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Development of Thermoplastic Composites for Fdm-Type 3d Printers

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Abstract

FDM – type 3D printing has greatly increased in recent years but there is still a demand for stronger and stiffer materials. The objective of this work is to extrude and test various types of thermoplastic composite filament to be used for 3D printing. ABS thermoplastics was combined with various lengths of fiberglass. Using these thermoplastic composites several specimens were prepared per ASTM D638 by compression molding and tested. The fiberglass was introduced to increase mechanical strength and stiffness of the thermoplastic filament. Three types of fiber sizing were evaluated, the original epoxy-based sizing, an alkoxysilane Gelest sizing, and a water-based Michelman sizing. One hundred specimens were fabricated from composite material. Specimens varied by sizing, by fiberglass lengths, and by fiberglass volume fraction. Out of all the specimens tested, those with Michelman sizing produced the most consistent and overall best bonding. The Gelest sizing produced the highest and lowest values. Epoxy sizing produced almost as good results, and no sizing was worst. FDM thermoplastic filament of 1.75 mm diameter was extruded, and was used on a ROBO 3D FDM printer to 3D print objects. Mechanical strength and stiffness were not improved as expected because fiber lengths were much shorter than advertised. Other possible reasons include incomplete mixing of materials, processing errors, voids in specimens, and improper treatment of fibers with sizing.

Key words*:* FDM 3D Printer – Fused Deposition Modeling type 3D printer, 3D printer Filament, Thermoplastic Material, ABS Fiberglass, Extrusion, Sizing.

1. Introduction

Extruders are used to produce plastic products such as flexible pipes and plastic sheets. They can also be used to mix materials. Basically, extrusion is a process of applying heat and pressure to melt a polymer and force it through an orifice in a continuous process. It is used to produce polymer products of uniform shape and density. Extruder used to mix different polymers with additional materials like pigment, fillers, reinforcers etc. Melting is accomplished by frictional heating within barrel as material undergo shearing between screw barrel set up. Because the barrel is generally heated with heaters mounted around it. The barrel section temperature is optimized so that the viscosity of the melt is low enough to allow conveying down the barrel and proper mixing. Figure 1 shows a general extruder setup with single screw. Most extruders are electrically heated with either band-type resistance heaters, cast-in block heaters or tubular resistance heaters wrapped around the barrel. An efficient barrel cooling system is important to control the tendency for mechanical shear heat developed in the melt to override the electrical heater controls. The optimal extruder barrel length for extruder is 30-32 times its internal diameter (30:1 L/D, 32:1 L/D). Although shorter barrels can be used, mixing efficiency and melt uniformity are not optimal. Cooling to the extruder feed throat is critical to prevent surging or bridging. Internal cooling to the screw is not needed [1]. The objective of this paper is to study mechanical properties of thermoplastic material used in 3D printer and enhanced its Mechanical properties by adding various filling material as well as sizing materials to make it much more stronger and cost effective.

2. Discussion And Comparison

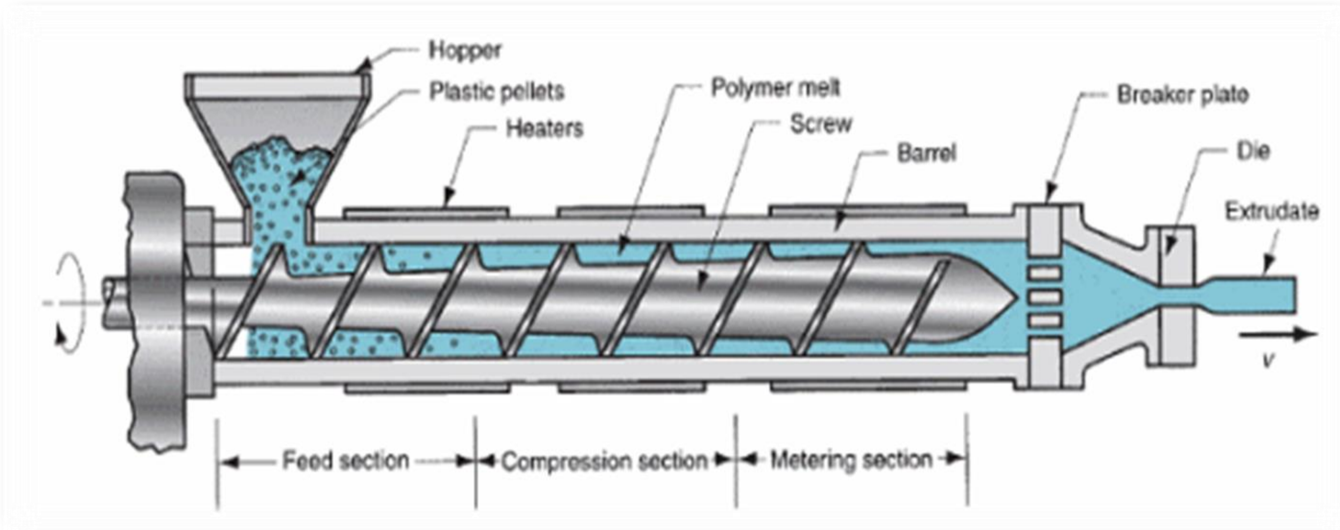

Figure 1. Components and features of an extruder for plastics and elastomers [2].

Material flow in single screw extruders is driven by the properties of the material. Depending on the material being fed, a different screw can be used to handle the new material. Single screw extruders are popular and can handle some of the toughest materials. The single screw extruder pictured as shown in Figure 1 comes with a flame-hardened screw for handling abrasion and corrosion. In single screw extruders, a screw mixer melts the entering plastic materials, pushes the material through the extruder, and forms the plastic into the desired shape [3].

Extruders have three key components [3],

(a) The hopper, where material is fed to the extruder.
(b) The screw, which runs along the length of the machine.
(c) The optional static mixers at the end.

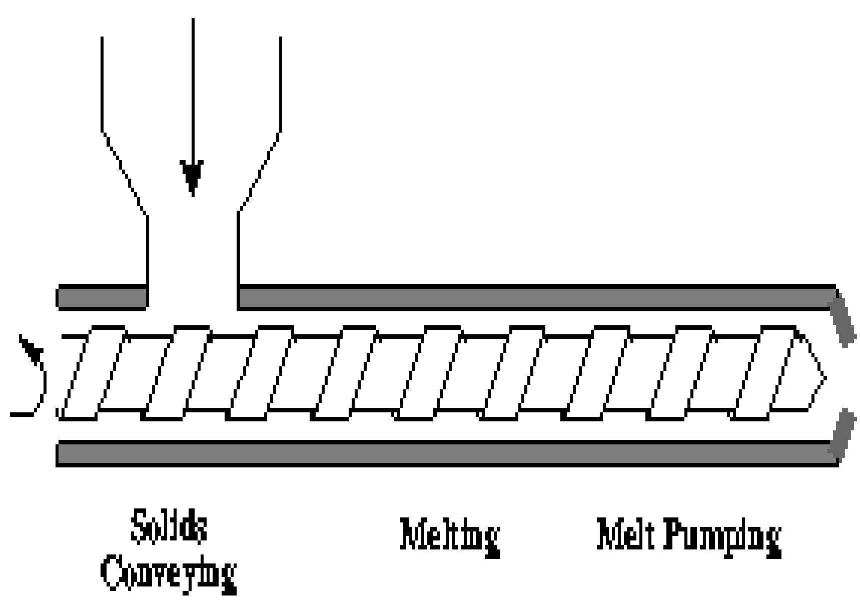

Figure 2. Single screw extruder [3].

Figure 2 shows single screw extruder set up. Single screw extruders rely on the friction between the material and the barrel for flow: the greater the friction, the slower the flow. One way to increase friction is to increase the length of the barrel, but this could result in a change in viscosity with position. The extruder temperature can be adjusted to control the viscosity [3].

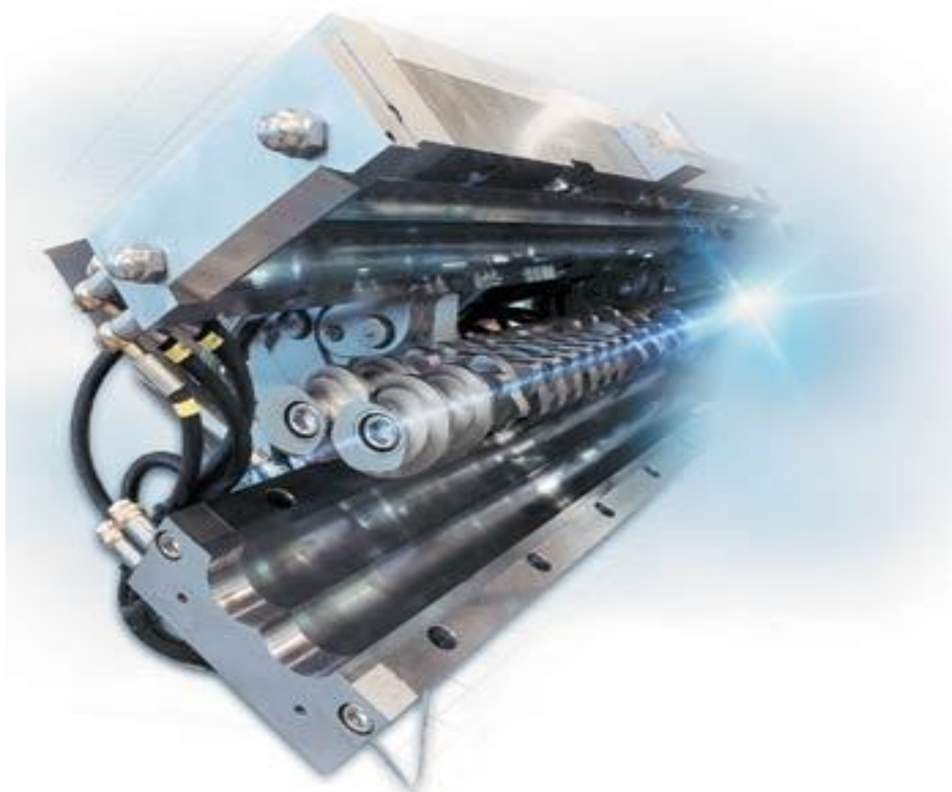

Figure 3. Twin screw extruder [3].

Figure 3 shows the setup of twin screw extruder. Not all extruders with two screws are twin screw extruders. Screw placement and type are also important determinants. Twin screw extruders have two intermeshing screws and operate in the same manner as a single screw extruder. The picture shows the barrels of the extruder exposed. Twin screw extruders depend minimally on the friction of the material against the barrel to move forward. They rely instead on the properties of the extruder and the screws. Meshing characteristics and type of rotation are the two most key features of twin screw extruders. Intermeshing screws can engage each other fully, partially, or not at all. Non-intermeshing twin screws would operate as parallel single screw extruders, and the flow would be governed by material properties. Nonconjugate screws are those in which there is ample clearance between the two screws. Conjugated screws result in minimum clearance and narrow flights. In counterrotating screws, a travel between screws rotating in opposite directions. In corotating screws, two streams of material travel in parallel along two screws rotating in the same direction. In additive manufacturing process such as FDM 3D printing, the building material is 3D printer filament. This 3D printer filament is produced using extruders. Apart from using large commercial extruder for making filaments, some private individuals have developed desktop extruders to produce filaments which termed as “Filament Extruder” as shown in Figure 4 [3].

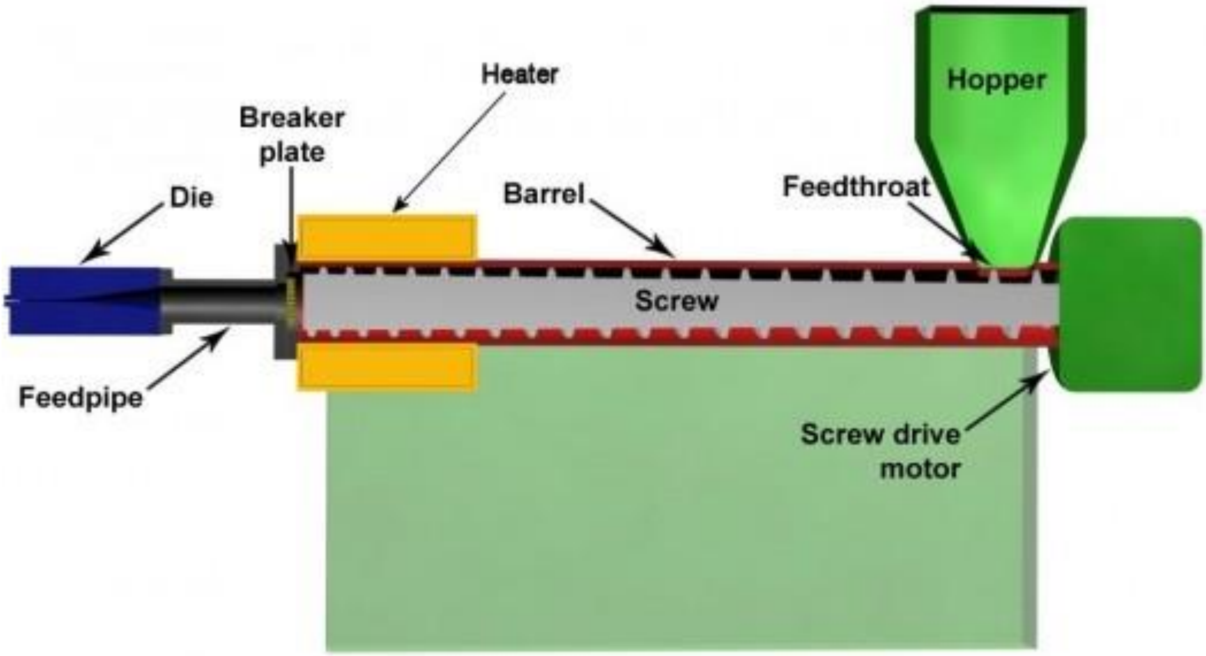

Figure 4. Filament extruder layout [3].

The main part of the extruder is a barrel containing a screw (auger), which is encased by a heater towards its far end. On the other end, the screw is connected to an electric motor which will, via mechanical action, transport thermoplastic pellets through the barrel towards the heater. Pellets are gravity-fed continuously from a hopper. As the motor is continuously driving the auger, the resin pellets are pushed into the heater. The thermoplastic pellets will soften and melt because of the heat and are then pushed mechanically through a die. Pushing the soft thermoplastics through the die will cause it to form a continuous filament strand with the diameter of the die. The filament is passed through a water bath and cooling fan which cool the filament and is pulled by a puller at constant speed. After that a filament winder is used to make a spool. This process is called extrusion. In most filament extruder, two diameters of filaments are produced, either 0.069 inch (1.75 mm) or 0.112 inch (2.85 mm) [3].

The most common FDM 3D printing filament materials are ABS and PLA. Reinforced thermoplastic materials also used to make 3D printing filaments. ABS and Fiberglass can be combined to making reinforced thermoplastic filament. Carbon fibers or CNT can also be used as reinforcement. W. Zhong shows a method.

The most common FDM 3D printing filament materials are ABS and PLA. Reinforced thermoplastic materials are also used to make 3D printing filaments. ABS and Fiberglass can be combined to make reinforced thermoplastic filament. Carbon fibers or CNT can also be used as reinforcement. W. Zhong shows a method to make reinforced FDM 3D printing filaments [4]. For example, ABS were selected as raw material due to its ready availability in the market and good balance of processing and performance properties. Its softening point is approximately 212 F (100°C), which could meet the heat-resistance requirement of the FDM parts. ABS begin to flow at about 392 F (200°C). So, the part-building temperature cannot be too high. ABS begin to decompose at approximately 482 F (250°C). Thus, there is a difference of 122 F (50°C) between the flowing and decomposing temperature. This makes the heating temperature range wide enough to allow for a wide processing window in which the material can be heated to flow properly without decomposing. Pure ABS exhibits excessively large shrinkage, resulting in less-than-satisfactory part accuracy. To improve the mechanical properties of ABS, glass fiber was added as a reinforcement. Compared with pure ABS, the strength and stiffness of glass fiber reinforced ABS composite were increased, and both the softening temperature and the heat distortion temperature were increased as well. Also, shrinkage was decreased and the surface rigidity was improved, but the surface toughness was reduced. These are issues to consider in polymer composite extrusion, whether for FDM or injection molding, such as force required for extrusion/injection and tool wear caused by glass fibers. An increased fiber content in a thermoplastic composite will increase the forces required for extrusion/injection and will increase the tool wear rate, so the determination of an appropriate fiber content in the filament for FDM must strike a compromise between processing difficulty and performance characteristics of the resulting composites [4].

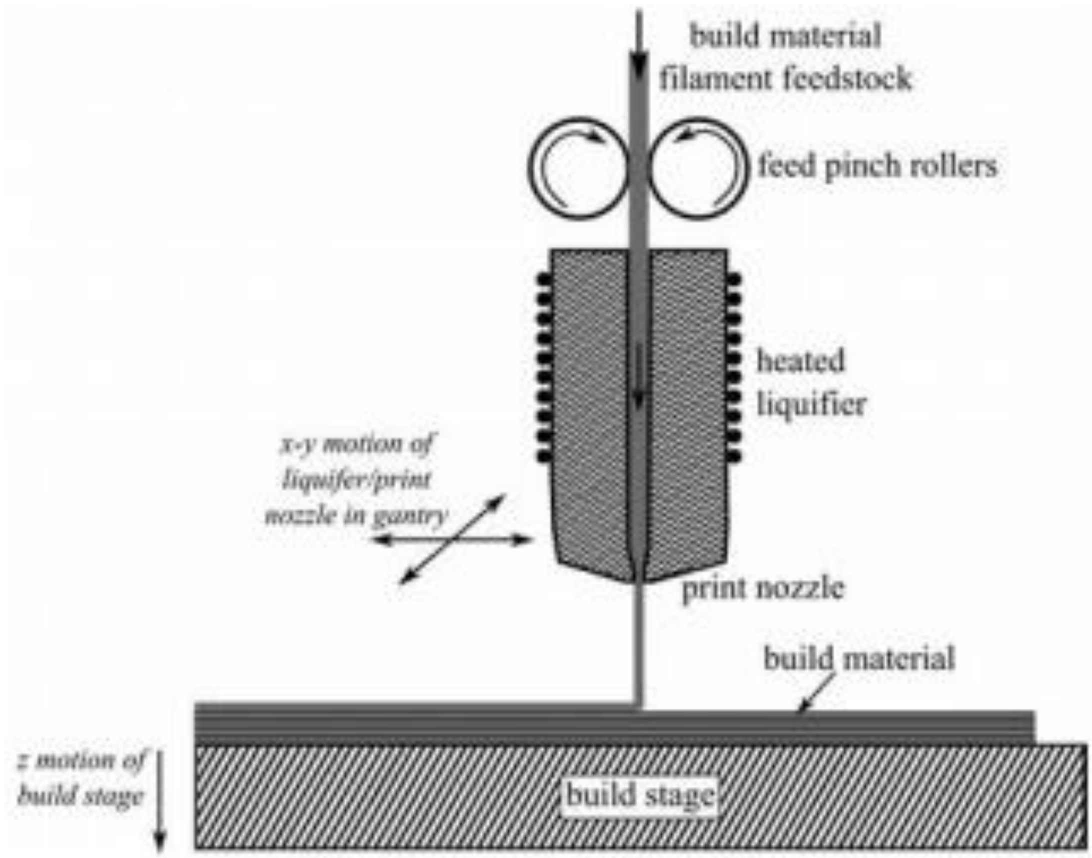

Figure 5. Extrusion based AM process [7].

A. General Overview of the FDM 3D Printing Process

Fused deposition modeling (FDM) is an additive manufacturing technology commonly used for modeling, prototyping, and production applications. It used in variety of applications like aerospace, automotive, marine and construction industries. Additive manufacturing (AM) is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [5]. For FDM, several types of thermoplastic filaments are used. 3D printing filament is a very fine thread or threadlike structure. ABS is widely used filament for 3D printing. It melts consistently at around 437 F (225°C), relatively strong, a little flexible and has a relatively high "glass transition temperature" of around 212 F (100°C). That is the temperature above which a plastic goes from its solid state to a pliable state where it can lose its shape. These characteristics mean ABS is very suitable to 3D Print functional parts, like spare parts for machines or objects that are exposed to elevated temperatures like sunlight or hot water. To increase strength and stiffness of filament several types of fibers like fiber glass, carbon fiber and carbon nanotubes used to make reinforced thermoplastics [5]. "Composite material refers to bonding between two or more homogeneous materials with different material properties to derive a final product with certain desired material and mechanical properties" [6].

Key elements of a FDM type 3D printing extrusion system include a material feed mechanism, liquefier and print head, gantry, build surface and build environment. Components of a generic system as illustrated in Figure 5. For 3D printing, generally 0.0689-inch (1.75 mm) or 0.1181-inch (3.00 mm) diameter filaments are used. The filament is pushed through the system using a pinch roller mechanism. One or both rollers may have a grooved or toothed surface like a gear to create sufficient friction for the roller to grab the filament and feed it to the liquefier without slippage. The basic process of 3D printers has several steps such as first CAD geometry is prepared and converted into a STL file format & the STL file is imported in a 3D printer software, which will generate G-codes and runs the 3D printer. A Larger nozzle diameter creates faster parts and a smaller nozzle creates finer details [7].

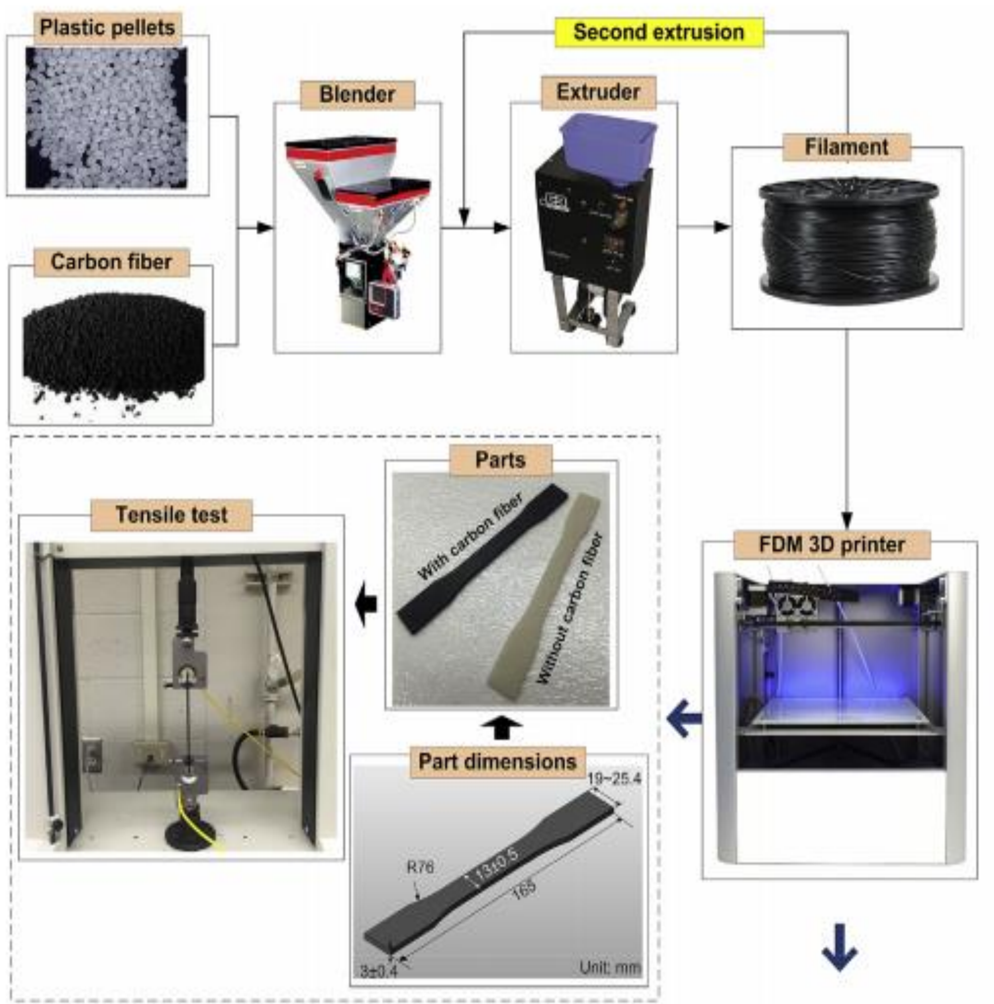

Figure 6. Set up of fabrication test procedure for carbon fiber/ABS [8].

Ning F. and Cong W. explain the entire fabricating process of thermoplastic matrix CFRP composites as shown in Figure 6 [8]. The raw materials used in this paper were virgin ABS thermoplastic pellets and carbon fiber powder. The carbon fiber powder had two different average carbon fiber lengths, 0.006 inch (0.15 mm) and 0.004 inch (0.10 mm), with a common fiber diameter of 0.00028 inch (0.007 mm). The pellets and carbon fiber powders were mixed in a blender with varying carbon fiber contents (3 wt%, 5 wt%, 7.5 wt%, 10 wt%, and 15 wt%) [8].

A plastic extruder was used to fabricate the carbon fiber filled filaments. During the extrusion processes, extrusion temperature, filament yield speed, and nozzle diameter were set at 428 F (220°C), 79 in/min (2006 mm/min), and 0.1122 inch (2.85 mm), respectively. The filaments could be cut into small pieces and re-fed in the extruder for a second extrusion to increase bulk density, which led to more consistent flow rates and fusion on each layer. During such process, filaments with more homogeneous distribution of carbon fibers could be obtained, thereby improving the FDM fabrication process and parts performance. The ASTM D638-10 and ASTM D790-10 standards were followed for tensile test and flexural tests, respectively. Five thermoplastic matrix CFRP composite specimens of each sample were prepared by FDM for both tests. Typical tensile strain stress curves with varying carbon fiber contents are illustrated in Figure 7. With the increase of carbon fiber content from 0 wt% to 5 wt%, tensile strength firstly increased, and then decreased with the levels of carbon fiber content increasing from 5 wt% to 10 wt% (especially when the carbon fiber content increased from 7.5 wt% to 10 wt%, a sharp reduction of tensile strength occurred) as shown in Figure 8 [8].

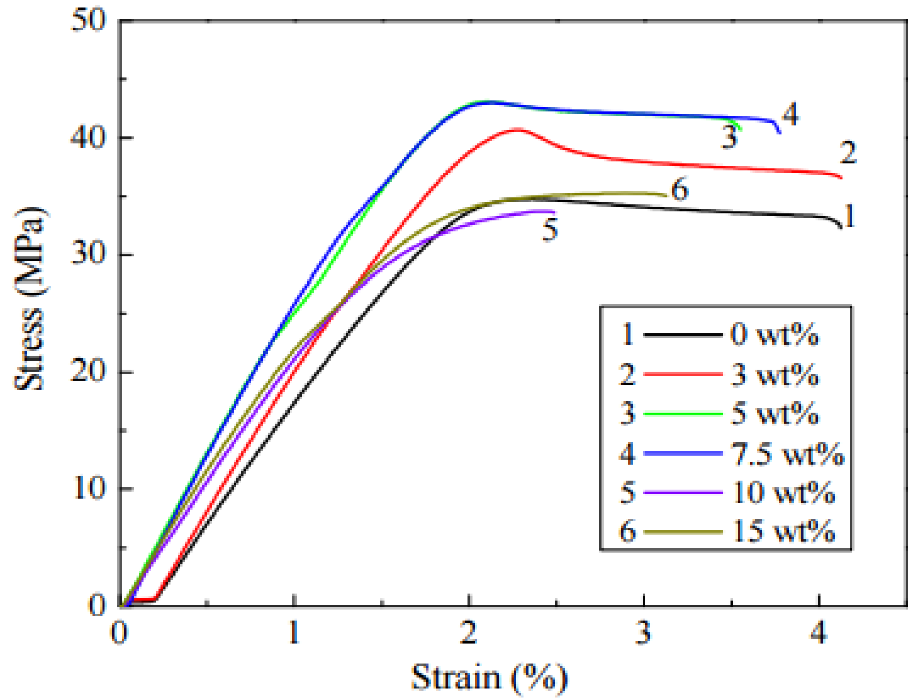

Figure 7. Ning-Cong tensile strengths of carbon fiber/ABS as function of %wt of CF [8].

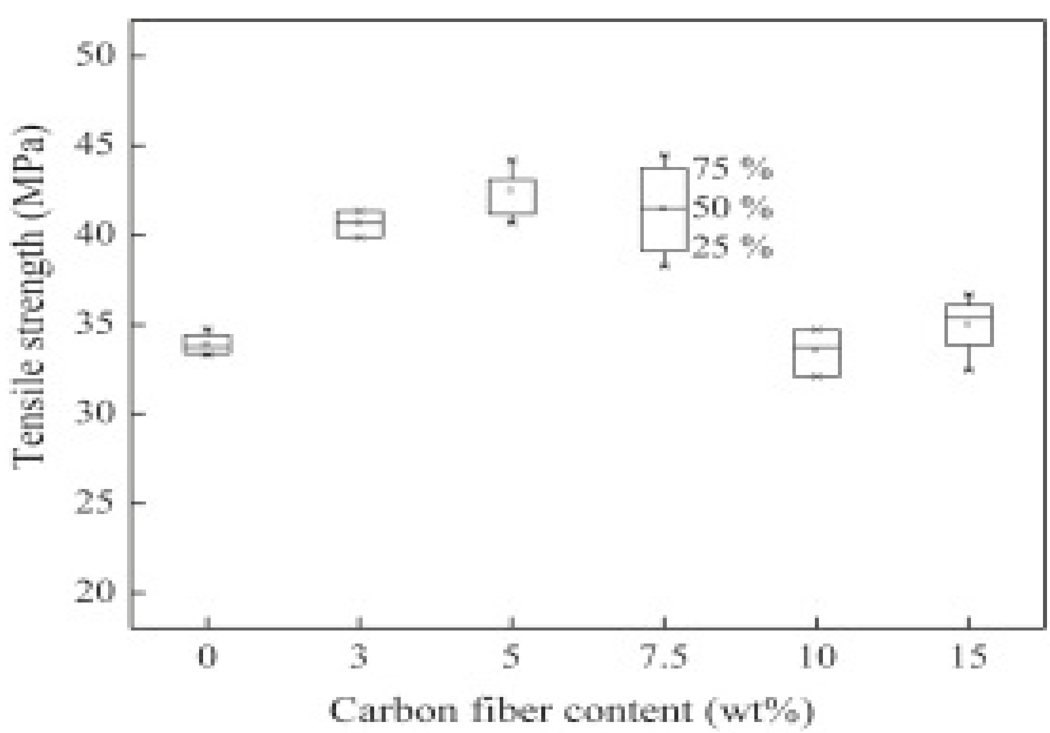

Figure 8. Ning-Cong tensile strengths of carbon fiber/ABS as function of %wt of CF [8].

After an increase of Young's Modulus with an increase of carbon fiber content from 0 wt% to 7.5 wt%, there was also a sudden decrease in Young's Modulus when the carbon fiber content increased from 7.5 wt% to 10 wt%, as shown in Figure 9. Continuing increase in carbon fiber content to 15 wt% resulted in Young's Modulus increasing again [8].

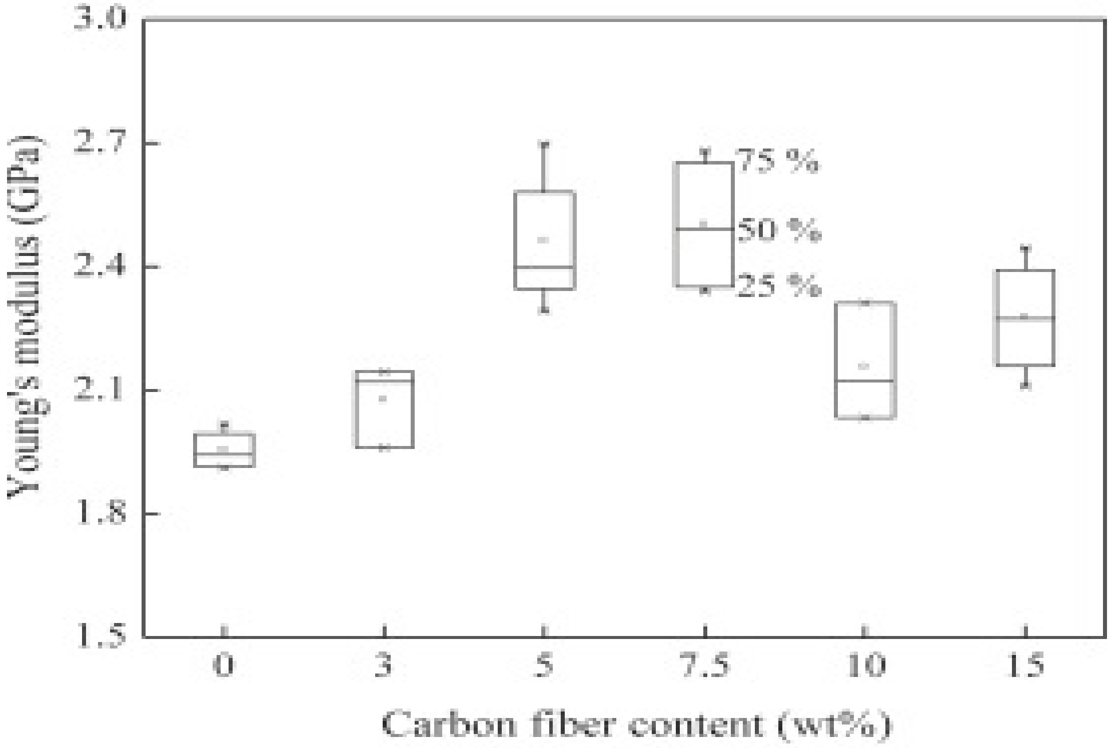

Figure 9. Young's Modulus result of CF/ABS specimen as function of % wt CF [8].

CFRP composite filaments were firstly prepared from carbon fiber and ABS by extrusion processes. Experimental investigations on if adding carbon fiber (different content and length) into ABS plastic can improve the mechanical properties of FDM fabricated parts have been conducted. After testing specimens, their conclusions were as follow [8].

1. Compared with pure plastic specimen, adding carbon fiber into plastic materials could increase tensile strength and Young's Modulus, but may decrease toughness, yield strength, and ductility.
2. Specimen with 5 wt% carbon fiber content had the largest mean value of tensile strength and specimen with 7.5 wt% carbon fiber content had the largest mean value of Young' Modulus. The tensile strength and Young's Modulus of fabricated specimen with 5 wt% or 7.5 wt% carbon fiber content could increase 22.5% and 30.5%, respectively [8].

Strength of fiberglass is almost as high as carbon fiber, so for strength intensive applications fiberglass is a good and cheaper choice. Fiberglass has 1/10th price of carbon fiber. Also, fiberglass is 30 times stiffer than ABS. Figure 10 and Figure 11 represents the comparison of tensile strength and tensile modulus for neat ABS, CF-AS 4 and GF-E type respectively.

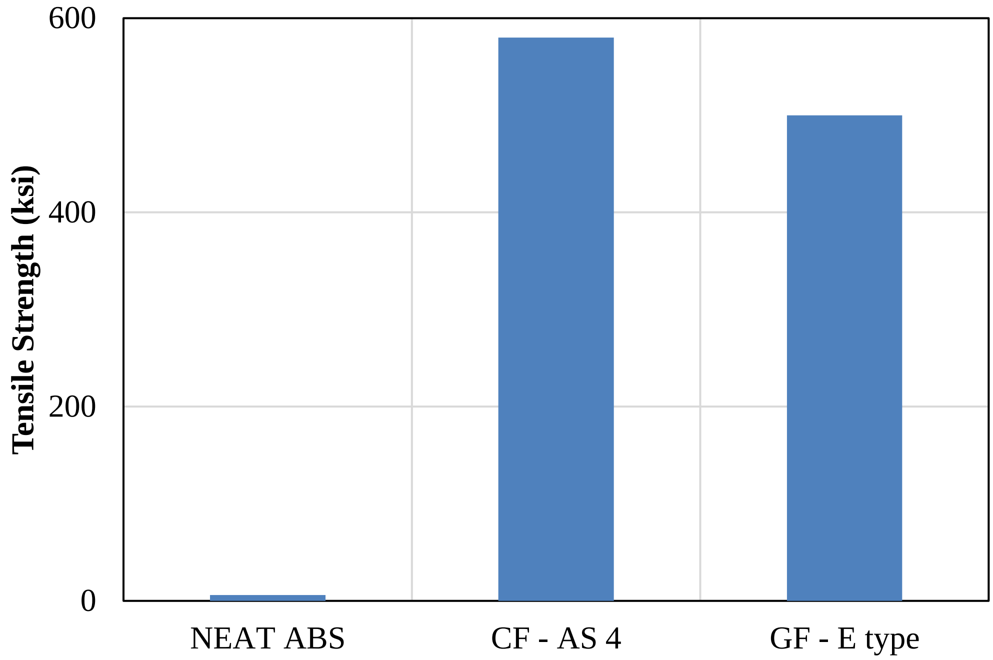

Figure 10. Tensile strength comparison for neat ABS, CF-AS 4 and GF-E type [9].

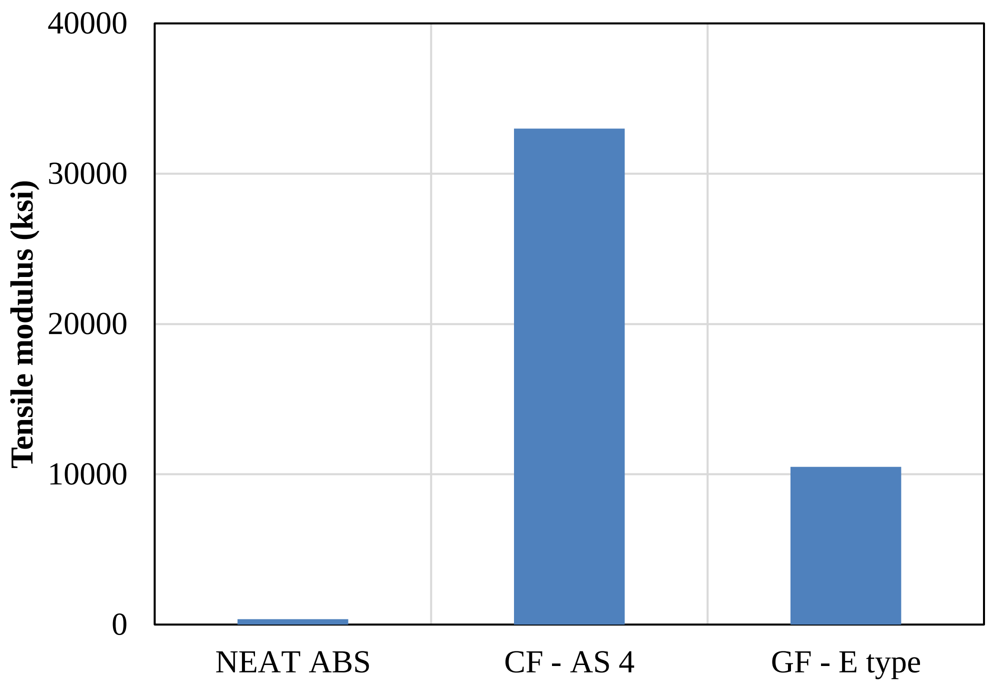

Figure 11. Tensile modulus comparison for neat ABS, CF-AS 4 and GF-E type [9].

Research Objectives

The primary objective of this work is to create reinforced thermoplastic composite filaments for 3D printing. Varying the amount of fibers such as glass fiber with ABS material. Specifically, the tasks to complete these objectives are:

1. Apply several types of sizing to chopped fibers, mix with ABS and determine which sizing is best for our use.
    a. Mix sized and un-sized fibers with ABS.
    b. Fabricate and test dog bone specimen. All material should have same volume fraction. The various configurations of the test specimens are listed in Table 1.

Table 1. Test specimens configuration for ABS/FG.

ABS	%V_f FG	Fiber Length
Without Fiber	10%,15%,20%	
Unsized Fiber – Acetone Treated	10%,15%,20%	FG 1-16, FG 1-32
Sized Fiber – Michelman	10%,15%,20%	FG 1-16, FG 1-32
Sized Fiber – Gelest	10%,15%,20%	FG 1-16, FG 1-32
Sized Fiber - Epoxy	10%,15%,20%	FG 1-16, FG 1-32

c. Using best sizing, extrude filament with fiber and thermoplastic at various volume fraction.

d. 3D Print dog bone specimens from filament and test.

3. Fabrication Of Specimens & Testing

A. Fabrication Process

The importance of various extrusion parameters such as die swell, extrusion speed, puller speed, type of material, temperature, and viscosity were discussed. So before making 3D printer filaments, we need to evaluate the mechanical properties of our filled composites. Various thermoplastic composite specimens were made from ABS and chopped fiberglass. It includes the application of sizing on fiberglass, proper mixing of ABS matrix with fiberglass, and the fabrication of tensile dog bone specimens. It also includes the determination of chopped fiberglass dimensions, and actual fiber volume fractions.

Two different lengths of E-type chopped fiberglass were used. They are identified as FG 1-16 and FG 1-32. Initially, we used chopped fiberglass which had an advertised length of 1/32 inch but we determined after microscopic examination that it was actually not 1/32 inch but was much shorter. It was then termed FG 1-32. We ordered another set of chopped fiberglass. It had an advertised length of 1/16 inch, but after measurement of its length we concluded that the average length of it was also shorter than advertised length. Thus, it was termed FG 1-16. Fiberglass with 1/8 inch length was termed FG 1-8. We should have used actual 1/16-inch and 1/32-inch fiberglass for this work, but due to time constraints we were unable to do so.

The fabrication process includes mixing of an ABS polymer matrix and fiberglass that has the proper sizing. It is then pressed in an ASTM D638 aluminum mold to make tensile dog bone specimens. The specimens varied by sizing, fiberglass volume fraction, and fiberglass length. Four specimens were fabricated for each material configuration. Table 2 shows the various specimen configurations for ABS with fiberglass to make thermoplastic tensile dog bone specimens. To summarize there are 4 neat ABS specimens, 24 specimens total of ABS with two unsized fiberglass lengths and three fiberglass volume fractions,24 specimens total of ABS with two Michelman- sized fiberglass length and three fiberglass volume fractions, 24 specimens total of ABS with two Gelest-sized fiberglass lengths and three fiberglass volume fractions, and 24 specimens total of ABS with two epoxy-sized fiberglass length and three fiberglass volume fractions. The total number of specimens were 100.

Table 2. Test specimen configurations for ABS/FG.

Material	V_F of FG (%)	Fiberglass length	#Specimens
ABS Without Fiber	0%		4
ABS/Unsized Fiber	10%, 15%, 20%	FG 1-16, FG 1-32	24

ABS/Sized Fiber – Michelma n ABS/Sized Fiber – Gelest ABS/Sized Fiber – Epoxy Sizing	10%, 15%, 20% 10%, 15%, 20% 10%, 15%, 20%	FG 1-16, FG 1-32 FG 1-16, FG 1-32 FG 1-16, FG 1-32	24 24 24

The standard procedure to apply sizing on fiberglass is summarized in the following section. First, the current sizing is removed using acetone. A water-based HP3-02 sizing from Michelman or an alkoxysilane based SIM 6487.5 sizing from Gelest were then applied. The solution is applied on the chopped fiberglass surface by immersing the fiberglass in the solution for 15 hours. The ratio of water or isopropyl alcohol and sizing was critical to make proper solution, so take care to add the right fraction of each part. To avoid fiberglass clumping, use a shallow pan to soak chopped fiberglass in solution and make a thin layer as shown in Figure 12 ensuring that as the fibers dry, that they don't clump. The fibers were heavier than the solution thus they didn't float in the solutions. Sizing must be diluted in required quantity as recommended by the company because too much or too little sizing may create fiberglass clumping.

Figure 12. Loose FG 1-32 with Michelman Sizing in a shallow pan.

Other methods to apply sizing on fiberglass include vapor phase deposition, spin on, and spray application. For a vapor phase deposition, sizing can be applied to substrates under dry aprotic conditions by chemical vapor deposition methods. These methods favor monolayer deposition. In the spin on method, these applications can be made under hydrolytic conditions which favor maximum functionalization and poly layer deposition or dry condition which favor monolayer deposition. The most widely used application method is the spray method. This method widely used for continuous fiberglass. They involve alcohol solutions and continuously hydrolyzed aqueous solutions employed in architectural and masonry applications" [10].

ABS and chopped fiberglass must be mixed together to make a homogeneous mixture such is essential to provide consistent mechanical properties, and to eliminate the clogging. For a better mixture of fiberglass and ABS matrix, make a thin ABS layer on heated press plate and scatter fiberglass uniformly onto it. Now, fold and press it in heat press for 8-10 times to mix it evenly. Then shred it in the heavy-duty shredder.

Figure 13. Heavy Duty shredder used to make small granules.

Thermoplastic specimens were fabricated to determine tensile stress, tensile Modulus, and strain at break. For plastics, the ASTM D638 test method should be used. It helps in making better 3D printing filaments with optimum mechanical properties. An ASTM D638 mold was designed and fabricated by Panchal [11], who fabricated thermoplastic composite tensile test specimens for his project work. For fabrication of specimens, the mold must be cleaned with acetone and paper towel. Frekote WOLO mold release is applied to the aluminum mold and it is dried for 10-12 minutes in an oven at 320°F (160°C). A weighted amount of ABS/FG pellets is placed into the lower part of the mold as shown in Figure 21. Insert upper half of the mold properly and place it in heat press as shown in Figure 22 at 380°F (181°C) temperature and 10,000 to 11,000 lbs. force for 15-18 minutes. The mixture will have filled the cavity and produce dog-bone specimen.

After the dog-bone specimen is removed from an aluminum mold, it is place in front of a fan to cool down for 10-15 minutes. Figure 16 shows some thermoplastic specimens from the mold.

Figure 14. ASTM D638 Aluminum mold

Figure 15. Heated press for compression molding.

Figure 16. Thermoplastic specimens from an ASTM D638 mold using compression molding.

The quality of specimens should be better to tensile test it. Specimens should have similar thickness to get consistent tensile test result. Feed enough material in mold to get perfect specimen without voids. Some post processing steps include remove flashing of specimens using utility knife.

B. Testing Of Specimens

The fabricated specimens were tested under tension with a MTS Universal Testing Machine. All the tensile tests were conducted according to ASTM D638, which is the standard test method for tensile testing of plastics. For testing, an MTS 632.26E-43 model extensometer, which has a gauge length of 0.5 inches, was used to measure actual strain in the specimens. An MTS load cell with a 5 kN load capacity was used in tensile testing, as it was more accurate, compared to a larger load cell with 100 kN load capacity. MTS wedge grips were used to hold the specimen during testing. The grips and extensometer used in the tensile tests are shown in Figure 17. Figure 18 show some of the tested specimens. Width and thickness of each specimen was measured using a digital caliper to determine cross-sectional area of specimen. The tests were carried out with a grip separation of 4.5 inches, at a test rate of 0.2 in/min. The load frame used in the current work is a MTS model C45 universal testing machine. The load and displacement were converted into stress and strain respectively.

A shortened notation used for the specimen configuration is as follows:

ABS – XX – YY – FG – ZZ – n

Where: ABS = ABS thermoplastic,
XX = sizing type; US = Unsized,
ES = Epoxy Sizing,
MS = Michelman Sizing,
GS = Gelest Sizing.
YY = Fiber volume fraction; 10%, 15%, and 20% by volume,
FG = Fiberglass,
ZZ = Advertised fiberglass length; 16 = 1/16 inch,
32 = 1/32 inch,
08 = 1/8 inch.
and n = the specimen number. For example, ABS-ES-10-FG-32-1 means ABS thermoplastic, epoxy sizing with 10% fiber volume fraction, has an advertised fiber length of 1/32 inch and is specimen number 1.

Figure 17. MTS Grips and Extensometer setup.

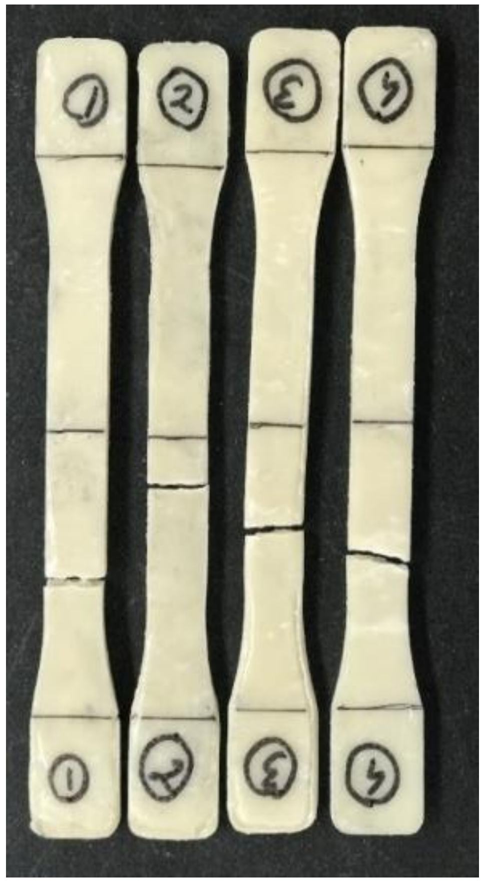

Figure 18. Tested Composite Specimens.

Table 3 shows data from neat ABS specimens which gives tensile strength, stiffness, failure strain and standard deviation for each specimen. S defined as tensile stress, E defined as Young's Modulus and ε_f defined as failure strain.

Table 3. Test summary of neat ABS specimens.

Specimen Configuration	Specimen #	S (psi)	E (psi)	ε_f (in/in)
Published ABS	-	6670	355,000	0.180
ABS Only	1	6155	451,826	0.018
	2	5254	345,093	0.048
	3	3917	279,261	0.013
	4	4085	391,371	0.011
Average, Std. Dev.		**5165±1038**	**396,096±55,018**	**0.027**

Table 4. Test summary of ABS/FG 1-32 without sizing

Specimen Configuration	Specimen #	Actual (V_f)	S (psi)	E (psi)	ε_f (in/in)
10% Fiberglass	1		2735	257,284	0.017
	2		3103	270,434	0.023
	3		2552	341,923	0.008
	4		2221	297,647	0.009
Average, Std. Dev		**0.097**	**2652±367**	**291,822±37,391**	**0.014**
15% Fiberglass	1		2140	351,752	0.026
	2		3500	309,445	0.019
	3		3215	387,038	0.012
	4		3771	371,877	0.015
Average, Std. Dev.		**0.146**	**3156±714**	**355,028±33,650**	**0.015**
20% Fiberglass,	1		2639	453,548	0.012
	2		2987	462,273	0.011
	3		2208	305,515	0.010
	4		2424	438,433	0.006
Average, Std. Dev.		**0.193**	**2564±332**	**451,418±12,061**	**0.010**

Table 4 shows test data of ABS and FG 1-32 without any sizing for various fiber volume fractions that is 10%, 15% and 20%. Also, average V_f, S, E, and ε_f are given.

Table 5. Test summary of ABS/FG 1-32 epoxy sizing specimens.

Specimen configuration	Specimen #	Actual (V_f)	S (psi)	E (psi)	ε_f (in/in)
10% Fiberglass	1		3274	271,582	0.024
	2		3540	366,699	0.014
	3		4252	299,518	0.015
	4		4139	447,557	0.010
Average, Std. Dev.		**0.097**	**3801±470**	**346,339±78,401**	**0.016**
15% Fiberglass	1		4365	681,246	0.009
	2		4157	502,482	0.024
	3		3372	563,780	0.030
	4		3300	361,228	0.009
Average, Std. Dev.		**0.146**	**3798±541**	**582,502±90,840**	**0.018**
20% Fiberglass	1		3247	421,604	0.025
	2		3214	568,796	0.008
	3		3337	509,469	0.027
	4		**3153**	**472,377**	**0.028**
Average, Std. Dev.		**0.197**	**3237±76**	**516,880±48,634**	**0.022**

Table 5 shows summary data of ABS and FG 1-32 with epoxy sizing for various fiber volume fractions that is 10%, 15% and 20%. Also, average V_f, S, E, and ε_f are given.

Table 6 shows data of ABS and FG 1-32 with Michelman sizing for various fiber volume fraction that is 10%, 15% and 20%. Also, average V_f, S, E, and ε_f are given.

Table 6. Test summary of ABS and FG 1-32/Michelman sizing (HP3-02) specimens.

Specimen configuration	Specimen #	Actual (V_f)	S (psi)	E (psi)	ε_f (in/in)
10% Fiberglass	1		4243	491,564	0.016
	2		4139	368,970	0.011
	3		3490	441,907	0.013
	4		3503	478,667	0.010
Average, Std. Dev.		**0.097**	**3843±403**	**445,277±55,050**	**0.012**
15% Fiberglass	1		4312	520,123	0.009
	2		4020	501,908	0.025
	3		3350	487,786	0.030
	4		3480	485,887	0.009
Average, Std. Dev.		**0.150**	**3790±446**	**498,926±15,836**	**0.018**
20% Fiberglass	1		2630	450,565	0.012
	2		2960	460,765	0.011
	3		2208	310,345	0.010
	4		2418	424,165	0.006
Average, Std. Dev.		**0.197**	**2554±172**	**411,460±69,152**	**0.010**

Table 7 shows data of ABS and FG 1-16 with Michelman sizing for various fiber volume fractions that is 10%, 15% and 20%. Also, average V_f, S, E, and ε_f are given.

Table 7. Test summary of ABS and FG 1-16 with Michelman sizing (HP3-02) specimens.

Specimen configuration	Specimen #	Actual (V_f)	S (psi)	E (psi)	ε_f (in/in)
10% Fiberglass	1		3835	473,354	0.009
	2		4704	435,558	0.013
	3		2537	426,578	0.006
	4		4475	360,621	0.016
Average, Std. Dev.		**0.097**	**4338±450**	**424,027±46,879**	**0.011**
15% Fiberglass	1		4243	454,887	0.015
	2		4244	480,406	0.011
	3		3430	311,379	0.013
	4		3420	385,336	0.010
Average, Std. Dev.		**0.146**	**3834±473**	**408,002±75,917**	**0.012**
20% Fiberglass	1		3621	467,522	0.008
	2		4271	476,244	0.011
	3		2993	412,738	0.008
	4		2522	446,046	0.007
Average, Std. Dev.		**0.193**	**3351±760**	**450,637±28,274**	**0.008**

Table 8 shows the data with ABS matrix and FG 1-32 with Gelest sizing for various fiber volume fraction that is 10%, 15% and 20%. Also, average V_f, S, E, and ε_f are given.

Table 8. Summary of ABS and FG 1-32/Gelest Sizing (SIM 6487.5) Specimens.

Specimen configuration	Specimen #	Actual (V_f)	S (psi)	E (psi)	ε_f (in/in)
10% Fiberglass	1		2309	271,957	0.011
	2		1710	216,351	0.015
	3		2711	371,758	0.015
	4		2767	369,833	0.012
Average, Std. Dev.		**0.097**	**2595±249**	**337,849±57,072**	**0.013**
15% Fiberglass	1		2271	263,694	0.011
	2		2093	313,969	0.009
	3		2207	281,554	0.010
	4		2576	417,081	0.007
Average, Std. Dev.		**0.146**	**2286±206**	**319,074±68,571**	**0.009**
20% Fiberglass	1		2414	339,778	0.007
	2		2221	323,861	0.009
	3		2343	402,001	0.006
	4		2734	253,962	0.016
Average, Std. Dev.		**0.197**	**2428±213**	**355,213±41,293**	**0.010**

Table 9 shows the data with ABS matrix and FG 1-16 with Gelest sizing for various fiber volume fraction that is 10%, 15% and 20%. Also, average V_f, S, E, and ε_f are given.

Table 9. Test summary of ABS and FG 1-16/Gelest sizing (SIM 6487.5) specimens.

Specimen configuration	Specimen #	Actual (V_f)	S (psi)	E (psi)	ε_f (in/in)
10% Fiberglass	1		4427	518,091	0.016
	2		3991	367,437	0.020
	3		4037	432,638	0.014
	4		5365	407,838	0.039
Average, Std. Dev.		**0.010**	**4455±637**	**431,501±63,674**	**0.022**
15% Fiberglass	1		4715	317,964	0.019
	2		3270	373,481	0.010
	3		3850	334,521	0.025
	4		5106	247,133	0.038
Average, Std. Dev.		**0.146**	**4557±642**	**341,988±52,829**	**0.023**
20% Fiberglass	1		3345	347,003	0.020
	2		1968	290,963	0.008
	3		3199	488,556	0.015
	4		3109	596,130	0.009
Average, Std. Dev.		**0.193**	**3217±119**	**542,343±76,066**	**0.013**

4. Conclusion

Composite specimens were fabricated using ABS and various lengths of chopped fiberglass. Various specimens were tested under tension on an MTS, per ASTM D638. Tensile test results were grouped according to sizing used, fiber volume fraction, and fiber length. Overall, mechanical properties of the thermoplastic composite specimens were not improved compared to neat ABS. This is probably because fiber lengths were much shorter than minimum critical lengths. Other reasons for poor results, include poor bonding between matrix and fiberglass, fabrication errors, processing errors, and poor mixing of ABS and chopped fiberglass.

No one sizing completely dominated. ABS/FG specimens with Epoxy sizing and Gelest sizing had better strength than other types of sizing. ABS/FG with Michelman sizing and epoxy sizing had better stiffness than other types of sizing. After comparing current test results with previous work of Panchal's results, mechanical properties of current composites were not improved. Unsized specimens had the lowest strength and stiffness. Overall, Gelest sizing specimens had the highest and lowest individual strengths and stiffnesses, Michelman sizing specimens had the most consistent strength and stiffness and Epoxy sized specimens were almost as good as the others. Specimens with longer fibers had better strength and stiffness than those with shorter fibers, as expected.

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