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Effects of sizing agents on mechanical properties of carbon fiber–polymer composites via fused filament fabrication additive manufacturing.

Benjamin D. Mitchell
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EFFECTS OF SIZING AGENTS ON MECHANICAL PROPERTIES OF CARBON FIBER–POLYMER COMPOSITES VIA FUSED FILAMENT FABRICATION ADDITIVE MANUFACTURING

By
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B.S. in Mechanical Engineering, University of Louisville, 2021

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ABSTRACT

EFFECTS OF SIZING AGENTS ON MECHANICAL PROPERTIES OF CARBON FIBER–POLYMER COMPOSITES VIA FUSED FILAMENT FABRICATION ADDITIVE MANUFACTURING

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This study demonstrated the effects of changing the sizing agent parameter during the preparation of carbon fibers on the mechanical properties of composite made with acrylonitrile butadiene styrene (ABS) as the matrix material and carbon fibers as the fiber material. Three types of sizing agents produced by Allnex were used to coat three different batches of carbon fibers that were mixed with a torque rheometer and extruded with a barrel-style melt extruder into continuous spools of 1.75 mm filament for use with commercial 3D printers. Tensile tests were conducted on the filaments and tensile bars printed from the materials. Results showed that mechanical properties improved for each sizing agent when compared to nominal properties for ABS, but when compared to previously studied properties for fibers sized with an epoxy-based agent, modulus was not as high but tensile stress was around the same. This indicated that the physical limitation of the properties of the tensile strength of the fibers is independent of sizing agent chosen, but tensile modulus changed accordingly with the sizing agent chosen. Further studies should be done to document effects of a wider library of sizing agents on the mechanical properties of carbon fiber composites.

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INTRODUCTION

The design and manufacturing of composites has been a major focal point for materials engineering innovation. The idea of interspersing a mundane low-cost material with parts of a valuable high-cost material with limited availability, in order to "borrow" its superior properties at a lower price, has found a wide range of applications, from structural uses where compressive and tensile strength is important, to the field of smart materials where piezoelectric or material self-healing properties are desired. One of these sought-after materials, carbon fiber, has been hailed as a possible addition to the low-density, high-strength materials that has the potential to revolutionize how structural, load-bearing components of buildings and moving assemblies are envisioned.

Recently, the use of 3D printing to create more complex geometries from composites has been considered. At this point, for carbon fiber composites, there exist many different PLA or ABS filaments that have been filled with carbon fibers and that are being manufactured and sold in bulk as generic composite material in various online marketplaces. Study and documentation of the processing of such composites is an ongoing effort, however, as industrial application and experimental use of carbon fiber polymer composites seemed at one point to have totally outpaced the research of these materials. A body of working research knowledge is growing, as one study by Dou et. al. focused on varying many different printing parameters in a slicing software to document the effects on tensile testing of printed carbon fiber composite samples, including layer height, nozzle temperature, extrusion width, and print speed [5]. This research is growing not only in quantity, but also in breath: there is even work that has investigated the sustainability of

carbon fiber composites by testing their recyclability over multiple regrind and re-extrusion cycles. Significantly, one cycle in the study was found to increase mechanical properties of the composite material in a very rare non-downgrade recycling process [7]. For ABS, the effects of composition of fibers by weight percent and their orientation within the matrix has been examined by Tekinalp et. al. [6]. Work with ABS-carbon fiber composites in this study will be compared to this data as a baseline reference, and all manufacturing and printing process conditions cited in the paper for the composite material were preserved for this study.

In order to properly disperse the carbon fibers through the matrix as a fiber material, sizing agents must be used. Pure carbon fibers normally have an inert surface that has poor wettability, which has been expected to lead to poor interfacial adhesion consequently when mixed into a polymer composite on their own [8, 9]. To solve this problem, a simple technique called sizing is used, where fibers are coated with a thin film of special adhesive-type polymer that directly target the interfacial adhesion aspect of the carbon fibers and matrix material [9]. These polymers are known as sizing agents. Sizing agents tend to be polymer specific, especially those distributed by specialized manufacturers [2, 3, 4]. These sizing agents tend to thermally degrade easily when typical polymer melt temperatures are reached, making it challenging to guarantee the full adhesive properties of a sizing agent within the resultant composite. One category of sizing agent that has been used is polyurethane dispersants (PUDs), which have been shown to significantly increase interfacial adhesion between fibers and matrix by more than 90% [9]. In the work of Tekinalp et. al. [6], carbon fibers in the composites used were sized with epoxy resin.

The use of certain formulations of epoxy-based resin seems to be part of the standard

treatment process to produce carbon fiber composites. However, unfortunately for the body of knowledge contained within research databases, these formulations and the testing done on them are usually kept a trade secret by producers in the carbon fiber manufacturing industry [9]. Testing of the effects of many other materials used as sizing agents for the carbon fibers on the mechanical properties of parts made with fused filament fabrication has only been studied to a limited extent in academic and research settings. This paper aims to help facilitate a new avenue of research that could potentially allow the true potential to be reached of not just carbon fiber composites, but a wide range of composites that use compatible fibers as their strengthening material within the matrix.

MATERIALS AND METHODS

The process of materials in this study was based on the work done by Tekinalp et. al. [6]. Differences in data obtained in this study should mostly stem from the difference choice of sizing agent, since all other manufacturing process parameters of the resultant carbon fiber polymer composite that were specified in this previous work were kept identical.

Pellets of pure unfilled ABS, specifically CYCOLAC™ RESIN EX58, were obtained from SABIC Plastics and used as the matrix material of all 3 composites. Relevant properties of the CYCOLAC™ ABS are presented in

Table *1*.

Table 1. CYCOLAC™ RESIN EX58 material properties considered in this paper.

Property	Value
Tensile Stress	39 MPa
Tensile Modulus	2.080 GPa
Melt Viscosity at 240 C	15500 P
Density	1.03 g/cm^3

Carbon fibers were provided by Oak Ridge National Laboratory, who prepared them for this study by coating them with 3 different blends of sizing agents produced by Allnex: Daotan® TW 6450/30WA, Daotan® TW 6490/35WA, and Duroxyn® SEF 968w/25WA. Relevant properties of each sizing agent are presented in **Table 2**, **Table 3**, and **Table 4**.

Table 2. Daotan® TW 6450/30WA material properties considered in this paper.

Property	Value
Dynamic Viscosity	50 mPa-s (max)
Density	1.04 g/cm^3

Table 3. Daotan® TW 6490/35WA material properties considered in this paper.

Property	Value
Dynamic Viscosity	35 mPa-s (average)
Density	1.04 g/cm^3

Table 4. Duroxyn® SEF 968w/25WA material properties considered in this paper.

Property	Value
Dynamic Viscosity	12.5 mPa-s (average)
Density	1.03 g/cm^3

Each group of coated fibers, having an average fiber length of 3 cm, were then blended with melted ABS pellets using a Brabender Intelli Plasti-Corder Torque Rheometer that

was set to 220°C. For each composite, 10 weight percent of fibers (21.57 grams) was collected and blended with 194.16 grams worth of ABS pellets. 10 weight percent was chosen as the fiber loading composition because there was reference data in the work of Tekinalp et. al. [6] with a manufacturing process detailed that could be matched against as a control condition without sizing agents. To avoid the torque from going too high and causing damage to the Brabender machine, the speed was lowered and progressively raised in steps to help thoroughly mix the material by the end of the process. Plastic was then scraped from the machine and fed through an industrial grinder, which produced grinded pellets of composite material.

To produce composite filament that could be used for printing, a Filabot Extruder Setup was used that included a Filabot EX2 Filament Extruder, a Filabot Airpath, and a Filabot Spooler. The continuous turning barrel of the Filabot EX2 Filament Extruder was set to a constant temperature of 220°C, and the micrometer included within the Filabot Spooler was utilized to help ascertain that each produced spool of composite material did not exceed 1.75 mm in diameter.

Next, a modified Creality Ender 3 printer was used to produce printed parts with 1.75 mm diameter filament from each spool of composite material. The dimensions called out by ASTM D638 were followed to print tensile test specimens of Type V. A hardened steel extruder stepper motor gear was used to feed the material into the PTFE tube through to the hotend; however, this gear had a slightly larger diameter than the stock brass gear that came with the printer. As a result, sometimes enough force was generated to totally strip the filament if it experienced too much resistance to push filament through. This caused the gear to lose its grip and become unable to extrude further material without user

intervention if the printer was not monitored for occasional clogging of the nozzle. The stock white PTFE tube from the printer was replaced with a dark blue Capricorn brand PTFE tube that had more resistance to thermal degradation at the elevated temperatures used to print the material. A borosilicate glass bed with a rough texture on top was used as the surface for the print bed. A coating of Vision Miner's Nano Polymer Adhesive was applied to the bed before each print for extra adhesion and to help combat the natural tendency of ABS to warp at the corners from the bed during printing.

A hardened steel 0.5 mm nozzle was used to print from the composite; however, in Ultimaker Cura, the parameters for an expected 0.4 nozzle diameter were selected to account for the increase in effective viscosity from the presence of the adhesive sizing agent on the fibers interacting with the flowability of the ABS matrix material through the nozzle. When the preloaded settings for a typical 0.5 nozzle diameter printing experience was selected in Cura, it was harder to extrude the composite material through the nozzle used, because even at elevated temperatures, it did not flow as easily as pure unfilled ABS. In addition, choosing the downsized 0.4 mm nozzle diameter parameters meant that the lines that came out of the actual nozzle were drawn more closely together on the physical print, allowing more geometry from the edges of existing lines to melt into the new drawn lines. It was understood that this helped to bridge the selected 100% print infill as close to a cross section of pure material as possible for tensile testing, with infill line directions being oriented 0° longitudinally parallel to the direction of loading.

A very slow print speed of 7.5 mm/s and a layer height of 0.2 mm were selected for use with all replicates produced for tensile testing of the carbon fiber composites at a nozzle temperature of 260°C and a bed temperature of 110°C, which were the maximum selectable

hardware temperatures by the Ender 3's Marlin firmware. These high temperatures with slow print speeds were determined to help mitigate most of the nozzle clogging issues that were encountered. Since ABS was used as the matrix material, it was expected that warpage could prove to be an issue if it was not considered during printing preparations. Therefore, the Ender 3 was placed inside of an enclosure that was generously provided to the lab by Shenzhen Warmy Industrial Co. Ltd., which was found to heat to 43.2°C on average from the ambient air of the bed heat alone during prints. It was later found while troubleshooting that under these thermal conditions, reliable printed parts could be obtained at faster nozzle travel speeds. Future testing should help determine the highest print speed that can be used with these composites without filament slippage and nozzle clogging occurring.

Table *5* summarizes the critical parameters selected in Cura that, through trial and error, proved to yield the most repeatable method to successfully print high-strength tensile testing specimens with all three blends of composite fibers, in addition to other physical parameters that were present during printing. With all print settings applied, the estimated total print time displayed in the Ultimaker Cura slicer was 48 minutes per tensile bar with an estimated print mass of 2 grams.

Table 5. Printer process parameter settings used to print composite tensile testing bars.

Process Parameter	Setting
Printer Model	Creality Ender 3
Nozzle Diameter - Actual	0.5 mm
Nozzle Material	Hardened Steel
Bed Material	Borosilicate Glass
Bed Adhesive	Vision Miner Nano Polymer Adhesive
Nozzle Diameter – Ultimaker Cura Selection	0.4 mm
Nozzle Temperature	260°C
Bed Temperature	110°C
Layer Height	0.2 mm
Print Speed	7.5 mm/s
Infill Density	100%
Infill Pattern	Lines
Infill Direction	[90, 90]
Enclosure Temperature	43.2°C (ambient from bed)

Each ASTM D638 Type V tensile bar and unprinted composite filament was tested for tensile strength using a Instron 5569A electromechanical test machine. For every testing case, the gauge length was set to 20 mm, and shear pin-based clamps were used.

RESULTS AND DISCUSSION

The Brabender Intelli Plasti-Corder Torque Rheometer was successfully used to produce hardened material for each of the three composites that was grinded and pelletized using an industrial grinder. When these pellets were then fed into the Filabot Extruder

Setup, the diameter of the resultant filament varied and was difficult to control before the rollers that stabilized the filament for measurement with the micrometer were moved to a position that induced less tension on the hardened filament. Results at each step of the process are shown below.

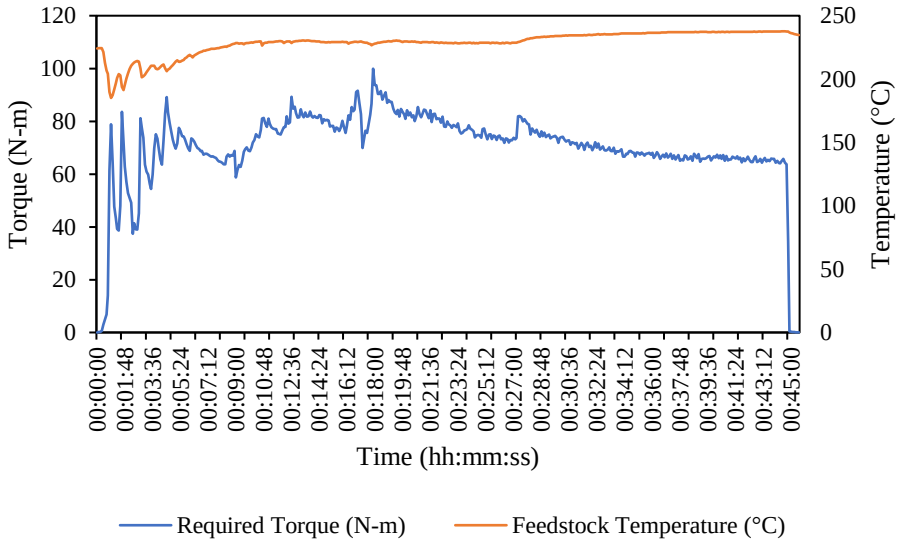

Figure 1. Torque and feedstock temperature within the Brabender equipment versus time during the mixing operation for the composite sized with Daotan TW 6490/35WA, where mixing speed was increased at intervals when torque approached equilibrium at each speed.

Figure 2. Sample of one category of sized carbon fibers from Oak Ridge National

Laboratory.

Figure 3. Sample of one of the resulting composites from the torque rheometer mixing, placed into a sheet of aluminum foil to safely cool for handling before further processing.

Figure 4. Insertion of a hardened composite sample into the industrial grinder.

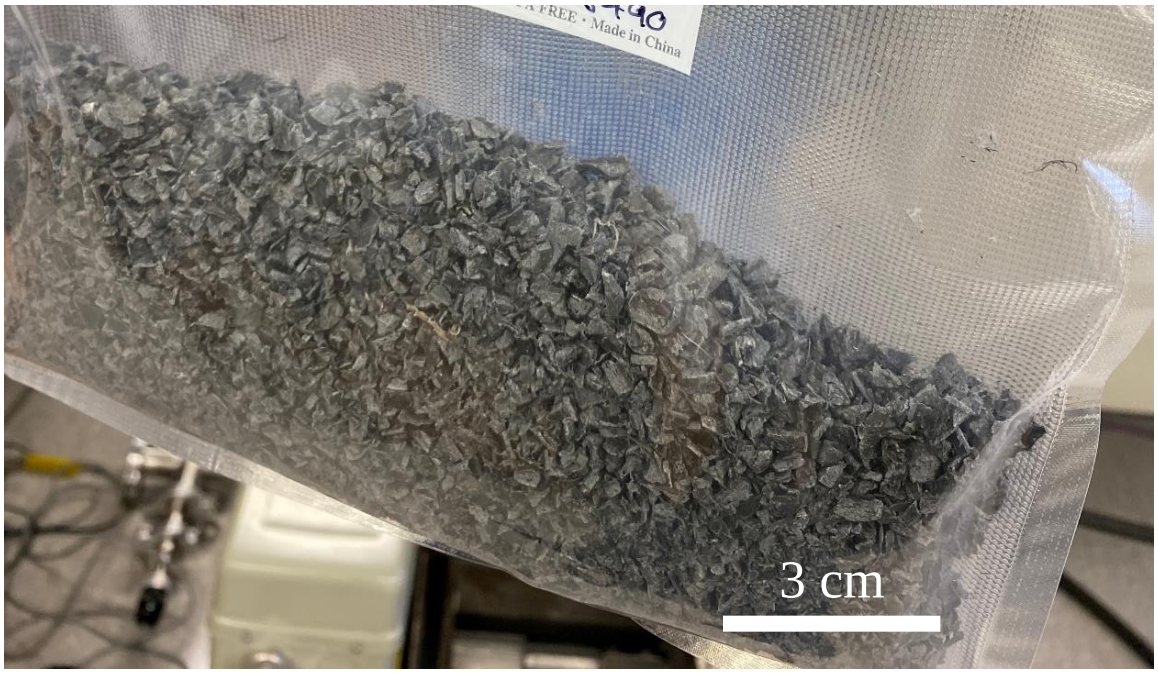

Figure 5. Pelletized material for the composite with fibers sized with Daotan TW 6490/35WA.

Figure 6. Filabot Extruder Setup that was used to create the composite filament with sized carbon fibers (different polymer pictured).

Figure 7. Filament produced with fibers coated with the Daotan® TW 6450/30WA sizing agent.

Figure 8. Filament produced with fibers coated with the Daotan® TW 6490/35WA sizing agent.

Figure 9. Filament produced with fibers coated with the Duroxyn® SEF 968/25WA sizing agent.

Figure 10. Enlarged photo of the surface of the sized carbon fiber composites.

To help characterize the input material, a pycnometer was used with compressed helium gas to measure the density of the grinded feedstock used to produce the filaments. Returned densities were compared to nominal values of interest in **Table 6**.

Table 6. Measured density of each composite compared to densities of ABS and of sizing agent.

Parameters	Measured Density (g/cm^3)	Difference from ABS	Difference from sizing agent used
ABS + 10wt% CF [Daotan® TW 6450/30WA]	1.0546	2.36%	1.39%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	1.0601	2.88%	1.39%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	1.0529	2.20%	2.36%

Measured densities did not seem to have any correlation to trends observed in the tensile testing results. However, the manufacturing processes used helped to pack the fibers and ABS together more tightly than standalone ABS as seen by the comparison in density values, indicating that porosity may not have been an issue in the feedstock used. As a result, the quality of each filament material was high upon visual inspection. No voids or pockets of air were observed on the surface or in the cross section of the filament produced,

and surface quality was very smooth, shown in **Figure 10**. To verify sufficient packing of material within the volume of the filaments, SEM images were obtained for the cross-sectional view of the filament, shown below.

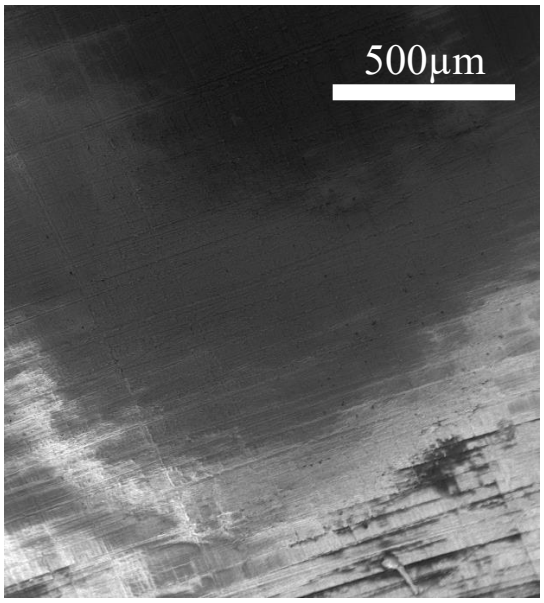

Figure 11. 500 µm scale view of SEM imaging performed on the cross section of the carbon fiber composite filaments (Duroxyn® SEF 968w/25WA sized composite used).

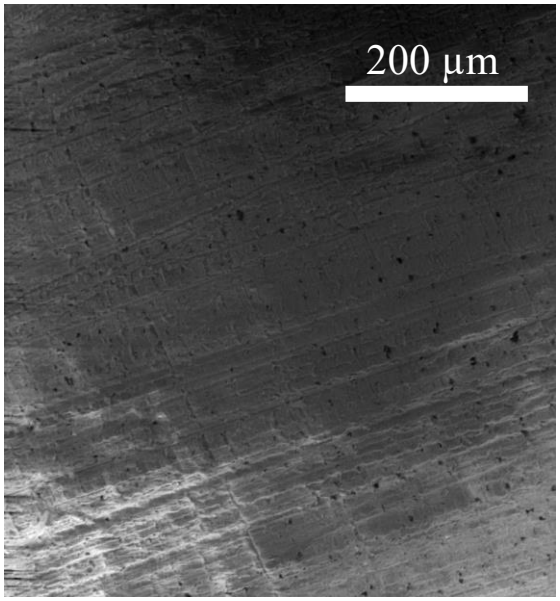

Figure 12. 200 µm scale view of SEM imaging performed on the cross section of the carbon fiber composite filaments (Duroxyn® SEF 968w/25WA sized composite used).

Voids were very small and difficult to notice at the 500 μm zoom level. At the 200 μm zoom level, these voids were small and spaced evenly throughout the material. These voids are understood to be the locations of the carbon fibers evenly dispersed in the matrix material, since most of the holes were uniformly sized. Thus, porosity of the feedstock material used for printing tensile bars was demonstrated not to be an issue and was not considered when analyzing test results for either filaments or tensile bars.

Cooled filament that was spooled was structurally solid in the longitudinal direction, but any transverse force applied to the filament caused it to whiten and shear very easily for all three types of composites. Generally, pure ABS filament is weaker in the transverse direction, especially during bending, than other standard filaments used for most prints such as PLA in the transverse loading direction, so it could be considered that the resultant composite materials were brittle in nature with respect to their fracture mechanics. This transverse loading weakness also observed for printed tensile bars during testing.

Each composite filament also underwent tensile testing, in addition to the Type V tensile bars that were printed with the filament. Gauge length used was 20 mm for all tensile tests conducted. Filament diameter was inconsistent between samples, so an average diameter of 1.6 mm was used for all cross-sectional area calculations performed for stress. Moduli for each tensile test of the filament and tensile bars was determined by taking the slope between two points that best described the entire elastic region of the test, given by

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \qquad \textbf{Equation 1}$$

where σ was a chosen stress data point and ε was its corresponding strain location. Yield strength was analytically found by setting an arbitrary point x on the plot far away from the line, and finding what a new point y would be if the destination of the line were offset

by 2% by using

$$y = Ex(1 + 0.02) - Ex(0.02) \qquad \textbf{Equation 2}$$

. Tensile strength was taken as the highest stress value that the material gave during the entire duration of the tensile test until fracture. Results of the data obtained from tensile testing the filaments of each composite material are tabulated below.

Table 7. Tensile modulus data obtained (n=5) for each type of composite filament strand.

Parameters	Tensile Modulus (GPa)	Standard Deviation (GPa)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	3.09	0.29	9.28%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	3.73	0.34	9.06%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	3.49	0.41	11.72%

Table 8. Yield strength data obtained (n=5) for each type of composite filament strand.

Parameters	Yield Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	42.75	4.23	9.89%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	41.66	3.57	8.58%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	40.96	4.36	10.64%

Table 9. Tensile strength data obtained (n=5) for each type of composite filament strand.

Parameters	Tensile Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	45.36	3.79	8.35%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	48.15	2.79	5.79%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	48.05	4.19	8.71%

Table 10. Percent elongation at fracture data obtained (n=5) for each type of composite filament strand.

Parameters	Percent Elongation at Fracture (%)	Standard Deviation (%)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	1.85	0.22	12.00%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	2.09	0.19	8.97%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	2.23	0.28	12.54%

Of the three materials, the composite that was mixed with the carbon fibers sized with Daotan® TW 6450/30WA proved to be the most difficult material from which a consistent diameter that fell below 1.75 mm was obtained. The full length of the fan setup and some applied tension (with no slack in the line of self-suspended filament above the fans) was required to stretch the material enough as it came out of the barrel to shrink it to a small enough diameter for use with 1.75 mm diameter filament printing methods.

Tensile testing results showed that tensile modulus was not statistically different across

the three different composite filament categories tested. The filament made with Daotan® TW 6490/35WA produced the highest value for tensile strength, while Daotan® TW 6450/30WA produced the highest value of yield strength. This higher yield strength value for Daotan® TW 6450/30WA is thought to be correlated to the difficulty that was experienced in extruding it as feedstock during manufacturing and from the nozzle during printing.

Plotted stress versus strain curve data for the strongest specimens from each of the three composites are shown below.

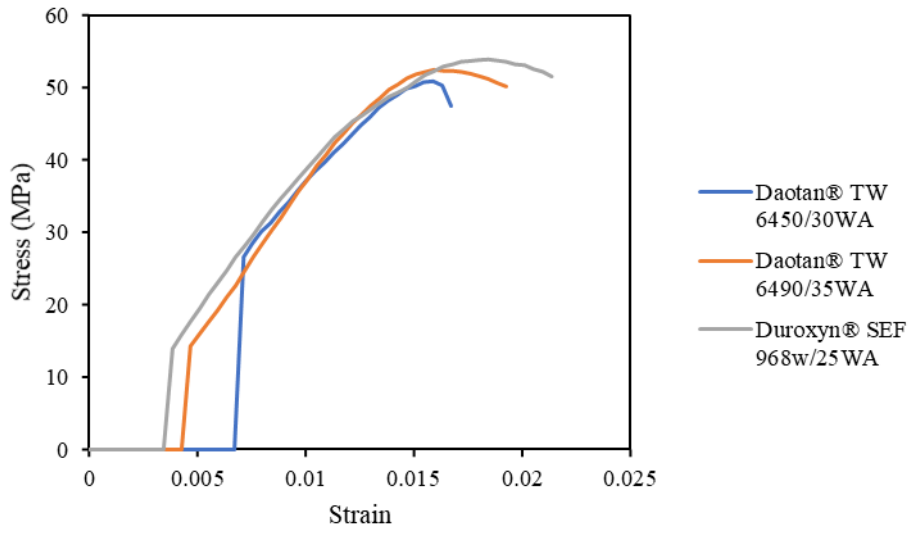

Figure 13. Plotted stress versus strain for the strongest of each category of composite filament samples tested made with each of three different types of sizing agent.

Slippage occurred at the onset of tensile testing that caused prolonged regions of zero stress to exist that frontloaded each curve, but fortunately this only had a minor impact on the readability of the data. Well-defined elastic deformation regions and plastic deformation regions existed within all the samples that were tested, which led to the straightforward collection data presented in the immediately preceding tables. Relative to the material properties for pure ABS, the properties of the composite filaments straight out

of the Filabot Extruder Setup showed improvements, which was a good sign that the sizing agents were working to increase interfacial adhesion within the composite as intended.

Using the process parameters identified in

Table *5*, three replicates of each tensile bar test case were successfully printed. Dimensions and images of the printed replicates are shown in

Table 11, **Figure 14**, **Figure 15**, and **Figure 16** and compared to the original ASTM D638 dimensions for Type V tensile bars.

Table 11. Measured dimensions of each tensile bar used before tensile testing.

Parameters	Width		Thickness		Total Length		Remarks
	Measured (mm)	Percent Difference from CAD	Measured (mm)	Percent Difference from CAD	Measured (mm)	Percent Difference from CAD	
ABS + 10wt% CF [Daotan® TW 6450/30WA]	3.31	4.01%	2.66	-24.42%	62.43	-1.68%	Vertical gaps observed in samples in the geometry transition between infill and inner wall embedded in the clamp points. Known Cura slicer issue that occurs with under-extrusion of material.
	3.23	1.56%	2.66	-24.42%	62.47	-1.62%	
	3.31	4.01%	2.71	-22.59%	62.47	-1.62%	
ABS + 10wt% CF [Daotan® TW 6490/35WA]	3.28	3.10%	2.57	-27.81%	63.27	-0.35%	Seems under-extruded at the clamp points, but middle tensile testing area appears fine.
	3.31	4.01%	2.48	-31.29%	63.27	-0.35%	
	3.35	5.21%	2.44	-32.88%	63.3	-0.30%	
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	3.34	4.91%	2.32	-37.76%	63.28	-0.33%	
	3.35	5.21%	2.33	-37.35%	63.34	-0.24%	
	3.32	4.31%	2.32	-37.76%	63.3	-0.30%	
ASTM D638 Type V Bar	3.18		3.4		63.49		

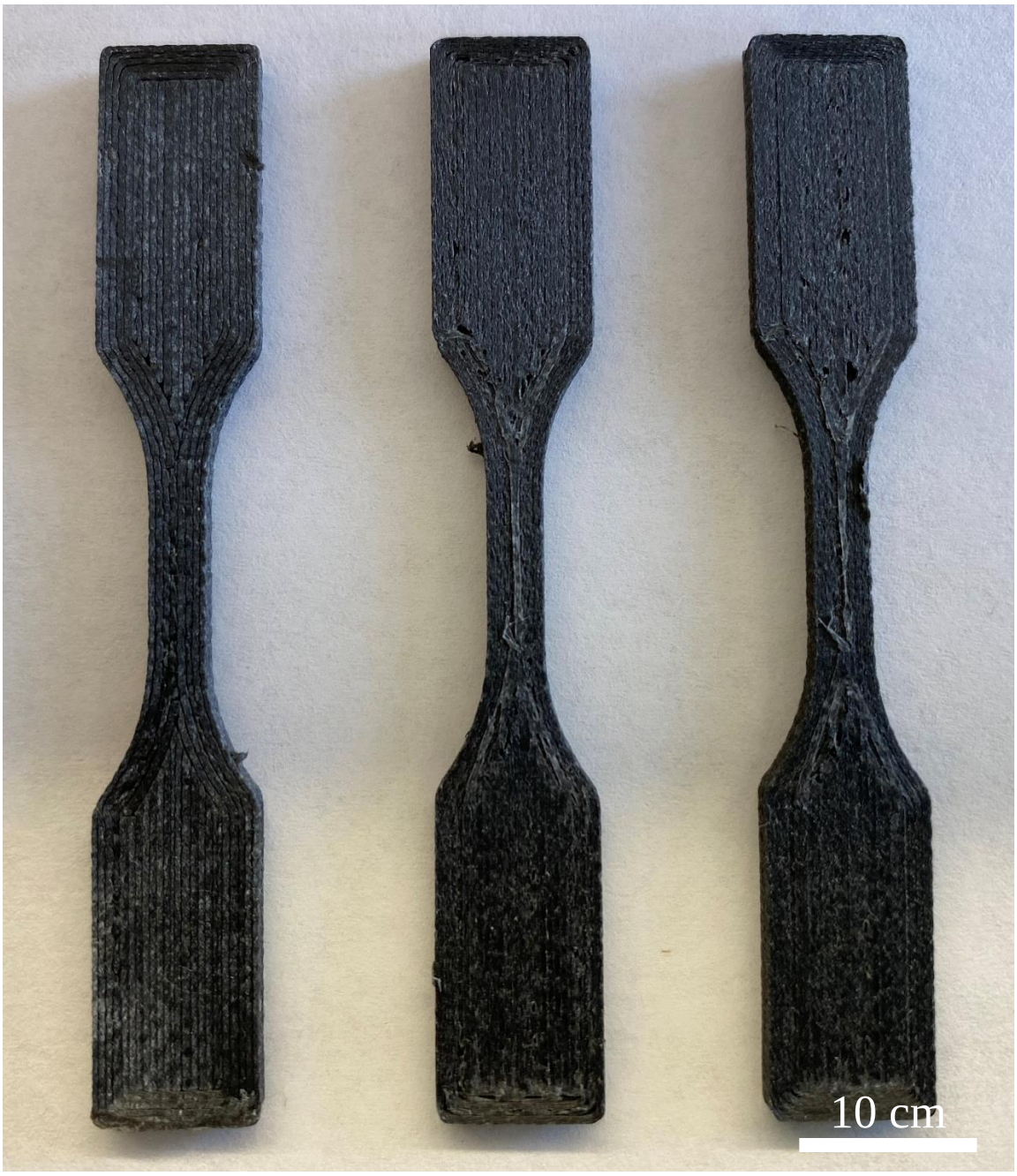

Figure 14. Printed replicates of ASTM D638 Type V specimens from the ABS composite with fibers sized with Duroxyn® SEF 968w/25WA.

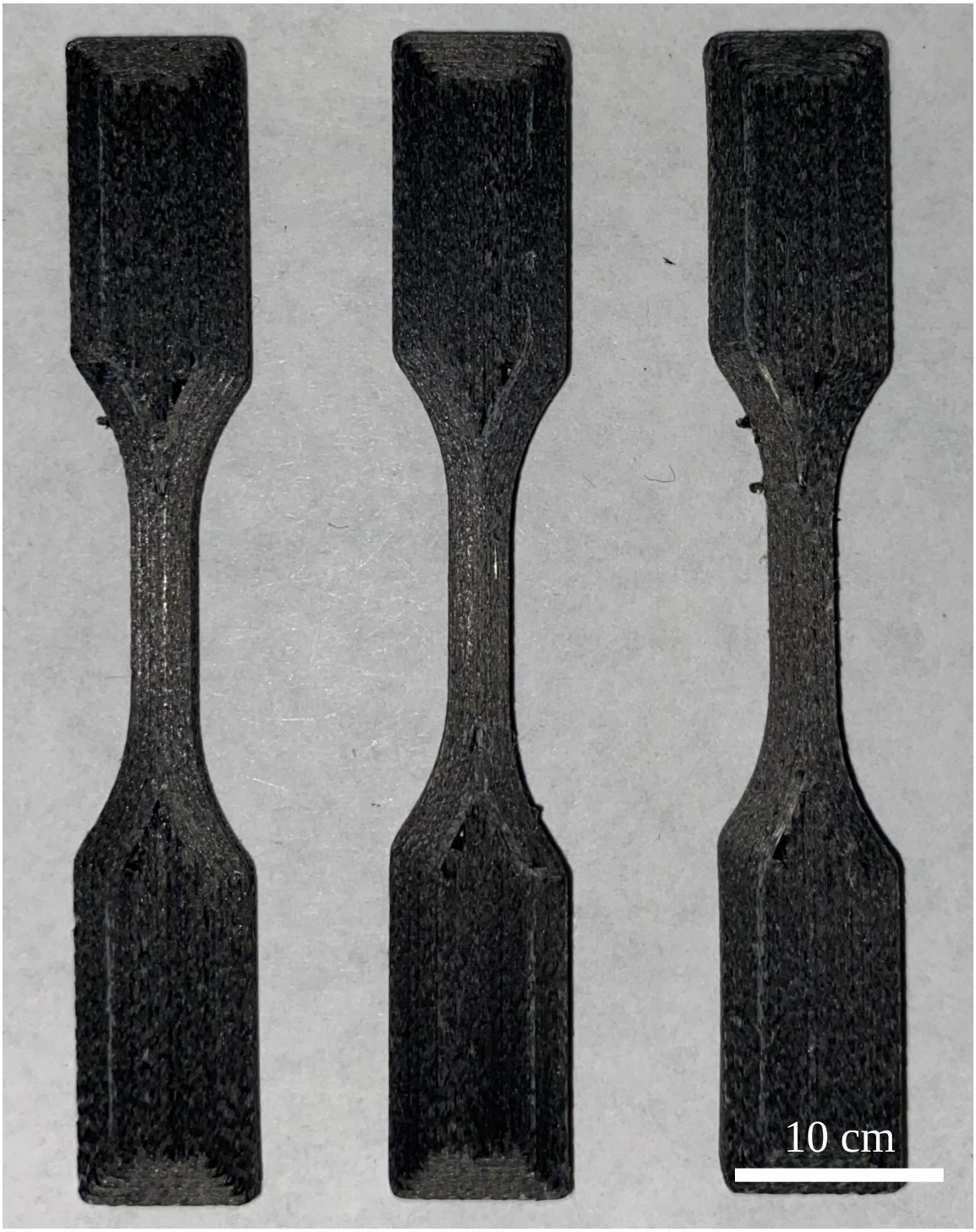

Figure 15. Printed replicates of ASTM D638 Type V specimens from the ABS composite with fibers sized with Daotan® TW 6450/30WA.

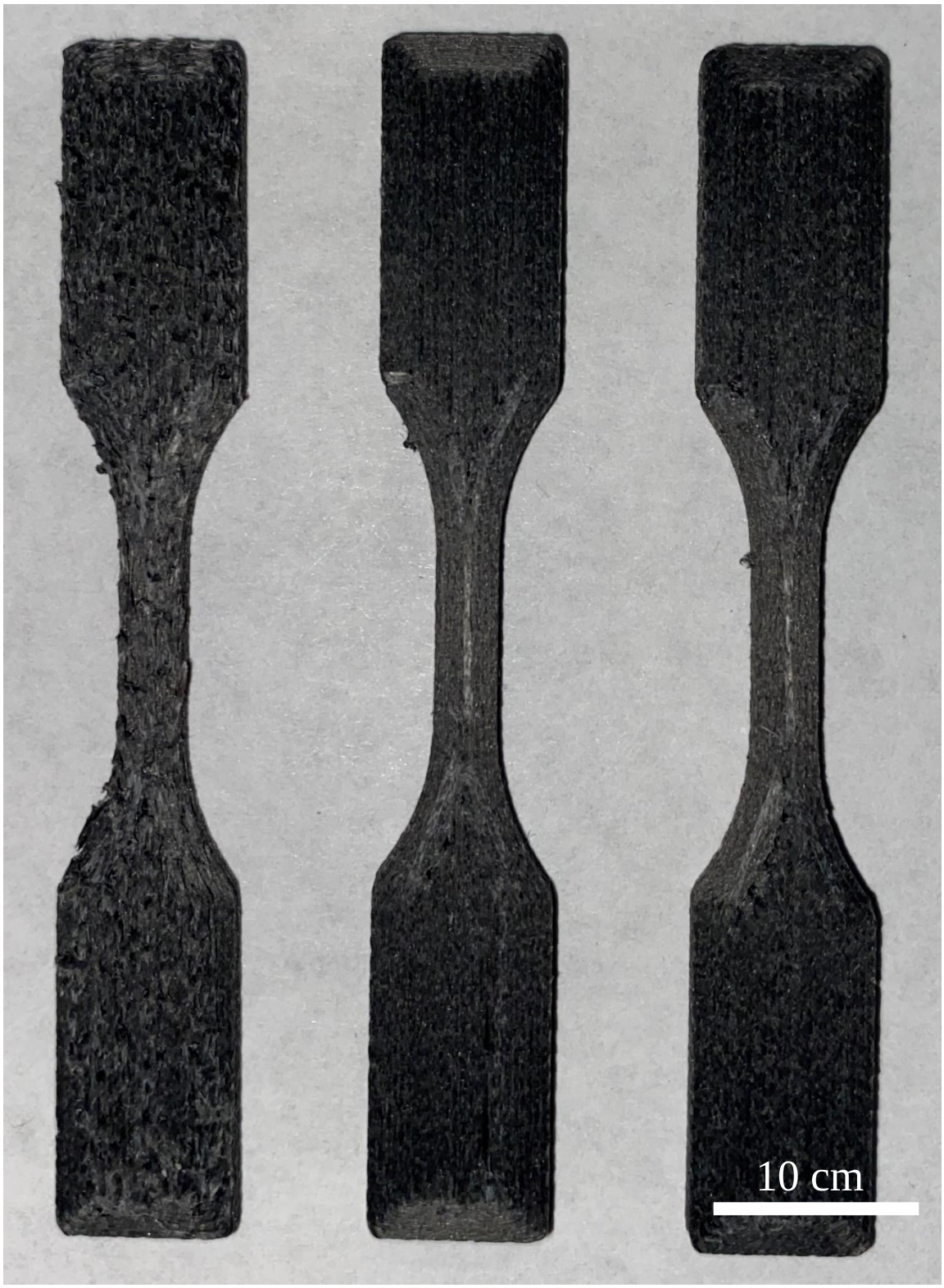

Figure 16. Printed replicates of ASTM D638 Type V specimens from the ABS composite with fibers sized with Daotan® TW 6490/35WA.

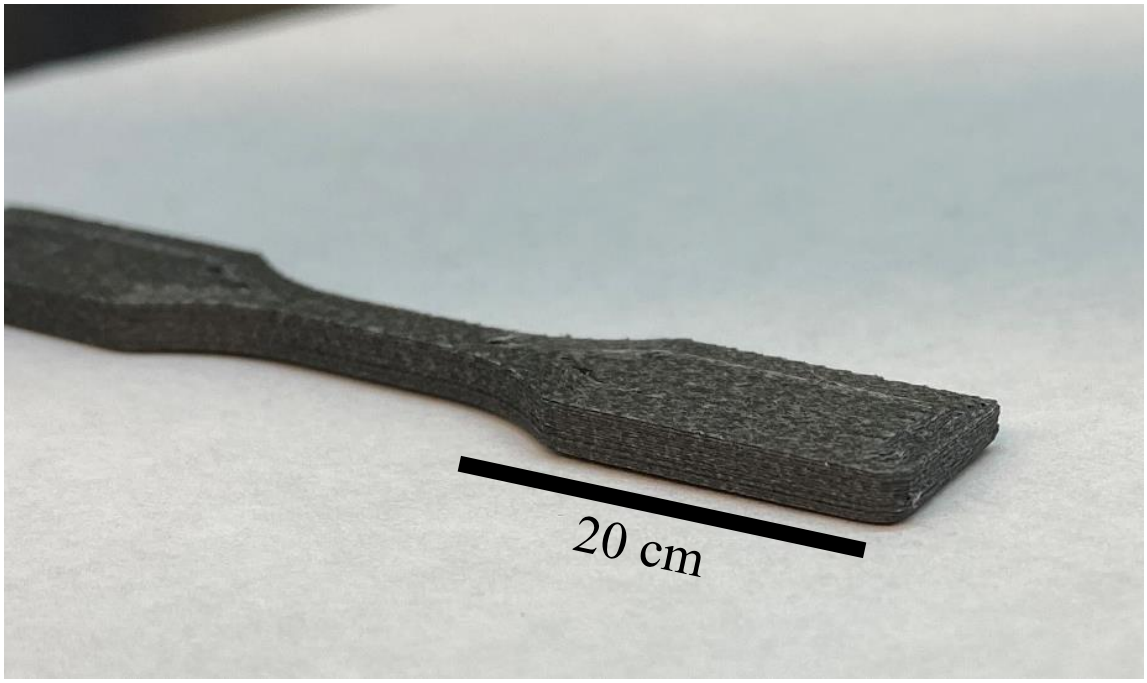

Figure 17. Side view of one of the printed tensile bar samples.

It was observed that each sample consistently differed significantly from the nominal thickness of ASTM D638 Type V tensile bars. After further testing with printing the same geometry with other materials, it was determined that the cause of the issue was an advanced setting for the Z-axis steps per millimeter value of the Ender 3, which was set by factory default to a value slightly below what it should have been in practice. Results of the data obtained from tensile testing these prints are tabulated below. Gauge length used was 20 mm for all tensile tests conducted. Also, plotted stress versus strain curve data for the strongest specimens from each of the three composites are shown.

Table 12. Tensile modulus data obtained across three replicates for each type of ABS composite tensile bar.

Parameters	Tensile Modulus (GPa)	Standard Deviation (GPa)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	3.19	0.49	15.39%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	1.84	0.64	34.80%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	2.39	0.21	8.91%

Table 13. Yield strength data obtained across three replicates for each type of ABS composite tensile bar.

Parameters	Yield Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	41.57	6.00	14.43%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	35.94	11.62	32.34%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	50.15	2.85	5.68%

Table 14. Tensile strength data obtained across three replicates for each type of ABS composite tensile bar.

Parameters	Tensile Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	55.03	5.35	9.72%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	38.33	12.90	33.66%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	53.51	4.07	7.60%

Table 15. Fracture strain data obtained across three replicates for each type of ABS composite filament.

Parameters	Percent Elongation at Fracture (%)	Standard Deviation (%)	Coefficient of Variance
ABS + 10wt% CF [Daotan® TW 6450/30WA]	2.34	0.29	12.44%
ABS + 10wt% CF [Daotan® TW 6490/35WA]	2.86	0.41	14.17%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]	2.96	0.39	13.06%

Standard deviation was high in the data obtained for the composite Daotan® TW 6490/35WA because the printed bar on the left seen in **Figure 16** was under-extruded. As a result, it was weaker and failed earlier than the other specimens. If the outlier data from this sample is removed from consideration, the mean tensile modulus for this category improves to 2.17±0.53 GPa, and the mean tensile strength improves to 47.45±0.00 GPa, which is still weaker than the results obtained from tensile bars containing the other two sizing agents. The aforementioned observed material weakness in transverse loading for these composites may help to explain the early onset of failure for this part if the cross section of the neck was not totally uniform, as imperfections may cause a slight net bending moment to be generated when the center of loading for the bar is shifted away from the axis along which its true center of mass lies.

During printing, the composite filament made with Daotan® TW 6490/35WA put up much resistance to extruding, and external force had to be applied to the filament to give the extruder gear enough strength to force sufficient material through the nozzle. The most significant reason this occurred was because of the inconsistent diameter of most of the filament extruded, causing some portions of the filament to be larger than 1.75 mm in diameter and resulting in a very difficult fit through the PTFE tube. This effect also occurred in the under-extruded sample shown in **Figure 16**. However, resistance, albeit

less significant, was still experienced with a second batch of material extruded with tighter control on the filament diameter. This could have been influenced by a higher viscosity of the sizing agent used, with the reported maximum value for viscosity of this sizing agent listed in **Table 2** to be 50 mPa-s, higher than the average viscosity of either of the other two sizing agents tested in this study, but other reasons are more likely than this. Although all sizing agents were diluted with water during the preparation of the fibers, the interaction of the individual constituent particles the comprise each sizing agent with the flowability of the ABS matrix material through the nozzle could have had some impact that led to the printing resistance experienced.

Stress-strain curves are plotted for each category of composite tensile bar specimens below.

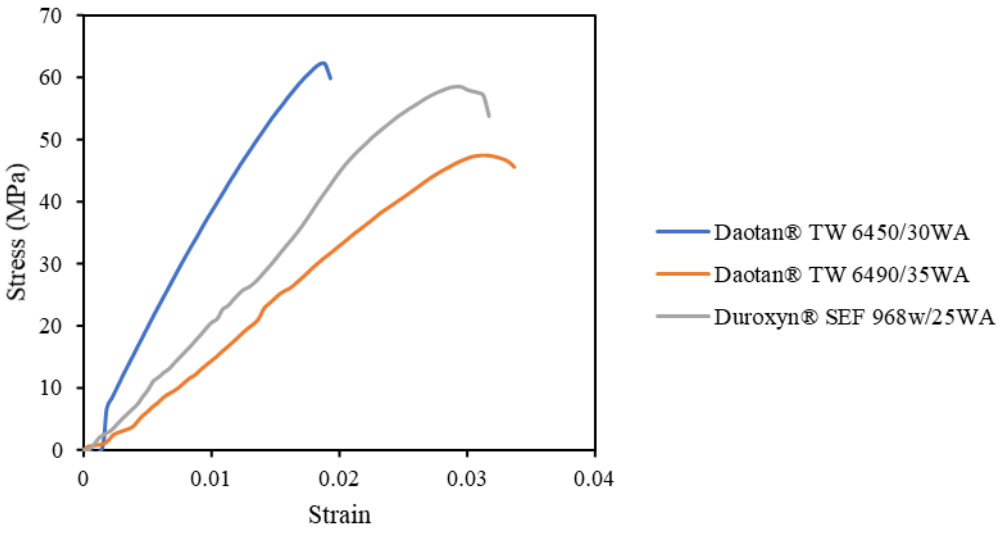

Figure 18. Plotted stress versus strain for the strongest of each category of composite tensile bar samples tested made with each of three different types of sizing agent.

Relative to conventional curves for pure ABS tensile testing, the specimens tested produced stress-strain curves that behaved differently. Once pure ABS reaches yield strength, it normally cannot sustain the high stress and falls to a lower stress state while

plastically deforming. However, the sized carbon fiber composite samples that were tested survived stresses that were higher than the yield strength, and they continued to rise in stress while plastically deforming. This illustrates that the addition of sized carbon fibers to unfilled ABS improves its mechanical performance behavior under axial loading conditions.

Data from tensile testing the tensile bars was compared to the nominal properties for CYCOLAC EX58, cited in

Table *1*, and to the results obtained by Tekinalp et. al. [6] for 10 wt% epoxy-sized carbon fiber loading, shown below. This information, along with comparisons with filament performance, is visually conveyed in bar charts plotted below.

Table 16. Tensile modulus data for tensile bars from each sizing agent composite studied compared with properties for the pure ABS used and for the epoxy-sized composite from literature.

Parameters	ABS Tensile Modulus	Difference from Nominal Value	Tekinalp et. al. Tensile Modulus	Difference from Nominal Value (%)
ABS + 10wt% CF [Daotan® TW 6450/30WA]	2.08	42.2%	7.75	-83.2888
ABS + 10wt% CF [Daotan® TW 6490/35WA]		4.30%		-112.455
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]		13.7%		-105.853

Table 17. Yield stress data for tensile bars from each sizing agent composite studied compared with properties for the pure ABS used.

Parameters	ABS Yield Stress	Difference from Nominal Value (%)
ABS + 10wt% CF [Daotan® TW 6450/30WA]	39	6.38%
ABS + 10wt% CF [Daotan® TW 6490/35WA]		-8.17%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]		25.0%

Table 18. Tensile strength data for tensile bars from each sizing agent composite studied compared with properties for the pure ABS used and for the epoxy-sized composite from literature.

Parameters	ABS Tensile Strength	Difference from Nominal Value (%)	Tekinalp et. al. Tensile Strength	Difference from Nominal Value (%)
ABS + 10wt% CF [Daotan® TW 6450/30WA]	30	58.9%	51	0.08
ABS + 10wt% CF [Daotan® TW 6490/35WA]		45.1%		-0.07
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]		56.3%		0.05

Table 19. Percent elongation data for tensile bars from each sizing agent composite studied compared with properties for the pure ABS used.

Parameters	ABS Percent Elongation	Difference from Nominal Value (%)
ABS + 10wt% CF [Daotan® TW 6450/30WA]	32	-172.8%
ABS + 10wt% CF [Daotan® TW 6490/35WA]		-167.2%
ABS + 10wt% CF [Duroxyn® SEF 968w/25WA]		-166.1%

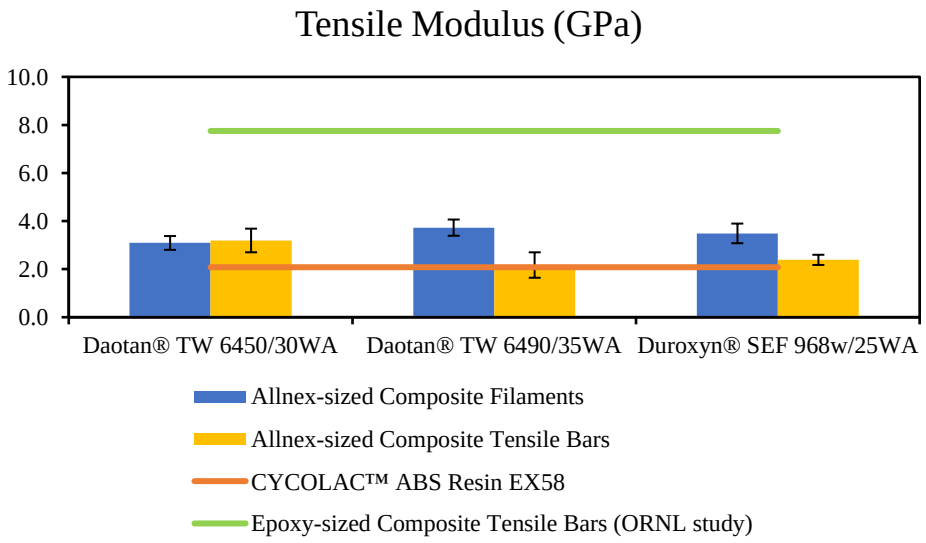

Figure 19. Clustered column chart of tensile modulus data for both filaments and tensile bars from each sizing agent composite studied compared with properties for the pure ABS used and for the epoxy-sized composite from literature.

Figure 19 shows a summary of the tensile modulus data obtained in this study. For composite sized with Daotan® TW 6450/30WA, mean filament tensile modulus was 3.09 GPa with a standard deviation of ±0.29 GPa, while mean tensile bar tensile modulus was 3.19 GPa with a standard deviation of ±0.49 GPa. Mean tensile bar tensile modulus was 3.3% better than mean filament tensile modulus, which was exceptionally good for

comparisons of this kind and illustrated excellent performance of the printed tensile bars in this category. Filament made from this composite performed 39.1% better than the nominal value of 2.08 GPa for ABS and 86% worse than the nominal value of 7.75 GPa for epoxy-sized composite from literature, whereas the tensile bars printed from the composite filament performed 42.2% better than ABS and 83.3% worse than the epoxy-sized composite from literature.

For composite sized with Daotan® TW 6490/35WA, mean filament tensile modulus was 3.73 GPa with a standard deviation of ±0.34 GPa, while mean tensile bar tensile modulus was 2.17 GPa with a standard deviation of ±0.53 GPa. Mean filament tensile modulus was 52.8% better than mean tensile bar tensile modulus, which indicated significant inconsistencies in the quality of the printed tensile bars. Filament made from this composite performed 56.7% better than ABS and 70.1% worse than the epoxy-sized composite from literature, whereas the tensile bars printed from the composite filament performed 4.3% better than ABS and 112.5% worse than the epoxy-sized composite from literature.

For composite sized with Duroxyn® SEF 968w/25WA, mean filament tensile modulus was 3.49 GPa with a standard deviation of ±0.41 GPa, while mean tensile bar tensile modulus was 2.38 GPa with a standard deviation of ±0.21 GPa. Mean filament tensile modulus was 37.5% better than mean tensile bar tensile modulus. Filament made from this composite performed 50.6% better than ABS and 75.9% worse than the epoxy-sized composite from literature, whereas the tensile bars printed from the composite filament performed 13.7% better than ABS and 105.9% worse than the epoxy-sized composite from literature.

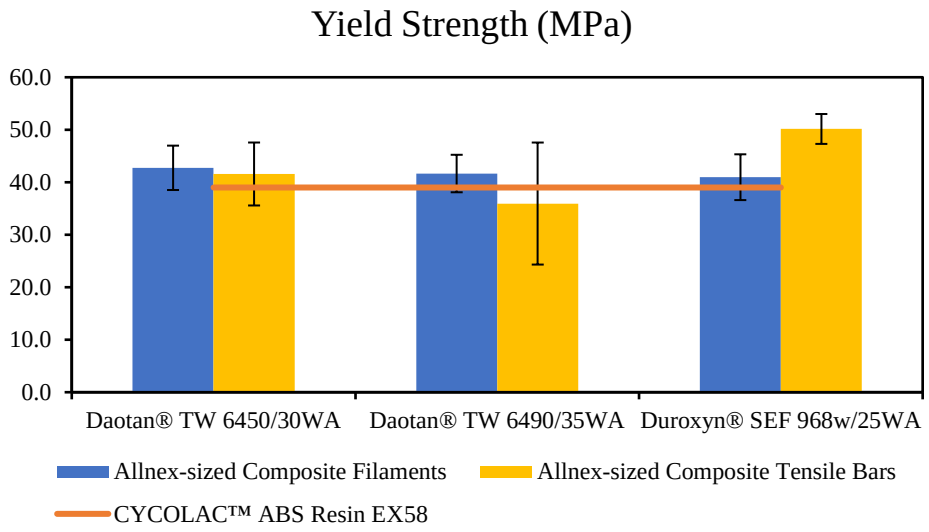

Figure 20. Clustered column chart of yield strength data for both filaments and tensile bars from each sizing agent composite studied compared with properties for the pure ABS used.

Figure 20Figure 19 shows a summary of the yield strength data obtained in this study, which was obtained with the help of **Equation 2**. For composite sized with Daotan® TW 6450/30WA, mean filament yield strength was 42.75 MPa with a standard deviation of ±4.23 MPa, while mean tensile bar yield strength was 41.57 MPa with a standard deviation of ±6.00 MPa. Mean filament yield strength was 2.8% better than mean tensile bar yield strength, which was exceptionally good for comparisons of this kind and illustrated excellent performance of the printed tensile bars in this category. Filament made from this composite performed 9.2% better than the nominal value of 39 MPa for ABS, whereas the tensile bars printed from the composite filament performed 6.4% better than ABS.

For composite sized with Daotan® TW 6490/35WA, mean filament yield strength was 41.66 MPa with a standard deviation of ±3.57 MPa, while mean tensile bar yield strength was 35.94 MPa with a standard deviation of ±11.62 MPa. Mean filament yield strength

was 14.7% better than mean tensile bar tensile strength, which was better than average for comparisons of this kind. Filament made from this composite performed 6.6% better than ABS, whereas the tensile bars printed from the composite filament performed 8.2% worse than ABS.

For composite sized with Duroxyn® SEF 968w/25WA, mean filament yield strength was 40.96 MPa with a standard deviation of ±4.36 MPa, while mean tensile bar yield strength was 50.15 MPa with a standard deviation of ±2.85 MPa. Mean filament yield strength was 20.2% worse than mean tensile bar yield strength, which indicated some inconsistencies in the quality of the composite filament that was tested. Filament made from this composite performed 4.9% better than ABS, whereas the tensile bars printed from the composite filament performed 25.0% better than ABS.

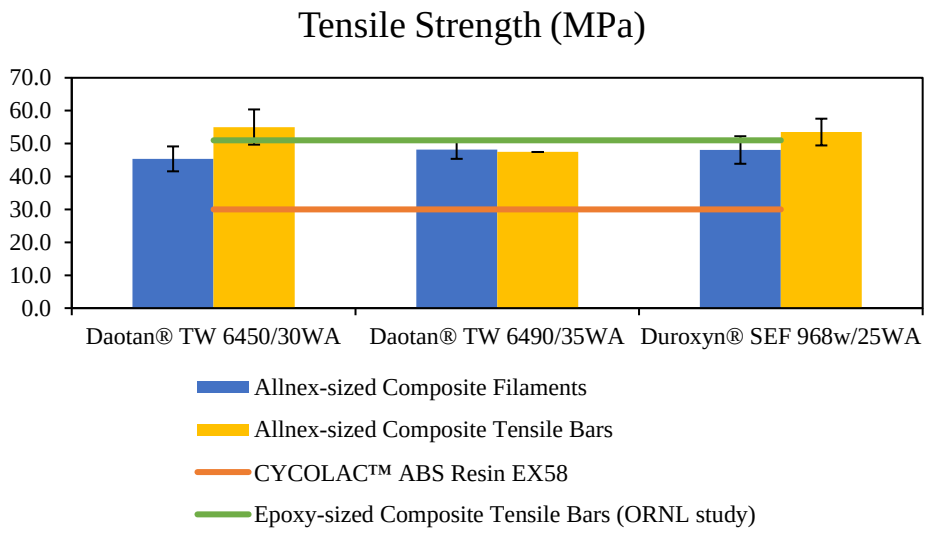

Figure 21. Clustered column chart of tensile strength data for both filaments and tensile bars from each sizing agent composite studied compared with properties for the pure ABS used and for the epoxy-sized composite from literature.

Figure 21 shows a summary of the tensile strength data obtained in this study. For composite sized with Daotan® TW 6450/30WA, mean filament tensile strength was 45.36

MPa with a standard deviation of ±3.79 MPa, while mean tensile bar tensile strength was 55.03 MPa with a standard deviation of ±5.35 MPa. Mean filament tensile strength was 19.3% worse than mean tensile bar tensile strength, which indicated some inconsistencies in the quality of the composite filament that was tested. Filament made from this composite performed 40.8% better than the nominal value of 30 MPa for ABS and 11.7% worse than the nominal value of 51 MPa for epoxy-sized composite from literature, whereas the tensile bars printed from the composite filament performed 58.9% better than ABS and 7.6% better than the epoxy-sized composite from literature.

For composite sized with Daotan® TW 6490/35WA, mean filament tensile strength was 48.15 MPa with a standard deviation of ±2.79 MPa, while mean tensile bar tensile strength was 47.45 MPa with a standard deviation of ±0.0038 MPa. Mean filament tensile strength was 1.5% better than mean tensile bar tensile strength, which was exceptionally good for comparisons of this kind and illustrated excellent performance of the printed tensile bars in this category. Filament made from this composite performed 46.5% better than ABS and 5.7% worse than the epoxy-sized composite from literature, whereas the tensile bars printed from the composite filament performed 45.1% better than ABS and 7.2% worse than the epoxy-sized composite from literature.

For composite sized with Duroxyn® SEF 968w/25WA, mean filament tensile strength was 48.05 MPa with a standard deviation of ±4.19 MPa, while mean tensile bar tensile strength was 53.51 MPa with a standard deviation of ±4.07 MPa. Mean filament tensile strength was 10.7% worse than mean tensile bar tensile strength, which indicated some inconsistencies in the quality of the composite filament that was tested. Filament made from this composite performed 46.3% better than ABS and 6.0% worse than the epoxy-

sized composite from literature, whereas the tensile bars printed from the composite filament performed 56.3% better than ABS and 4.8% better than the epoxy-sized composite from literature.

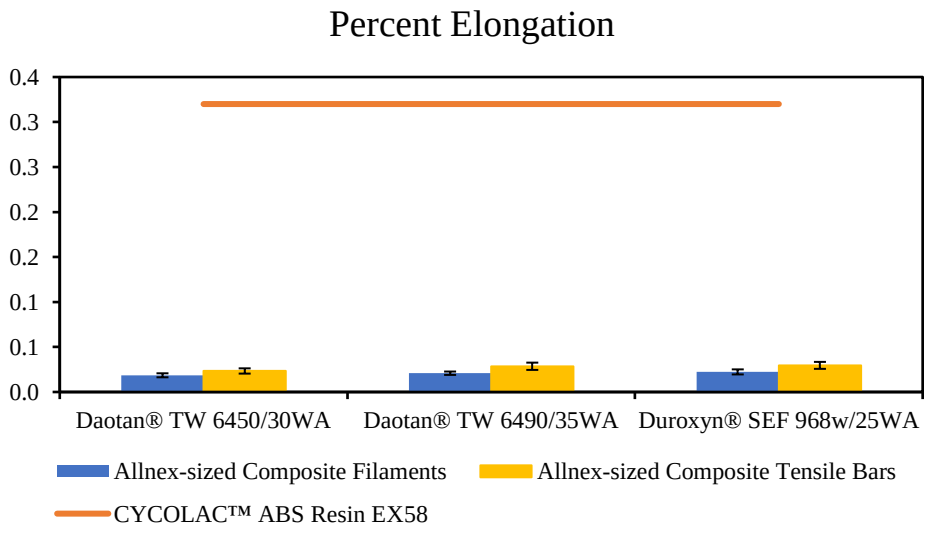

Figure 22. Clustered column chart of percent elongation data for both filaments and tensile bars from each sizing agent composite studied compared with properties for the pure ABS used.

Figure 22 shows a summary of the percent elongation data, relative to specimen original length, obtained in this study. For composite sized with Daotan® TW 6450/30WA, mean filament elongation was 1.85% with a standard deviation of ±0.22%, while mean tensile bar tensile strength was 2.34% with a standard deviation of ±0.29%. Mean tensile bar elongation was 23.0% higher than mean filament elongation. Filament made from this composite performed 178.1% worse than the nominal value of 32% for ABS, whereas the tensile bars printed from the composite filament performed 172.8% worse than ABS.

For composite sized with Daotan® TW 6490/35WA, mean filament elongation was 2.09% with a standard deviation of ±0.19%, while mean tensile bar tensile strength was

2.86% with a standard deviation of ±0.41%. Mean tensile bar elongation was 23.0% higher than mean filament elongation. Filament made from this composite performed 175.5% worse than ABS, whereas the tensile bars printed from the composite filament performed 167.2% worse than ABS.

For composite sized with Duroxyn® SEF 968w/25WA, mean filament elongation was 2.23% with a standard deviation of ±0.28%, while mean tensile bar tensile strength was 2.96% with a standard deviation of ±0.39%. Mean tensile bar elongation was 27.9% higher than mean filament elongation. Filament made from this composite performed 173.9% worse than ABS, whereas the tensile bars printed from the composite filament performed 166.1% worse than ABS.

It was generally seen that standard deviation for tensile modulus of the filaments was relatively low, with low corresponding coefficients of variable. This is desirable, as it demonstrates that the pure material that was extruded had easily reproduceable mechanical properties. On the other hand, standard deviation for the tensile bars was a bit higher, which makes sense since the occasional difficulties encountered with inconsistent filament diameter and rare nozzle clogging affected the quality of different parts of each print.

Ideally, if 3D printing were a perfect process, trends in mechanical properties would have matched those of the tensile testing data obtained for filaments. However, this was not the case, and the most significant reason for this is the voids formed within the part geometry by the imperfections of material deposition that follows the sliced model path. Although the outermost wall layer stacking will tend to look great from a side view, the extrusion lines on the inside won't form perfect seals as they are laid over each other across

layers, and thin continuous lines of air will exist inside the print. As a rule of thumb, it can be expected that part properties printed from material will achieve around 80% of the pure material properties.

Other minor reasons why results did not match include the observed whitening of the filament induced by the roller system of the Filabot Extruder System that exhibited some transverse stress on the filament, and possibly fracture onset at the microscopic level, as it bent the filament slightly to give the micrometer an accurate reading; the transferring of these cracks in the microstructure to the material that came out of the nozzle, which may have created weak points in the extruded material that cooled into the actual printed parts; and the noticeable holes in geometry between the outer walls and the infill that were partially caused by the Ultimaker Cura slicer software, as seen best in **Figure 15**. Also, since filament diameter was inconsistent, smaller or larger average cross-sectional areas used between composite samples might have influenced their load-bearing capacities, especially since filament area was small compared to printed tensile bar area.

As expected, the material properties for each sample category exceeded the material properties of the ABS used on average, illustrating the ability of the fibers to improve the mechanical properties of ABS when interspersed in a composite as the fiber material. However, the addition of fibers also made the material easier to break after yielding and less compliant during plastic deformation, which led to significantly lower values for percent elongation of both tensile bars and filaments relative to the nominal value for ABS. This is because as the fibers split apart in plastic deformation stress after yielding, residual voids form in the ABS matrix material where the fibers previously were, which rapidly decreases the overall effective cross-sectional area that is available for the tensile bar to

use internally. This continuous decrease in effective cross-sectional area from the formation of voids in the matrix led to the onset of fracture in the samples tested in this study, including the filaments for the composites, much more quickly than in pure homogenous materials.

Comparison indicates that the samples tested in this study had significantly lower moduli than the samples tested by Tekinalp et. al. [6], which were sized with an epoxy-based agent. This indicates that the adhesive ability of epoxy-based agents on the interfacial adhesion strength for carbon fiber composites with ABS is superior to the effects of the sizing agent blends by Allnex that were tested. However, tensile strength for all composites tested in this study remained similar compared to the study performed by Tekinalp et. al. [6], illustrating that although the addition of fibers to a composite does improve the tensile strength over the matrix material in general, the choice of sizing agent does not significantly alter the failure mode within carbon fiber composites, and that there is a physical limitation of carbon fiber composite tensile strength associated with the tensile strength of the fibers themselves.

Furthermore, Minitab statistical analyses were run using the results and compared to results from the study performed by Tekinalp et. al. [6] where applicable, and Fisher LSD method pairwise comparisons were performed on results that had p-values less than 0.05. Results are shown below.

Table 20. Conducted single-factor Analysis of Variance on tensile modulus data for tensile bar samples tested, with single-replicate average for epoxy-sized composite included (R^2 = 94.58%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sizing Agent	3	2.48082×10^{19}	8.26941×10^{18}	29.11	0.001

Error	5	1.42056×10^{18}	2.84112×10^{17}		
Total	8	2.62288×10^{19}			

Table 21. Grouping information for conducted pairwise comparison on statistical model from **Table 20** using Fisher LSD Method and 95% confidence. (Means that do not share a letter are significantly different.)

Sizing Agent	**N**	**Mean (10^9)**	**Grouping**	
Epoxy-based Resin	1	7.75	A	
Daotan® TW 6450/30WA	3	3.19		B
Duroxyn® SEF 968w/25WA	3	2.39		B
Daotan® TW 6490/35WA	2	2.17		B

Table 22. Conducted single-factor Analysis of Variance on yield strength data for tensile bar samples tested (R^2 = 46.35%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sizing Agent	2	1.14861×10^{14}	5.74306×10^{13}	2.16	0.211
Error	5	1.32973×10^{14}	2.65946×10^{13}		
Total	7	2.47834×10^{14}			

Table 23. Conducted single-factor Analysis of Variance on tensile strength data for tensile bar samples tested, with single-replicate average for epoxy-sized composite included (R^2 = 35.76%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sizing Agent	3	7.54024×10^{13}	2.51341×10^{13}	0.93	0.492
Error	5	1.35431×10^{14}	2.70862×10^{13}		
Total	8	2.10833×10^{14}			

Table 24. Conducted single-factor Analysis of Variance on percent elongation data for tensile bar samples tested (R^2 = 35.93%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Sizing Agent	2	0.6695	0.3348	1.68	0.263
Error	6	1.1937	0.1989		
Total	8	1.8632			

As mentioned above, the tensile moduli were shown to have differences between factor levels that were statistically significant in Minitab. While the composites sized with agents from Allnex all shared a grouping letter in **Table 21** since Minitab did not detect statistically significant differences between these with the data provided from the tensile testing experiments, the epoxy-based composite had a different grouping designation from the factor levels performed in this study, demonstrating that there is a statistical difference in tensile modulus associated with the choice of sizing agent used

for sizing the fibers in a carbon fiber composite.

CONCLUSION

The surface of carbon fibers is inert and does not normally respond well to polymers under load, so sizing agents must be used to prepare carbon fibers for blended composite polymers, which will unlock the true potential of the composite material. Here in this study, it was determined that the choice of sizing agent used during the preparation of carbon fibers had significant effects on the mechanical properties of the resulting composite. If this is true, then even better sizing agents can be developed that further increase the strength of the composite polymer, and the best sizing agent that could possibly exist might bring the composite properties to a maximum threshold where composite properties nearly match the fiber properties in the fiber-loading direction. In applications where high strength, low weight materials like carbon fibers are needed, such as aerospace and formula one racing, new avenues of success can be explored as new and improved sizing agents are developed for carbon fibers.

FUTURE WORK

With this study, it is currently known that material property data has been obtained for the use of at least four different sizing agents in the preparation of carbon fibers composites. Further studies should be done to document effects of a wider library of sizing agents on the mechanical properties of carbon fiber composites. Additionally, comprehensive data for carbon fiber composites manufactured with unsized carbon fibers should also be

collected, to test the theory of poor expected mechanical performance put forth by Yang, Li, and Yang [8]. Limited strength data on unsized carbon fibers does exist [9], but more information needs to be collected and a set of standard process settings used to make this base composite defined. Not only should this data be collected to verify this assertion, but it will also serve as a control that will help to future researchers easily identify sizing agents that have superior effects on mechanical properties compared to other sizing agents, such as the epoxy-based agent used by Oak Ridge National Laboratory in the preparation of their fibers for their varied weight-percent study [6].

Sizing agents tend to thermally degrade at temperatures that are required to blend and extrude most polymers. Chemical engineering research should be done on ways that high temperature-resistant compounds can be implemented to thermally shield the sizing agents used in carbon fibers from damage and degradation during manufacturing processes. Across processes, these extreme temperatures must be reached multiple times (during torque mixing of polymer and fibers, during extrusion of filament material, and during deposition of filament into a printed part), so methods should be devised that such thermal shielding could survive multiple thermal loading cycles.

This study only examined the differences in sizing agent effects as they directly interacted with ABS as the matrix materials. The use of different matrix materials also should be explored with different sizing agents, as a different polymer such as poly-lactic acid (PLA) or nylon might be able to generate different chemical bonds with the sizing agents that were provided for this study by Allnex, which may be either stronger or weaker. Allnex shared that some polyurethane-based sizing agents are designed to work with ABS, but the effects of using a different polymer matrix material than intended has not yet been

demonstrated. There may even exist a polymer that has poor interaction with the industry-standard epoxy-based sizing used for carbon fibers, but excellent interaction with the sizing agents from Allnex. This avenue should be comprehensively explored to expand a possible library of sizing agent effects on carbon fiber composites to include considerations for the effects of varying the polymer used, ranging from many industry-standard polymers such ABS, nylon, and PLA, to more specific polymers such as those smart material polymers that exhibit shape-memory properties.

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APPENDICES

APPENDIX A: TECHNICAL DATA SHEETS

For reference to the manufacturer specifications of the materials used, the provided technical data sheets are included here.

CYCOLAC™ RESIN EX58

REGION AMERICAS

DESCRIPTION

High impact ABS for sheet extrusion and blow molding applications.

TYPICAL PROPERTY VALUES

Revision 20210812

PROPERTIES	TYPICAL VALUES	UNITS	TEST METHODS
MECHANICAL			
Tensile Stress, yld, Type I, 5 mm/min	39	MPa	ASTM D638
Tensile Stress, brk, Type I, 5 mm/min	30	MPa	ASTM D638
Tensile Strain, yld, Type I, 5 mm/min	3.1	%	ASTM D638
Tensile Strain, brk, Type I, 5 mm/min	32	%	ASTM D638
Tensile Modulus, 5 mm/min	2080	MPa	ASTM D638
Flexural Stress, yld, 1.3 mm/min, 50 mm span	66	MPa	ASTM D790
Flexural Modulus, 1.3 mm/min, 50 mm span	2160	MPa	ASTM D790
Hardness, Rockwell R	102	-	ASTM D785
Tensile Stress, yield, 50 mm/min	41	MPa	ISO 527
Tensile Stress, break, 50 mm/min	30	MPa	ISO 527
Tensile Strain, yield, 50 mm/min	2.6	%	ISO 527
Tensile Strain, break, 50 mm/min	21	%	ISO 527
Tensile Modulus, 1 mm/min	1970	MPa	ISO 527
Flexural Stress, yield, 2 mm/min	60	MPa	ISO 178
Flexural Modulus, 2 mm/min	2000	MPa	ISO 178
IMPACT			
Izod Impact, notched, 23°C	432	J/m	ASTM D256
Izod Impact, notched, -30°C	299	J/m	ASTM D256
Instrumented Dart Impact Total Energy, 23°C	37	J	ASTM D3763
Izod Impact, notched 80*10*4 +23°C	35	kJ/m²	ISO 180/1A
Izod Impact, notched 80*10*4 -30°C	23	kJ/m²	ISO 180/1A
Charpy 23°C, V-notch Edgew 80*10*4 sp=62mm	37	kJ/m²	ISO 179/1eA
THERMAL			
Vicat Softening Temp, Rate B/50	106	°C	ASTM D1525
HDT, 0.45 MPa, 3.2 mm, unannealed	91	°C	ASTM D648
HDT, 1.82 MPa, 3.2mm, unannealed	76	°C	ASTM D648
CTE, -40°C to 40°C, flow	1.01E-04	1/°C	ASTM E831
CTE, -40°C to 40°C, xflow	1.04E-04	1/°C	ASTM E831
Vicat Softening Temp, Rate B/50	95	°C	ISO 306
Vicat Softening Temp, Rate B/120	97	°C	ISO 306
HDT/Af, 1.8 MPa Flatw 80*10*4 sp=64mm	78	°C	ISO 75/Af
Relative Temp Index, Elec	60	°C	UL 746B
Relative Temp Index, Mech w/impact	60	°C	UL 746B
Relative Temp Index, Mech w/o impact	60	°C	UL 746B
PHYSICAL			

CHEMISTRY THAT MATTERS™

Figure 23. Page 1 of the technical datasheet for CYCOLAC™ Resin EX58.

PROPERTIES	TYPICAL VALUES	UNITS	TEST METHODS
Specific Gravity	1.03	-	ASTM D792
Mold Shrinkage, flow, 3.2 mm	0.6 – 0.8	%	SABIC method
Melt Viscosity, 240°C, 100 sec-1	15500	Poise	ASTM D3825
Density	1.03	g/cm³	ISO 1183
Melt Flow Rate, 220°C/10.0 kg	4	g/10 min	ISO 1133
ELECTRICAL			
Arc Resistance, Tungsten {PLC}	5	PLC Code	ASTM D495
Hot Wire Ignition {PLC}	4	PLC Code	UL 746A
High Voltage Arc Track Rate {PLC}	1	PLC Code	UL 746A
High Ampere Arc Ign, surface {PLC}	4	PLC Code	UL 746A
Comparative Tracking Index (UL) {PLC}	0	PLC Code	UL 746A
FLAME CHARACTERISTICS			
UL Yellow Card Link	E121562-220684	-	-
UL Recognized, 94HB Flame Class Rating	1.5	mm	UL 94
EXTRUSION BLOW MOLDING			
Drying Temperature	80 – 90	°C	
Drying Time	4 – 5	Hrs	
Drying Time (Cumulative)	24	Hrs	
Maximum Moisture Content	0.02	%	
Melt Temperature (Parison)	215 – 230	°C	
Barrel - Zone 1 Temperature	205 – 225	°C	
Barrel - Zone 2 Temperature	205 – 225	°C	
Barrel - Zone 3 Temperature	205 – 225	°C	
Barrel - Zone 4 Temperature	205 – 225	°C	
Adapter - Zone 5 Temperature	210 – 230	°C	
Head - Zone 6 - Top Temperature	215 – 230	°C	
Head - Zone 7 - Bottom Temperature	215 – 230	°C	
Screw Speed	20 – 60	rpm	
Extruder Feed Zone Temperature	60 – 75	°C	
Mold Temperature	40 – 80	°C	
Die Temperature	215 – 235	°C	
SHEET EXTRUSION			
Drying Temperature	80 – 95	°C	
Drying Time	4	Hrs	
Maximum Moisture Content	0.02	%	
Melt Temperature	215 – 260	°C	
Barrel - Zone 1 Temperature	170 – 200	°C	
Barrel - Zone 2 Temperature	180 – 220	°C	
Barrel - Zone 3 Temperature	190 – 225	°C	
Barrel - Zone 4 Temperature	200 – 240	°C	
Adapter Temperature	205 – 250	°C	
Die Temperature	205 – 250	°C	
Roll Stack Temp - Top	90 – 95	°C	
Roll Stack Temp - Middle	95 – 105	°C	
Roll Stack Temp - Bottom	100 – 105	°C	

CHEMISTRY THAT MATTERS™

Figure 24. Page 2 of the technical datasheet for CYCOLAC™ Resin EX58.

DISCLAIMER

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CHEMISTRY THAT MATTERS™

Figure 25. Page 3 of the technical datasheet for CYCOLAC™ Resin EX58.

TECHNICAL DATASHEET

allnex
The Coating Resins Company

DAOTAN® TW 6450/30WA

PRELIMINARY PRODUCT INFORMATION

TYPE

Aqueous aliphatic polyurethane dispersion, polycarbonate based

FORM OF DELIVERY (f.o.d.)

30 % in water (30WA)
(also containing 4.3 % Dipropylenglycol-dimethylether and 1 % Methoxypropanol)

DEVELOPMENT PRODUCT

This product is serving for trial purposes only. Deviations which might occur during transfer into manufacturing in a commercial scale are possible and do not constitute any material defect.

Neutralization agent

approx. 1 % N,N-dimethylethanolamine, as salt

TENTATIVE PRODUCT DATA

Determined per batch:

Dynamic Viscosity DIN EN ISO 3219		
dynamic viscosity (100 1/s; 23 °C)	[mPa.s]	max. 50
Non-Volatile Matter DIN 55671		
non-volatile matter (125 °C; 10 min; 0,6 g)	[%]	29 - 31

Not continually determined:

pH-Value DIN ISO 976		
pH-value (10 %)		7,3 - 9,0
Colour / Appearance VLN 250		
colour		whitish
appearance		cloudy
Density (Liquids) DIN EN ISO 2811-2		
density approx. (20 °C)	[g/cm³]	1,04
Flash Point (CCCFP) ASTM D 6450		
flash point	[°C]	> 95

SPECIAL PROPERTIES AND USE

Daotan TW 6450/30WA is recommended as the NMP / NEP- free alternative for Daotan (V)TW 1236. Alike latter Daotan TW 6450 is a polycarbonate-based, high molecular weight Polyurethanedispersion. Dried at ambient temperature Daotan TW 6450 is providing clear, crack- free films without further addition of organic solvents or additives. These films exhibit excellent elasticity and mechanical properties as well as very good adhesion to different plastic substrates like e.g. ABS, PC, PA, PVC, PC/PBT, ...

Accordingly Daotan TW 6450/30WA is particularly recommended for waterborne plastic primer and waterborne auto OEM Basecoats with outstanding requirements in terms of stone chip resistance properties. A further use is as modifier resin to improve stone chip resistance properties of e.g. auto OEM primer surfacer formulations.

DILUTABILITY

Daotan TW 6450/30WA provides unlimited dilutability with deionized water, compatibility with organic solvents is limited; e. g. butyl glycol or butyl diglycol cause a strong swelling of Daotan TW 6450. With Proglyde DMM Daotan TW 6450 is completely incompatible. According to our experience Dowanol DPM is a quite suitable diluent. In general it is recommendable to pre-dilute the solvent with deionized water before adding to Daotan TW 6450.

STORAGE

At temperatures up to 25 °C storage stability packed in original containers amounts to at least 365 days.

It is important to protect Daotan TW 6450/30WA from frost; at low temperatures it has therefore to be stored under frostproof conditions.

Lowest storage temperature: 5 °C

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Figure 26. Page 1 of the technical datasheet for Daotan® TW 6450/30WA.

DISTINGUISHING FEATURES

Compared to Daotan (V)TW 1236 Daotan TW 6450 provides quicker drying speed at ambient temperature. Properties like adhesion to different plastic substrates, mechanical properties and humidity resistance are in the same range.

REMARK:

Data contained in this publication are based on careful investigations (and are intended for information only). Due to scale up of this product there is not yet sufficient experience concerning serial production. We can therefore not exclude, that based on future knowledge product data and other indicated properties in upcoming Technical Data Sheets will be subject to change. We reserve the right to leave the product name unchanged, even if product data or other indicated properties will vary from the present product info. Regardless of the data contained in this publication any user is obliged to carry out tests under his own responsibility as to the suitability of the product for a particular use and to investigate the possible violation of industrial property rights of third parties. Information is therefore not binding and cannot be construed as guaranteeing specific properties of products. We apply our General Sales Conditions.

4.0/30.03.2017 (replaces 3.1/30.10.2013)

Figure 27. Page 2 of the technical datasheet for Daotan® TW 6450/30WA.

TECHNICAL DATASHEET

allnex
The Coating Resins Company

DAOTAN® TW 6490/35WA

PRELIMINARY PRODUCT INFORMATION

TYPE

Waterborne, aliphatic polyurethane dispersion, solventfree

FORM OF DELIVERY (f.o.d.)

35 % in water (35WA)

DEVELOPMENT PRODUCT

This product is serving for trial purposes only. Deviations which might occur during transfer into manufacturing in a commercial scale are possible and do not constitute any material defect.

Neutralization agent

approx. 1.0 % triethylamine, as salt

TENTATIVE PRODUCT DATA

Determined per batch:

Dynamic Viscosity DIN EN ISO 3219		
dynamic viscosity (100 1/s; 23 °C)	[mPa.s]	10 - 60
Acid Value DIN EN ISO 2114		
acid value (solids)	[mg KOH/g]	15 - 22
pH-Value DIN ISO 976		
pH-value (10 %)		8,5 - 10
Non-Volatile Matter DIN EN ISO 3251		
non-volatile matter (1 h; 125 °C; 1 g)	[%]	34 - 36

Not continually determined:

Colour / Appearance VLN 250		
colour		whitish
appearance		slightly cloudy
Particle Size VLN 220		
particle size (25 °C)	[nm]	< 150
Density (Liquids) DIN EN ISO 2811-2		
density approx. (20 °C)	[g/cm³]	1,04
Flash Point (Pensky-Martens) DIN EN ISO 2719		
flash point	[°C]	> 94

SPECIAL PROPERTIES AND USE

Daotan TW 6490 is a waterborne, aliphatic polyurethane dispersion, free of solvents and emulsifiers. Dried at ambient temperature Daotan TW 6490 yields transparent, crack-free films.
Coatings based on Daotan TW 6490 provide properties as:
- very good adhesion to plastic substrates like e.g. ABS, PVC, PC, PMMA
- high elasticity and toughness
- excellent mechanical properties (especially stone chip resistance)
- little yellowing at elevated temperature

Thus Daotan TW 6490 is recommended for waterborne plastic Primers and Basecoats. Moreover Daotan TW 6490 can be used as modifier resin in waterborne OEM Primer Surfacer recipes to improve stone chip resistance properties. For latter application Daotan TW 6490 needs to be crosslinked with melamine resins (preferably HMMM-grades like e. g. Cymel 303). Optimum results are obtained by using a blending ratio Daotan TW 6490 : Cymel 303 = 85 : 15 (calculated on solid resin).

To further improve water- and chemical resistance properties of coatings dried at ambient temperature Daotan TW 6490 can be crosslinked with
- Polyaziridine (e. g. Crosslinker CX-100, Fa. DSM, Netherlands)
- Carbodiimide (e. g. Crosslinker XL-701 or XL-702, Fa. Picassian Polymers, Netherlands)

COMPATIBILITY

Compatibility of Daotan TW 6490 with other resins or additives has to be checked case by case. According to our experience the dispersing additive Additol VXW 6208 and the leveling and substrate wetting agent Additol VXW 6503N lead to excellent results.

STORAGE

At temperatures up to 25 °C storage stability packed in original containers amounts to at least 365 days.

It is important to protect Daotan TW 6490/35WA from frost; at low temperatures it has therefore to be stored under frostproof conditions.

Lowest storage temperature: 5 °C

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Figure 28. Page 1 of the technical datasheet for Daotan® TW 6490/35WA.

REMARK:

Data contained in this publication are based on careful investigations (and are intended for information only). Due to scale up of this product there is not yet sufficient experience concerning serial production. We can therefore not exclude, that based on future knowledge product data and other indicated properties in upcoming Technical Data Sheets will be subject to change. We reserve the right to leave the product name unchanged, even if product data or other indicated properties will vary from the present product info. Regardless of the data contained in this publication any user is obliged to carry out tests under his own responsibility as to the suitability of the product for a particular use and to investigate the possible violation of industrial property rights of third parties. Information is therefore not binding and cannot be construed as guaranteeing specific properties of products. We apply our General Sales Conditions.

8.0/30.03.2017 (replaces 7.0/30.03.2017)

Figure 29. Page 2 of the technical datasheet for Daotan® TW 6490/35WA.

DUROXYN® SEF 968w/25WA

Technical Datasheet

DEVELOPMENT PRODUCT

This product is serving for trial purposes only. Deviations which might occur during transfer into manufacturing in a commercial scale are possible and do not constitute any material defect.

TYPE

Non-drying epoxy resin ester, water emulsifiable

FORM OF DELIVERY (f.o.d.)

25 % in water (25WA)

TENTATIVE PRODUCT DATA

Determined per batch:

Dynamic Viscosity DIN EN ISO 3219		
dynamic viscosity (500 1/s; 23 °C)	[mPa.s]	5 - 20
Acid Value DIN EN ISO 2114		
acid value (form of delivery)	[mg KOH/g]	<= 3
Non-Volatile Matter DIN EN ISO 3251		
non-volatile matter (1 h; 125 °C; 1 g)	[%]	24,5 - 25,5

Not continually determined:

Colour / Appearance VLN 250		
colour		pale yellow
appearance		clear to light cloudy
Density (Liquids) DIN EN ISO 2811-2		
density approx. (20 °C)	[g/cm³]	1,03
Flash Point (Pensky-Martens) DIN EN ISO 2719		
flash point	[°C]	> 100

SPECIAL PROPERTIES AND USE

Duroxyn SEF 968w/25WA is used as binder for fiber sizing (glass and carbon). Duroxyn SEF 968w/25WA can be easily formulated and reduced with water to the required solids content. It can be used as the sole sizing material or formulated with other waterborne sizing components. Final compatibility and sizing bath stability needs to be evaluated. Duroxyn SEF 968w/25WA provides excellent spreading properties of the fibers.

STORAGE

At temperatures up to 25 °C storage stability packed in original containers amounts to at least 180 days.

PRECAUTIONS

Please notice the information in the material safety data sheet (SDS).

REMARK:

Data contained in this publication are based on careful investigations (and are intended for information only). Due to scale up of this product there is not yet sufficient experience concerning serial production. We can therefore not exclude, that based on future knowledge product data and other indicated properties in upcoming Technical Data Sheets will be subject to change. We reserve the right to leave the product name unchanged, even if product data or other indicated properties will vary from the present product info. Regardless of the data contained in this publication any user is obliged to carry out tests under his own responsibility as to the suitability of the product for a particular use and to investigate the possible violation of industrial property rights of third parties. Information is therefore not binding and cannot be construed as guaranteeing specific properties of products. We apply our General Sales Conditions.

Figure 30. Technical datasheet for Duroxyn® SEF 968w/25WA.

APPENDIX B: OTHER 3D PRINTING STUDIES

Other filaments were manufactured with the Filabot filament extrusion machine, too. Ultem 1000 (polyetherimide), which was received from SABIC Plastics, was extruded at different temperatures all in the range of 400°C, and outgassing was observed at elevated temperatures that were too high, causing the resultant extrusion to contain many gas-filled bubbles. These were theorized to be due to either the hygroscopic properties of the polymer feedstock having absorbed moisture from the ambient air before melting, or the extreme temperatures required to fully melt the polymer serving as a catalyst for the polymer to thermally degrade after it exited the nozzle of the Filabot machine.

Additionally, there was a need in lab for more available reliable printing methods of flexible polymers such as Hytrel, TPU, shape-memory polymers, and composites that blend any of these with soybean-husks. An additional Ender 3 V2-type machine was purchased, and it was fitted with a 0.8 mm nozzle with Cura settings expecting a 0.6 mm nozzle to account for resistance from the natural fibers in the composites used. A composite with PLA as the matrix material and soybean husk fibers as the fiber material was tested at 210°C nozzle temperature to print an intended stand for a 3D-printed University of Louisville mascot logo. Results were aesthetically pleasing, and layer height stayed consistent between layers on the first print attempt. Further use of this printer and nozzle to print with soybean husk fiber-based composites will likely see continued good results.

Figure 31. Soybean husk fiber with PLA composite successfully extruded from the nozzle of the additional printer that was purchased for use with natural fibers.

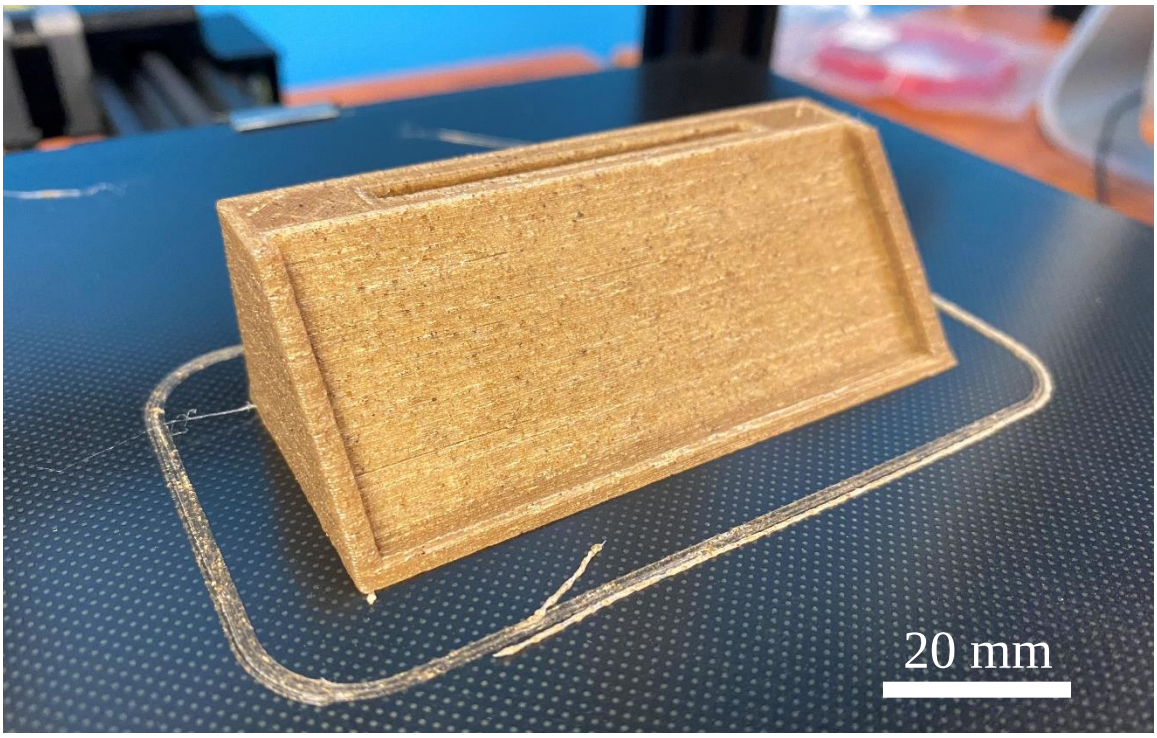

Figure 32. Successful aesthetic print from the additional Ender 3 printer for a part made from soybean husk fiber with PLA composite. No warping occurred, and final part has great mechanical strength and interfacial layer adhesion while handling. Scale bar shown to roughly illustrate the size of the printed part.

Similar experimental work to the work on sized carbon fiber composites was performed on a batch of regrinded nylon filled with glass beads and glass fibers, obtained from the Campbellsville, Kentucky manufacturing plant location of the Murakami Corporation. Tensile bars were printed at three different nozzle and bed temperature combinations, with a 0.4 mm nozzle, using otherwise identical process settings to the default profile for PLA for Creality Ender 3 series printers in the Ultimaker Cura slicer software. A modified Creality Ender 3 V2 was used to print the nylon-glass composite extrusions: the stock heater assembly was replaced with the Micro Swiss All Metal Hotend Kit to provide better durability protection from the abrasiveness of the glass and to promote better thermal conductivity through the material, and the heater cartridge was replaced with one with more wattage that had the power to heat to higher temperatures much quicker and maintain those higher temperatures during printing much easier. Dimensions of printed bars pre-testing are shown below, along with final images of the feedstock used and filaments obtained from feedstock, as well as the Minitab analyses. Filaments were extruded at three different temperatures, and ASTM D638 Type IV tensile bars (shrunk to 75% of the nominal size dimensions) were printed at three different printer temperature combinations for a multi-factor study.

Table 25. Measured dimensions of each nylon-glass composite tensile bar used before tensile testing.

Parameters	Width		Thickness		Total Length	
	Measured (mm)	Percent Difference from CAD	Measured (mm)	Percent Difference from CAD	Measured (mm)	Percent Difference from CAD
Filabot 220°C Nozzle 245°C Bed 60°C	5.04	5.66%	2.51	-19.36%	84.82	28.76%
	5	4.87%	2.45	-21.75%		
	5.15	7.82%	2.48	-20.55%		
Filabot 220°C Nozzle 260°C Bed 80°C	5.21	8.97%	2.5	-19.75%	N/A	N/A
	5.16	8.01%	2.24	-30.56%		
	5.18	8.40%	2.56	-17.40%		
Filabot 220°C Nozzle 255°C Bed 65°C	5.12	7.24%	2.37	-25.03%	84.97	28.94%
	5.04	5.66%	2.57	-17.02%		
	4.9	2.85%	2.4	-23.79%		
Filabot 230°C Nozzle 260°C Bed 80°C	4.98	4.46%	2.49	-20.15%		
	4.97	4.26%	2.47	-20.95%		
	5.09	6.65%	2.41	-23.38%		
Filabot 230°C Nozzle 255°C Bed 65°C	5.07	6.25%	2.82	-7.77%	N/A	N/A
	4.92	3.25%	2.86	-6.36%		
	4.88	2.44%	2.76	-9.92%		
Filabot 230°C Nozzle 245°C Bed 60°C	5.03	5.46%	2.45	-21.75%		
	5.09	6.65%	2.5	-19.75%		
	5.03	5.46%	2.45	-21.75%		

Figure 33. Raw regrinded feedstock material for the nylon, glass fiber, and glass bead composite obtained from the Murakami Corporation manufacturing plant in Campbellsville, KY.

Figure 34. Filament obtained from the nylon-glass composite feedstock that was extruded at 210°C. Surface finish is too rough to be usable for printing due to the glass fibers and glass beads protruding through the surface and not mixing well enough with the polymer.

Figure 35. Filament obtained from the nylon-glass composite feedstock that was extruded at 220°C. Surface finish is rough enough to cause skin injuries when handled roughly due to the glass fibers on the surface, but it is usable for printing.

Figure 36. Filament obtained from the nylon-glass composite feedstock that was extruded at 230°C. Surface finish is smooth but is still abrasive enough to cause skin injuries due to some of the glass fibers on the surface. It is completely usable for printing.

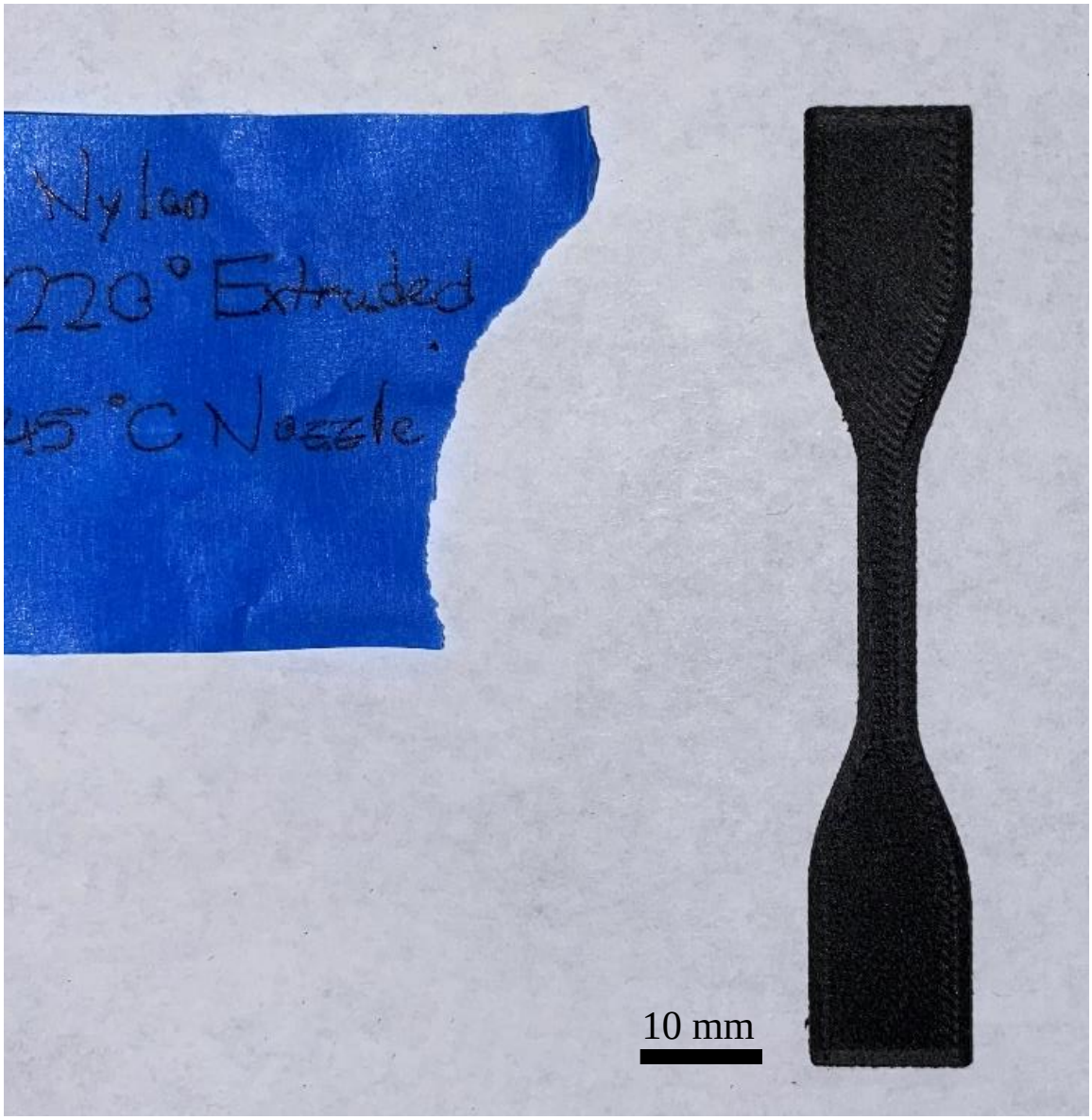

Figure 37. Tensile bar sample printed from nylon-glass composite extruded at 220°C, with a nozzle temperature of 245°C and a bed temperature of 60°C. Sample was printed on glass with hairspray used as an adhesive. Surface finish is smooth to the touch on the bottom, and visually smooth but rough to the touch on other surfaces exposed to air during the print process. All samples were visually similar to each other between factor levels. Scale bar shown to roughly illustrate the size of the tensile bar.

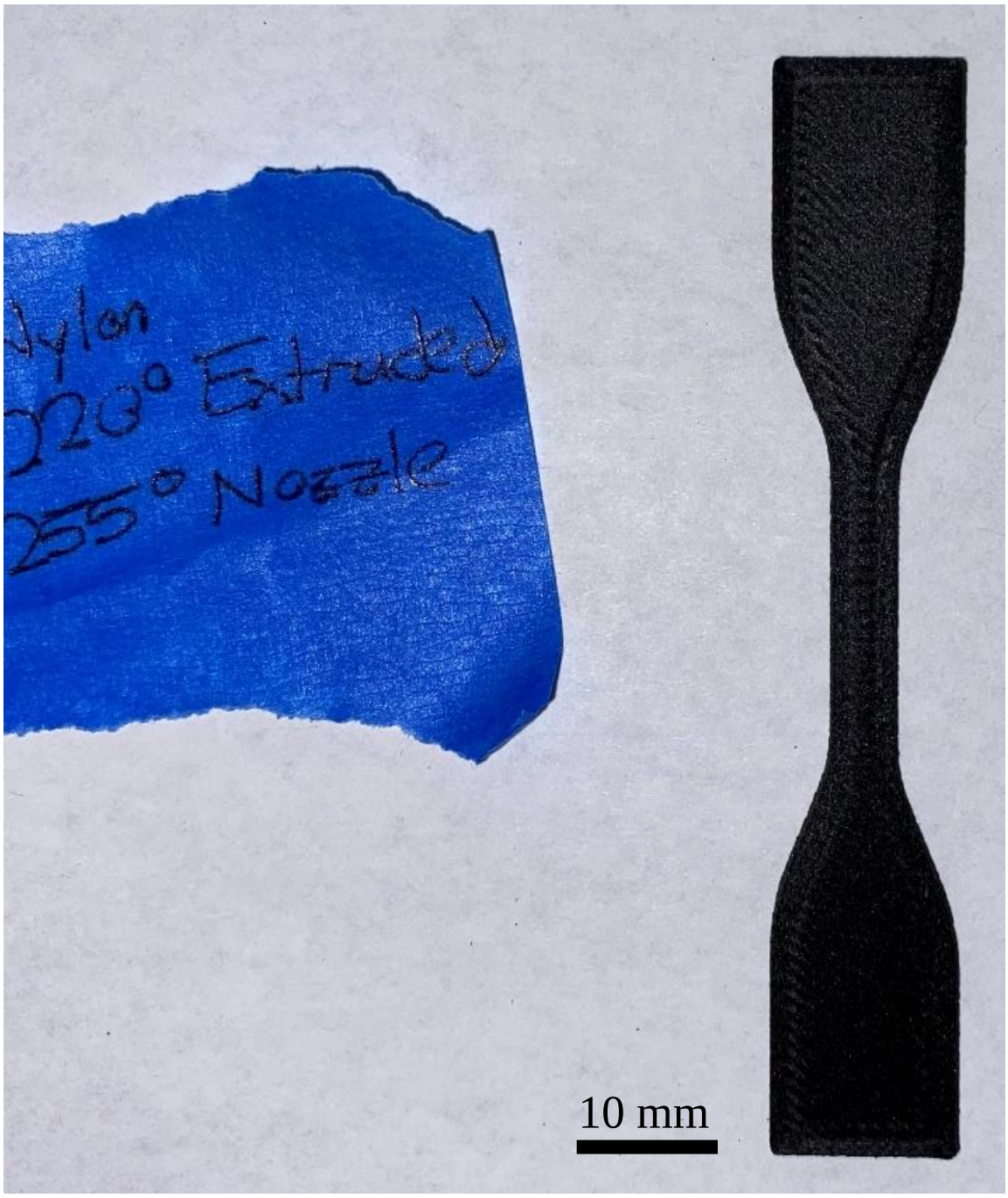

Figure 38. Tensile bar sample printed from nylon-glass composite extruded at 220°C, with a nozzle temperature of 255°C and a bed temperature of 65°C. Sample was printed on glass with hairspray used as an adhesive. Surface finish is smooth to the touch on the bottom, and visually smooth but rough to the touch on other surfaces exposed to air during the print process. All samples were visually similar to each other between factor levels. Scale bar shown to roughly illustrate the size of the tensile bar.

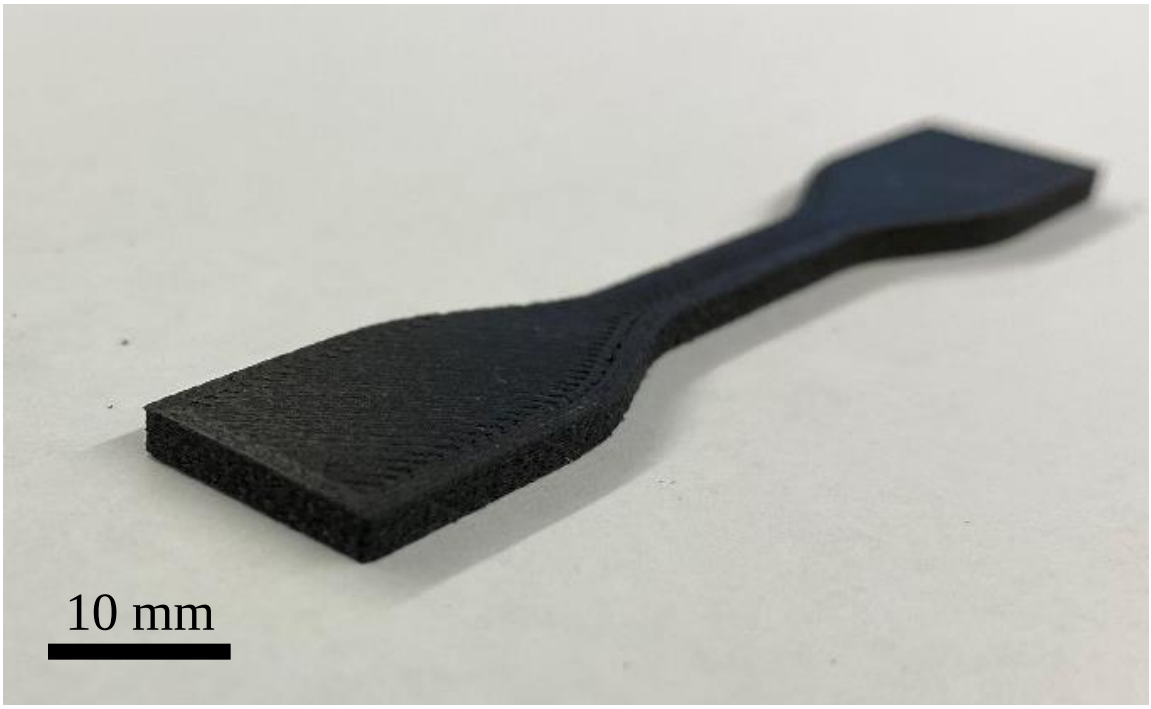

Figure 39. Close-up side view of one of the nylon-glass composite specimens printed. Visual smoothness and high aesthetic quality of the exposed print surfaces is readily apparent. Scale bar shown to roughly illustrate the size of the tensile bar.

Table 26. Tensile modulus data obtained across three replicates, with two outliers removed, for each factor level of nylon-glass composite tensile bar.

Extrusion Temp.	Nozzle/Bed Temp.	Tensile Modulus (GPa)	Standard Deviation (GPa)	Coefficient of Variance
220°C	245°C/60°C	1.41	0.022	1.55%
	260°C/80°C	1.71	0.234	13.66%
	255°C/65°C	1.46	0.128	8.79%
230°C	260°C/80°C	1.33	0.257	19.33%
	255°C/65°C	0.984	0.211	21.39%
	245°C/60°C	0.871	0.097	11.09%

Table 27. Yield strength data obtained across three replicates, with two outliers removed, for each factor level of nylon-glass composite tensile bar.

Extrusion Temp.	Nozzle/Bed Temp.	Yield Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variance
220°C	245°C/60°C	24.60	2.19	8.92%
	260°C/80°C	30.41	3.23	10.62%
	255°C/65°C	21.05	4.32	20.51%
230°C	260°C/80°C	21.39	4.70	21.98%
	255°C/65°C	18.96	2.62	13.84%
	245°C/60°C	22.74	3.78	16.62%

Table 28. Tensile strength data obtained across three replicates, with two outliers removed, for each factor level of nylon-glass composite tensile bar.

Extrusion Temp.	Nozzle/Bed Temp.	Tensile Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variance
220°C	245°C/60°C	38.91	2.03	5.21%
	260°C/80°C	48.64	3.52	7.23%
	255°C/65°C	39.56	4.56	11.52%
230°C	260°C/80°C	35.64	9.11	25.57%
	255°C/65°C	27.81	3.90	14.01%
	245°C/60°C	35.07	5.90	16.82%

Table 29. Percent elongation data obtained across three replicates, with two outliers removed, for each factor level of nylon-glass composite tensile bar.

Extrusion Temp.	Nozzle/Bed Temp.	Percent Elongation (%)	Standard Deviation (%)	Coefficient of Variance
220°C	245°C/60°C	5.476375	0.183675	3.35%
	260°C/80°C	5.974016667	0.498997856	8.35%
	255°C/65°C	7.73055	0.97935	12.67%
230°C	260°C/80°C	6.769716667	1.099368387	16.24%
	255°C/65°C	6.168483333	0.574967284	9.32%
	245°C/60°C	10.73988333	0.574967284	5.35%

Table 30. Conducted dual-factor Analysis of Variance on tensile modulus data for nylon-glass composite tensile bar samples tested (R^2 = 71.75%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Extrusion Temp.	1	8.34195E+17	8.34195E+17	14.81	0.003
Printer Temps.	2	4.43475E+17	2.21737E+17	3.94	0.055
Extrusion Temp.*Printer Temps.	2	1.64351E+16	8.21757E+15	0.15	0.866
Error	10	5.63108E+17	5.63108E+16		
Total	15	1.99324E+18			

Table 31. Grouping information for conducted pairwise comparison on Extrusion Temperature from statistical model of **Table 30** using Fisher LSD Method and 95% confidence. (Means that do not share a letter are significantly different.)

Extrusion Temp.	N	Mean (10^9)	Grouping	
220°C	7	1.53	A	
230°C	9	1.06		B

Table 32. Conducted dual-factor Analysis of Variance on yield strength data for nylon-glass composite tensile bar samples tested (R^2 = 54.89%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Extrusion Temp.	1	8.73467E+13	8.73467E+13	4.37	0.063
Printer Temps.	2	9.61350E+13	4.80675E+13	2.40	0.141
Extrusion Temp.*Printer Temps.	2	3.84218E+13	1.92109E+13	0.96	0.415
Error	10	2.00062E+14	2.00062E+13		
Total	15	4.43513E+14			

Table 33. Conducted dual-factor Analysis of Variance on tensile strength data for nylon-glass composite tensile bar samples tested (R^2 = 59.19%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Extrusion Temp.	1	3.65428E+14	3.65428E+14	7.58	0.020
Printer Temps.	2	1.94729E+14	9.73643E+13	2.02	0.183
Extrusion Temp.*Printer Temps.	2	5.41701E+13	2.70851E+13	0.56	0.587
Error	10	4.81894E+14	4.81894E+13		
Total	15	1.18085E+15			

Table 34. Grouping information for conducted pairwise comparison on Extrusion Temperature from statistical model of **Table 33** using Fisher LSD Method and 95% confidence. (Means that do not share a letter are significantly different.)

Extrusion Temp.	N	Mean (10^6)	Grouping	
220°C	7	42.57	A	
230°C	9	32.84		B

Table 35. Conducted dual-factor Analysis of Variance on percent elongation data for nylon-glass composite tensile bar samples tested (R^2 = 83.06%).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Extrusion Temp.	1	0.000867	0.000867	8.12	0.017
Printer Temps.	2	0.000816	0.000408	3.82	0.058
Extrusion Temp.*Printer Temps.	2	0.002898	0.001449	13.57	0.001
Error	10	0.001068	0.000107		
Total	15	0.006303			

Table 36. Grouping information for conducted pairwise comparison on Extrusion Temperature from statistical model of **Table 35 Table 33**using Fisher LSD Method and 95% confidence. (Means that do not share a letter are significantly different.)

Extrusion Temp.	N	Mean	Grouping	
230°C	9	0.0789269	A	
220°C	7	0.0639365		B

Table 37. Grouping information for conducted pairwise comparison on Extrusion Temperature * Printer Temperatures from statistical model of **Table 35 Table 33**using Fisher LSD Method and 95% confidence. (Means that do not share a letter are significantly different.)

Extrusion Temp.*Printer Temps.	N	Mean	Grouping	
230°C 245°C, 60°C	3	0.107399	A	
220°C 255°C, 65°C	2	0.077306		B
230°C 260°C, 80°C	3	0.067697		B
230°C 255°C, 65°C	3	0.061685		B
220°C 260°C, 80°C	3	0.059740		B
220°C 245°C, 60°C	2	0.054764		B

APPENDIX B: RESEARCH PROJECTS IN OTHER LABORATORIES

Additionally, work was done in the summer of 2021 to assist a Research Experience for Undergraduates (REU) student from Western Kentucky University with conducting a dielectrophoresis experiment in outer space aboard the International Space Station in collaboration with NASA, under the direction of Dr. Stuart Williams. Small glass capillaries whose thinnest dimensions were smaller than 0.2 mm were to be used to transport particles in colloidal suspension with a fluid over top of a belt-powered miniature desktop microscope whose objective lenses could be moved about a stage. 3D printed mounts were to be designed in SolidWorks and used to help suspend the glass capillary slides above the microscope while simultaneously being completely leak-proof and vibration-proof.

Many iterations of designs and print parameters of the desired capillary adapters were tested through the Ultimaker Cura slicing software used to print the tensile bars in the study of this thesis. The successful design for this application is shown below, fully installed with the microscope, and was manufactured on a personal Creality Ender 3 printer with a glass bed to guarantee dimensional accuracy of the cavity product's surface where the capillary is inserted. Interference-fit holes for a conductive pogo pin for use with conductive epoxy were printed on top, and current was successfully generated through the pin into the epoxy. This current was to be used to apply alternating electric fields at high frequencies to the samples inside the capillary tubes to effectively "trap" them in place, inducing the dielectrophoresis effect.

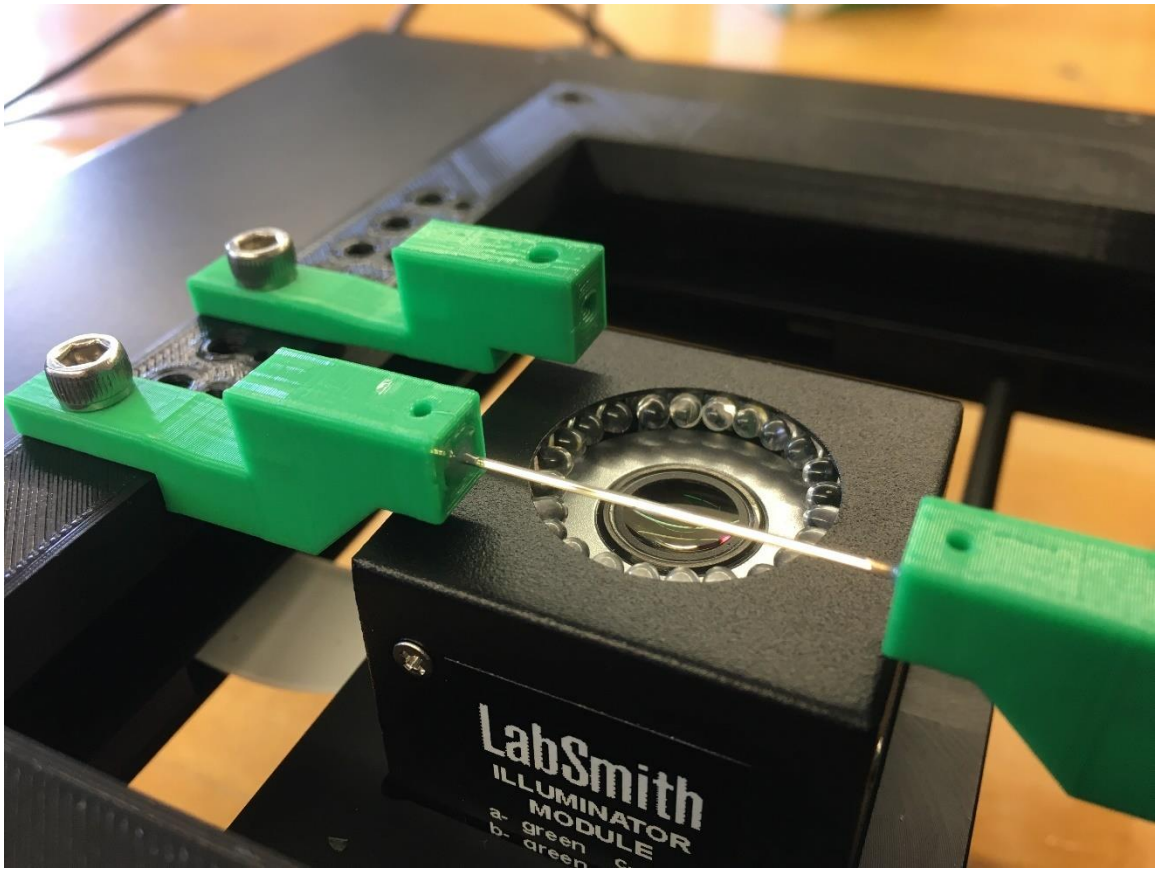

Figure 40. Leak-proof glass capillary mounts designed for a dielectrophoresis experiment in collaboration with NASA. Two-part epoxy was used to attach the glass capillaries to the printed products that were designed in SolidWorks, sliced in Ultimaker Cura, and printed on a Creality Ender 3 printer. Also pictured: black printed frame was designed in SolidWorks to mount the capillary adapters above the microscope via metric-sized screws from McMaster-Carr that were lined with Loctite.

CURRICULUM VITA & RESUME

NAME: Benjamin Mitchell

ADDRESS: 6340 Pond Lily St., Prospect, KY 40059

DOB: Los Alamitos, CA, USA – October 4, 1998

EDUCATION & TRAINING: B.S., Mechanical Engineering, University of Louisville (2017-21)

M.S., Mechanical Engineering University of Louisville (2021-22)

AWARDS: Mechanical Engineering Department Academic Achievement Award (2019)

Material Handling Systems Most Valuable Co-op (2019)

TRiO Student Support Services Senior of the Year (2021)

Student Achievement Mentorship Award (2021)

Robert C. Ernst Award (2021)

Lewis S. Streng Award (2022)

UofL Cardinal Marching Band Graduating Senior Award (2021)

PROFESSIONAL SOCIETIES:

Tau Beta Pi (2021-Present)

Benjamin Mitchell

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OBJECTIVE

To work for a company that offers fulfilling work that will advance my knowledge and expertise in fields relating to mechanical engineering, automation, or robotics, and provides opportunities to employ creativity in my solutions.

EDUCATION

University of Louisville, J.B. Speed School of Engineering — *Louisville, KY*

Master of Engineering/Mechanical Engineering GPA 4.0 May 2021-May 2022

Bachelor of Science in Mechanical Engineering GPA 4.0 Aug 2017-May 2021

PROJECTS

Master of Engineering Thesis in Mechanical Engineering May 2021-May 2022

- Explored sizing agent effects on interfacial adhesion within 3D-printed carbon fiber-reinforced ABS.
- Investigated the mechanical properties and sustainability of 3D-printed recycled glass fiber-reinforced nylon.

Capstone: Response of Microfluids in Microgravity Aboard the International Space Station Jan 2021-May 2022

- Communicated with NASA to refine research parameters and satisfy ISS protocol.
- Created SolidWorks prototypes of glass capillary holders and 3D printed them for testing.

Redbird Robotics Aug 2018-Mar 2020

- Independently researched optimal part and system designs for drones in team competition projects such as IARC.
- Created and 3D-printed parts for prototyping the team's designs.
- Facilitated a morning TV news segment featuring the team at the 2019 Louisville Maker Faire.

ENGINEERING EXPERIENCE

University of Louisville J.B. Speed School of Engineering *Louisville, KY Graduate Research Assistant*
Aug 2021-Present

- Provide expertise on 3D printing to partners in industry and fulfill 3D-printed prototype requests.
- Support Dr. Kunal Kate's laboratory research by assembling and customizing 3D printers, manufacturing composite polymer filaments from feedstock, and 3D printing with soy and fiber-based composites.

Material Handling Systems *Mount Washington, KY*
Mechanical Engineering Co-op Spring 2019; Fall 2019; Summer 2020

- Won "Most Valuable Co-op" company award in Spring 2019.
- Designed conveyor layouts in 3 different warehouses across the United States.
- Created, formatted, and revised construction-grade AutoCAD/Inventor installation drawings.
- Implemented conveyor railing/supports, implemented safety measures, and collaborated with other mechanical designers to meet critical project deadlines.
- Frequently collaborated with manufacturing to optimize quality control and assembly of conveyor components.
- Used Inventor and Vault to design and revise specialized parts to be manufactured for installation projects.
- Redesigned designer training modules for new hires while taking classes at UofL.

SKILLS/COURSEWORK

- 3D printing with self-owned Ender 3/Ultimaker Cura
- Autodesk Inventor/AutoCAD
- SolidWorks
- Fundamentals of Autonomous Robots
- Design of Experiments/Minitab
- LabVIEW
- Fluid Power Systems
- Mechanical Vibrations

ACTIVITIES & HONORS

- Robert C. Ernst Award
- Lewis S. Streng Award
- M.E. Dept. Academic Achievement Award
- UofL 2021 Cardinal Marching Band
- UofL 2021-2022 Cardinal Pep Band
- 2021 Student Achievement Mentorship Award

LICENSES & CERTIFICATIONS

- Lean Green Belt, ID #17949003
- Fundamentals of Engineering Exam (Pending registration)