variation Method')
zlabel('Mean Yeild Strength (psi)')
title('Sample Variation vs Mean Yield Strength')
lgd = legend('6', '15', '60', '120', '240','location',↙
'southoutside','Orientation','horizontal','Position',[0.2215 0.02 0.566 0.08]);
title(lgd,'UV Cure Time (minutes)')
set(gca, 'YTickLabel',{'ANUV','AOUV','SNUV','SOUV'}, 'XTickLabel',↙
{'6','15','60','120','240'} )
view(-90,0)

%% bar plot for 6 min cure time
variation = ["ANUV" "AOUV" "SNUV" "SOUV"]; % sample names
mean_modulus_UV6 = [ANUV6_mean_modulus, AOUV6_mean_modulus SNUV6_mean_modulus, ↙
SOUV6_mean_modulus]./1000;
```

```
mean_YS_stress_UV6 = [ANUV6_YS_stress,AOUV6_YS_stress,SNUV6_YS_stress, ↙
SOUV6_YS_stress]./1000;
UV6_std_modulus = [ANUV_std_modulus(1), AOUV_std_modulus(1),SNUV_std_modulus(1), ↙
SOUV_std_modulus(1)]./1000; % get stdev
UV6_std_YS = [ANUV_std_YS(1), AOUV_std_YS(1),SNUV_std_YS(1), SOUV_std_YS(1)]./1000;
figure
subplot(1,2,1)
bar(categorical(variation), mean_modulus_UV6)
hold on
errorbar(categorical(variation), mean_modulus_UV6, ↙
UV6_std_modulus,'Color','k','LineStyle','none')
xlabel('Sample Variation Method')
ylabel('Mean Modulus (ksi)')
title('UV cure 6-min Mean Moduli')
grid on
ytickformat('%1.1f')
ylim([0 220])

subplot(1,2,2)
bar(categorical(variation), mean_YS_stress_UV6)
hold on
errorbar(categorical(variation),mean_YS_stress_UV6, ↙
UV6_std_YS,'Color','k','LineStyle','none')
xlabel('Sample Variation Method')
ylabel('Mean Yeild Strength (ksi)')
title('UV cure 6-min Mean Yield Strengths')
grid on
ytickformat('%1.1f')

%% compile data for overall means
cat_modulus_6_min = cat(1,S_ANUV(1:5).max_m,S_AOUV(1:5).max_m,S_SNUV(1:5).max_m, ↙
S_SOUV(1:5).max_m); % concencate data per time
cat_modulus_15_min = cat(1,S_ANUV(6:10).max_m,S_AOUV(6:10).max_m,S_SNUV(6:10).max_m, ↙
S_SOUV(6:10).max_m);
cat_modulus_60_min = cat(1,S_ANUV(11:15).max_m,S_AOUV(11:15).max_m,S_SNUV(11:15). ↙
max_m,S_SOUV(11:15).max_m);
cat_modulus_120_min = cat(1,S_ANUV(16:20).max_m,S_AOUV(16:20).max_m,S_SNUV(16:20). ↙
max_m,S_SOUV(16:20).max_m);
cat_modulus_240_min = cat(1,S_ANUV(21:25).max_m,S_AOUV(21:25).max_m,S_SNUV(21:25). ↙
max_m,S_SOUV(21:25).max_m);
overall_mean_modulus_6_min = mean(cat_modulus_6_min)/1000; % mean modulus
overall_mean_modulus_15_min = mean(cat_modulus_15_min)/1000;
overall_mean_modulus_60_min = mean(cat_modulus_60_min)/1000;
overall_mean_modulus_120_min = mean(cat_modulus_120_min)/1000;
overall_mean_modulus_240_min = mean(cat_modulus_240_min)/1000;
overall_std_modulus_6_min = std(cat_modulus_6_min)/1000; % standard deviation
overall_std_modulus_15_min = std(cat_modulus_15_min)/1000;
overall_std_modulus_60_min = std(cat_modulus_60_min)/1000;
overall_std_modulus_120_min = std(cat_modulus_120_min)/1000;
```

```
overall_std_modulus_240_min = std(cat_modulus_240_min)/1000;

cat_YS_6_min = cat(1,S_ANUV(1:5).YS_stress,S_AOUV(1:5).YS_stress,S_SNUV(1:5). ↙
YS_stress,S_SOUV(1:5).YS_stress); % concencate data per time
cat_YS_15_min = cat(1,S_ANUV(6:10).YS_stress,S_AOUV(6:10).YS_stress,S_SNUV(6:10). ↙
YS_stress,S_SOUV(6:10).YS_stress);
cat_YS_60_min = cat(1,S_ANUV(11:15).YS_stress,S_AOUV(11:15).YS_stress,S_SNUV(11:15). ↙
YS_stress,S_SOUV(11:15).YS_stress);
cat_YS_120_min = cat(1,S_ANUV(16:20).YS_stress,S_AOUV(16:20).YS_stress,S_SNUV(16:20). ↙
YS_stress,S_SOUV(16:20).YS_stress);
cat_YS_240_min = cat(1,S_ANUV(21:25).YS_stress,S_AOUV(21:25).YS_stress,S_SNUV(21:25). ↙
YS_stress,S_SOUV(21:25).YS_stress);
overall_mean_YS_6_min = mean(cat_YS_6_min)/1000; % mean YS
overall_mean_YS_15_min = mean(cat_YS_15_min)/1000;
overall_mean_YS_60_min = mean(cat_YS_60_min)/1000;
overall_mean_YS_120_min = mean(cat_YS_120_min)/1000;
overall_mean_YS_240_min = mean(cat_YS_240_min)/1000;
overall_std_YS_6_min = std(cat_YS_6_min)/1000; % standard deviation
overall_std_YS_15_min = std(cat_YS_15_min)/1000;
overall_std_YS_60_min = std(cat_YS_60_min)/1000;
overall_std_YS_120_min = std(cat_YS_120_min)/1000;
overall_std_YS_240_min = std(cat_YS_240_min)/1000;
```



```
function [fitresult,fit_stats] = plotUV(t,Ydata,error)
% where type is AOUV or other UV cure by variation
[fitresult, fit_stats] = createFit(t, Ydata);
nexttile
errorbar(t, Ydata, error, "o",'Color', [.5 .5 .5], ↙
'MarkerFaceColor','k','MarkerSize',3)
hold on
plot(fitresult)
legend('hide')
grid on

end
```

```
% Suzie Dixon - Thesis results analysis
% Code for UV cure 6 min samples

clear all
clc
close all
%% Analysis: UV 6 min cure
T_UV6 = readtable('Sample_dimensions_pretest_control.xlsx','sheet',↙
'Sheet2','PreserveVariableNames',true); % read sample dimensions
P_UV6 = 'C:\Users\thist\Desktop\Thesis\Compression Testing\UV cure 6 min'; % file↙
directory
S_UV6 = dir(fullfile(P_UV6,'*.csv')); % only .csv files
names = ["ANUV" "AOUV" "SNUV" "SOUV"]; % sample names
fc = 0.1;  % cutoff frequency (for data filter)
fs = 16;   % sample frequency: 16 Hz _ Nyquist freq of 8 _> about 4 hz cutoff freq
[S_UV6] = calculations(S_UV6, P_UV6, T_UV6, fc, fs); % call function for data↙
calculations within data structure

% resize data for to the minimum length of the sample set
[~,S_UV6] = set_length(1,S_UV6);
[~,S_UV6] = set_length(6,S_UV6);
[~,S_UV6] = set_length(11,S_UV6);
[start,S_UV6] = set_length(16,S_UV6);

% summary data - call function for summary calculations
[UV_std_YS, UV_std_modulus, overall_mean_modulus, overall_mean_YS, ↙
overall_mean_strain, overall_mod_std, overall_YS_std] = SummaryData(S_UV6);

% individual data summaries
[ANUV6_mean_strain, ANUV6_mean_stress, ANUV6_stress, ANUV6_strain, ↙
ANUV6_mean_modulus, ANUV6_YS_stress, ANUV6_YS_strain] = mean_of_5(S_UV6,1,5); % call↙
function to calc mean of 5 samples
[AOUV6_mean_strain, AOUV6_mean_stress, AOUV6_stress, AOUV6_strain, ↙
AOUV6_mean_modulus,AOUV6_YS_stress, AOUV6_YS_strain] = mean_of_5(S_UV6,6,10);
[SNUV6_mean_strain, SNUV6_mean_stress, SNUV6_stress, SNUV6_strain, ↙
SNUV6_mean_modulus,SNUV6_YS_stress, SNUV6_YS_strain] = mean_of_5(S_UV6,11,15);
[SOUV6_mean_strain, SOUV6_mean_stress, SOUV6_stress, SOUV6_strain, ↙
SOUV6_mean_modulus,SOUV6_YS_stress, SOUV6_YS_strain] = mean_of_5(S_UV6,16,20);
% condense data to be plotted
mean_YS_strain = [ANUV6_YS_strain,AOUV6_YS_strain,SNUV6_YS_strain,SOUV6_YS_strain];
mean_YS_stress = [ANUV6_YS_stress,AOUV6_YS_stress,SNUV6_YS_stress,SOUV6_YS_stress];
mean_modulus = [ANUV6_mean_modulus, AOUV6_mean_modulus, SNUV6_mean_modulus, ↙
SOUV6_mean_modulus];
overall_mean_YS_stress = mean(mean_YS_stress);
overall_mean_modulus_2 = mean(mean_modulus);
overall_mod_std_2 = std(mean_modulus);
overall_YS_std2 = std(mean_YS_stress);
%%
% plot all control samples superimposed
```

```
for n = 1:length(S_UV6)
    plot(S_UV6(n).strain_comped,S_UV6(n).filtered_Stress, S_UV6(n).YS_strain, S_UV6 ↙
(n).YS_stress, '-o')
    xlabel('Strain (%)')
    ylabel('Stress (ksi)')
    title('Stress vs Strain')
    %legend(S(n).name, 'Location', 'SouthOutside') % fix
    hold on
    if mod(n,5)==0 % start a new figure every 5th sample
        figure

    end
end
hold off
%%
% plot superimposed means
figure
plot(ANUV6_mean_strain, ANUV6_mean_stress)
hold on
plot(AOUV6_mean_strain, AOUV6_mean_stress)
plot(SNUV6_mean_strain, SNUV6_mean_stress)
plot(SOUV6_mean_strain, SOUV6_mean_stress)
errorbar(mean_YS_strain, mean_YS_stress, UV_std_YS, "o",'Color', [.5 .5 .5],↙
'MarkerFaceColor','k')
xlabel('Strain (%)')
ylabel('Stress (ksi)')
title('Stress vs Strain')
legend('ANUV6', 'AOUV6', 'SNUV6', 'SOUV6')
hold off
%%
figure
subplot(1,2,1)
bar(categorical(names), mean_modulus)
hold on
errorbar(categorical(names),mean_modulus,↙
UV_std_modulus,'Color','k','LineStyle','none')
xlabel('Sample Variation Method')
ylabel('Mean Modulus (ksi)')
title('UV cure 6-min Mean Moduli')
grid on
ytickformat('%1.1f')

subplot(1,2,2)
bar(categorical(names), mean_YS_stress)
hold on
errorbar(categorical(names),mean_YS_stress,UV_std_YS, 'Color','k','LineStyle','none')
xlabel('Sample Variation Method')
ylabel('Mean Yeild Strength (ksi)')
title('UV cure 6-min Mean Yield Strengths')
```

```
grid on
ytickformat('%1.f')
```

```
%% Suzie Dixon
% One-way Statistical data analysis using Kruskal Wallis Test and kw_test function

%% control samples

% modulus and variation type
[pVal_control_mod,tbl_kw_control_mod,tbl_compare_control_mod] = kw_test(Control_results↙
{:,2},Control_results{:,1});
% Yield strength and var. type
[pVal_control_YS,tbl_kw_control_YS,tbl_compare_control_YS] = kw_test(Control_results{:,↙
3},Control_results{:,1});

%% water absorption results - seperated by pressure

% atmospheric pressure
[pVal_WA_mod,tbl_kw_WA_mod,tbl_compare_WA_mod] = kw_test(WA_SummaryResults{1:20,3},↙
WA_SummaryResults{1:20,1}); % modulus
[pVal_WA_YS,tbl_kw_WA_YS,tbl_compare_WA_YS] = kw_test(WA_SummaryResults{1:20,4},↙
WA_SummaryResults{1:20,1}); %YS

% 30-psi
[pVal_WA30_mod,tbl_kw_WA30_mod,tbl_compare_WA30_mod] = kw_test(WA_SummaryResults{21:↙
40,3},WA_SummaryResults{21:40,1}); % modulus
[pVal_WA30_YS,tbl_kw_WA30_YS,tbl_compare_WA30_YS] = kw_test(WA_SummaryResults{21:40,4},↙
WA_SummaryResults{21:40,1}); %YS

% 60-psi
[pVal_WA60_mod,tbl_kw_WA60_mod,tbl_compare_WA60_mod] = kw_test(WA_SummaryResults{41:↙
60,3},WA_SummaryResults{41:60,1}); % modulus
[pVal_WA60_YS,tbl_kw_WA60_YS,tbl_compare_WA60_YS] = kw_test(WA_SummaryResults{41:60,4},↙
WA_SummaryResults{41:60,1}); %YS

% 90-psi
[pVal_WA90_mod,tbl_kw_WA90_mod,tbl_compare_WA90_mod] = kw_test(WA_SummaryResults{61:↙
80,3},WA_SummaryResults{61:80,1}); % modulus
[pVal_WA90_YS,tbl_kw_WA90_YS,tbl_compare_WA90_YS] = kw_test(WA_SummaryResults{61:80,4},↙
WA_SummaryResults{61:80,1}); %YS

%% water absorption results seperated by variation type

WA_SummaryResults_byVar(:,4) = WA_SummaryResults_byVar(:,4)./1000;
WA_SummaryResults_byVar(:,5) = WA_SummaryResults_byVar(:,5)./1000;
%%
% ANA
[pVal_WA_ANA_mod,tbl_kw_WA_ANA_mod,tbl_compare_WA_ANA_mod] = kw_test↙
(WA_SummaryResults_byVar{1:20,4},WA_SummaryResults_byVar{1:20,3}); % modulus
[pVal_WA_ANA_YS,tbl_kw_WA_ANA_YS,tbl_compare_WA_ANA_YS] = kw_test(WA_SummaryResults_byVar↙
{1:20,5},WA_SummaryResults_byVar{1:20,3}); %YS

% AOA
[pVal_WA_AOA_mod,tbl_kw_WA_AOA_mod,tbl_compare_WA_AOA_mod] = kw_test↙
```

```
(WA_SummaryResults_byVar{21:40,4},WA_SummaryResults_byVar{21:40,3}); % modulus
[pVal_WA_AOA_YS,tbl_kw_WA_AOA_YS,tbl_compare_WA_AOA_YS] = kw_test(WA_SummaryResults_byVar↙
{21:40,5},WA_SummaryResults_byVar{21:40,3}); %YS

% SNA
[pVal_WA_SNA_mod,tbl_kw_WA_SNA_mod,tbl_compare_WA_SNA_mod] = kw_test↙
(WA_SummaryResults_byVar{41:60,4},WA_SummaryResults_byVar{41:60,3}); % modulus
[pVal_WA_SNA_YS,tbl_kw_WA_SNA_YS,tbl_compare_WA_SNA_YS] = kw_test(WA_SummaryResults_byVar↙
{41:60,5},WA_SummaryResults_byVar{41:60,3}); %YS

% SOA
[pVal_WA_SOA_mod,tbl_kw_WA_SOA_mod,tbl_compare_WA_SOA_mod] = kw_test↙
(WA_SummaryResults_byVar{61:80,4},WA_SummaryResults_byVar{61:80,3}); % modulus
[pVal_WA_SOA_YS,tbl_kw_WA_SOA_YS,tbl_compare_WA_SOA_YS] = kw_test(WA_SummaryResults_byVar↙
{61:80,5},WA_SummaryResults_byVar{61:80,3}); %YS

%% UV Cure results seperated by cure time
UV_summary_results_byVar(:,3) = UV_summary_results_byVar(:,3)./1000;
UV_summary_results_byVar(:,4) = UV_summary_results_byVar(:,4)./1000;
%%
% 6-min cure time
[pVal_UV6_mod,tbl_kw_UV6_mod,tbl_compare_UV6_mod] = kw_test(UV_summary_results_byVar{1:↙
20,3},UV_summary_results_byVar{1:20,1}); % modulus
[pVal_UV6_YS,tbl_kw_UV6_YS,tbl_compare_UV6_YS] = kw_test(UV_summary_results_byVar{1:↙
20,4},UV_summary_results_byVar{1:20,1}); %YS

% 15-min cure time
[pVal_UV15_mod,tbl_kw_UV15_mod,tbl_compare_UV15_mod] = kw_test(UV_summary_results_byVar↙
{21:40,3},UV_summary_results_byVar{21:40,1}); % modulus
[pVal_UV15_YS,tbl_kw_UV15_YS,tbl_compare_UV15_YS] = kw_test(UV_summary_results_byVar{21:↙
40,4},UV_summary_results_byVar{21:40,1}); %YS

% 60-min cure time
[pVal_UV60_mod,tbl_kw_UV60_mod,tbl_compare_UV60_mod] = kw_test(UV_summary_results_byVar↙
{41:60,3},UV_summary_results_byVar{41:60,1}); % modulus
[pVal_UV60_YS,tbl_kw_UV60_YS,tbl_compare_UV60_YS] = kw_test(UV_summary_results_byVar{41:↙
60,4},UV_summary_results_byVar{41:60,1}); %YS

% 120-min cure time
[pVal_UV120_mod,tbl_kw_UV120_mod,tbl_compare_UV120_mod] = kw_test↙
(UV_summary_results_byVar{61:80,3},UV_summary_results_byVar{61:80,1}); % modulus
[pVal_UV120_YS,tbl_kw_UV120_YS,tbl_compare_UV120_YS] = kw_test(UV_summary_results_byVar↙
{61:80,4},UV_summary_results_byVar{61:80,1}); %YS

% 240-min cure time
[pVal_UV240_mod,tbl_kw_UV240_mod,tbl_compare_UV240_mod] = kw_test↙
(UV_summary_results_byVar{81:100,3},UV_summary_results_byVar{81:100,1}); % modulus
[pVal_UV240_YS,tbl_kw_UV240_YS,tbl_compare_UV240_YS] = kw_test(UV_summary_results_byVar↙
{81:100,4},UV_summary_results_byVar{81:100,1}); %YS

%% UV results seperated by variation type
```

```
% ANUV samples (all cure times)
[pVal_ANUV_mod,tbl_kw_ANUV_mod,tbl_compare_ANUV_mod] = kw_test(UV_summary_results{1:↙
25,3},UV_summary_results{1:25,2}); % modulus
[pVal_ANUV_YS,tbl_kw_ANUV_YS,tbl_compare_ANUV_YS] = kw_test(UV_summary_results{1:25,4},↙
UV_summary_results{1:25,2}); %YS

% AOUV
[pVal_AOUV_mod,tbl_kw_AOUV_mod,tbl_compare_AOUV_mod] = kw_test(UV_summary_results{25:↙
50,3},UV_summary_results{25:50,2}); % modulus
[pVal_AOUV_YS,tbl_kw_AOUV_YS,tbl_compare_AOUV_YS] = kw_test(UV_summary_results{25:50,4},↙
UV_summary_results{25:50,2}); %YS

% SNUV
[pVal_SNUV_mod,tbl_kw_SNUV_mod,tbl_compare_SNUV_mod] = kw_test(UV_summary_results{51:↙
75,3},UV_summary_results{51:75,2}); % modulus
[pVal_SNUV_YS,tbl_kw_SNUV_YS,tbl_compare_SNUV_YS] = kw_test(UV_summary_results{51:75,4},↙
UV_summary_results{51:75,2}); %YS

% SOUV
[pVal_SOUV_mod,tbl_kw_SOUV_mod,tbl_compare_SOUV_mod] = kw_test(UV_summary_results{76:↙
100,3},UV_summary_results{76:100,2}); % modulus
[pVal_SOUV_YS,tbl_kw_SOUV_YS,tbl_compare_SOUV_YS] = kw_test(UV_summary_results{76:100,4},↙
UV_summary_results{76:100,2}); %YS

%% Conclusive overall mean
% mods except SOA atm
all_mods = cat(1,WA_SummaryResults_byVar(1:40,4),WA_SummaryResults_byVar(46:80,4));
all_mods_mean = mean(all_mods)
all_mods_stdev = (std(all_mods))

all_YS = cat(1,WA_SummaryResults_byVar(1:40,5),WA_SummaryResults_byVar(46:80,5));
all_YS_mean = mean(all_YS)
all_YS_stdev = (std(all_YS))

%% test if sample numbers matter
all_num = cat(1,WA_SummaryResults_byVar(1:40,2),WA_SummaryResults_byVar(46:80,2));
all_table = table(all_num,all_mods./1000,all_YS./1000); % ksi
%%
[pVal_num_mod,tbl_kw_num_mod,tbl_compare_num_mod] = kw_test(table2array(all_table{1:↙
75,1}),table2array(all_table{1:75,2})); % modulus
[pVal_num_YS,tbl_kw_num_YS,tbl_compare_num_YS] = kw_test(table2array(all_table{1:75,1}),↙
table2array(all_table{1:75,3})); %YS
```

```
%% function for kruskal wallis test
function[p,plt_tbl,tbl] = kw_test(data_col1,data_col2)
% input two column vectors and compare means
% data_col2 is the categorical variable
% data_col1 is numerical variable
% outputs:
    % p is p-value from ANOVA table of kruskal wallis test results
    % plt_tbl is ANOVA table of kruskal wallis test results
    % tbl is table of comparisons between variables to determine which
        % means are differnet
figure
[p,plt_tbl,plt_stats] = kruskalwallis(data_col1,data_col2)
grid on
tbl = [];
if p<=0.05
figure
[results,means,~,gnames] = multcompare(plt_stats) % bonferroni correction applied
tbl = array2table(results,"VariableNames", ...
    ["Group A","Group B","Lower Limit","A-B","Upper Limit","P-value"]);
tbl.("Group A")=gnames(tbl.("Group A"));
tbl.("Group B")=gnames(tbl.("Group B"))

else
    disp('means not significantly different') % display result
end
tbl = tbl;
end
```