# HYBRID COMPOSITES BASED ON DISCONTINUOUS S-2 GLASS® AND CARBON FIBER REINFORCED NYLON 6/6

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## ABSTRACT

Hybrid composites consisting of two or more fiber types dispersed within a common matrix provide the opportunity to tailor the properties of the system by varying the relative ratio of the fibers and achieve performance otherwise unattainable in a single fiber composite. *S-2 Glass®* is the state of the art high-performance glass fiber exhibiting a combination of high strength, modulus and elongation to failure. The fiber is best known in the aerospace industry for structures that need impact, ballistic, and/or fatigue resistance. Carbon fiber also exhibits high strength and modulus, but its low elongation to failure can lead to structures with poor damage tolerance often resulting in brittle, abrupt failure. While examples of hybrid composites based on continuous *S-2 Glass* and carbon fiber are known, we are not currently aware of hybrid systems based on a combination of the two fibers in discontinuous form. AGY has shown that Nylon 6/6 reinforced with chopped *S-2 Glass* fiber exhibits an Izod impact energy 86 % higher than Nylon 6/6 filled with conventional chopped E-Glass fiber. Nylon 6/6 reinforced with short carbon fiber exhibited a higher tensile modulus but reduced impact performance. This work will demonstrate that various combinations of discontinuous *S-2 Glass* and carbon fiber produce structures with good strength, stiffness, impact resistance that will give designers a simple, visible representation of the trade-offs in modulus, damage tolerance and strength that these hybrids provide.

## 1. INTRODUCTION

Through the use of hybrid fiber composites it is possible to combine the advantages of multiple fiber types while simultaneously diminishing their weaknesses. The objective of the work reported here is to demonstrate that, by combining short *S-2 Glass®* fiber with short carbon fiber in a thermoplastic matrix, the well-known deficiency in impact resistance associated with carbon fiber reinforced plastics can be diminished, while at the same time preserving the composites load bearing capability (strength) with minimal reduction in stiffness. Designers will acquire information on optimum hybrid compositions that give a balance of strength, stiffness and impact resistance.

Hybrid composites where two or more fiber types are contained within the same material system have been known since at least the 1970's. [1] Select hybrid composite types are as follows:

**1**. "Random" – the fibers are randomly distributed throughout the matrix material.
**2**. "Intraply" - where the fibers are commingled in a consistent manner within an individual ply.


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**3**. “Interply” – where the composite consists of discrete plies composed of individual fibers that are bonded together with matrix material, i.e., glass fiber overwrapped carbon fiber reinforced epoxy pressure vessels.

**4**. “Multi-material Hybrids” – consisting of plies of fiber embedded in a matrix material that are bonded to metal plies or sheets, i.e. fiber-metal laminates.

This report focuses solely on “Random” fiber hybrids where short *S-2 Glass* fiber is combined with short carbon fiber during extrusion compounding to produce a blended composition. Injection molding of the hybrid compound results in a composite part with a random distribution of the two fibers within the polymeric matrix, in this case Nylon 6/6. Although examples of hybrid composites based on short E-Glass and carbon fiber reinforced thermoplastics [2, 3] are known, we are unaware of any examples of the short *S-2 Glass* fiber analogue.

Examples of the hybrid composites defined in 1-4 above and based on continuous *S-2 Glass* and carbon fiber can be found in the both the scientific literature and in industry. For example, “Intraply” hybrids based on substituting *S-2 Glass* fiber tows for carbon during unidirectional (UD) tape production were recently described by Toray Composites America. [4] “Interply” hybrids of *S-2 Glass* fiber and carbon have been described by a number of authors including but not limited to the references given here. [5, 6, 7] Most if not all reports on the hybridization of *S-2 Glass* and carbon are associated with improving the impact resistance of carbon fiber reinforced plastics. These composites exhibit high-stiffness and excellent fatigue resistance but also possess low strain-to-failure and associated reduced energy absorption capability. “Multi-material hybrids” in the form of fiber-metal laminates were developed at Delft University of Technology during the early part of the 1980’s. [8] Application of Glass Aluminum Reinforced Epoxy (GLARE®) on the Airbus A-380 has recently been realized. GLARE is a hybrid system composed of alternating layers of *S-2 Glass* fiber reinforced epoxy and aluminum alloy sheet.

During the course of a previous study, AGY found that a significant improvement in mechanical performance over standard E-Glass products was possible through the reinforcement of Nylon 6/6 with short *S-2 Glass* fiber, Table 1.

Table 1. The % improvement in various mechanical properties of *S-2 Glass* fiber reinforced Nylon 6/6 over a standard E-Glass reinforcement.

| **Property** | Tensile Strength (MPa) | Tensile Modulus (GPa) | Tensile Elongation @ Break (%) | Notched Izod Impact (J/m) | Flexural Strength, (MPa) | Flexural Modulus, (GPa) |
|---|---|---|---|---|---|---|
| ***S-2 Glass* Fiber Reinforced Nylon 6/6 Percent Improvement** | 34% | 20% | 47% | 86% | 40% | 24% |

# 2. TECHNICAL APPROACH

## 2.1 Overall Approach

A cubic Simplex-Lattice mixture DOE was chosen as the design for the basic experiment since it has the advantage of providing all of the standard information afforded the simplex mixture designs plus the benefit of utilizing the fiber resin edge line points (along X1X2 and X1X3, respectively) to determine conformance to other predictive models associated with glass and carbon fiber reinforcements in resin. The 10 design points were translated from volume % targets to weight % targets for the purpose of controlling the input blends of materials into an extruder. The physical parameters selected as responses are listed below:

Tensile Strength (ASTM 638)
Tensile Modulus (ASTM 638)
Flexural Strength (ASTM 790)
Flexural Modulus (ASTM 790)
Izod Impact Strength (ASTM 256)

### 2.1.1 Mixture DOE Overview

When design factors are proportions of a blend, it is most appropriate to use a mixture design for experimentation. In a mixture experiment, the independent factors are proportions of different components of a blend. The fact that the proportions of the different factors must sum to 1 complicates the design as well as the analysis of mixture experiments. For a three component blend, the design space can be represented pictorially and graphically by a triangular depiction where each of the vertices represent 100 % mixture of the relative components, the connecting lines represent mixtures of the two components that it connects to varying degrees, and the inner space of the shape represents blends of all three components, Figure 1. The most common mixture designs for fitting such models are referred to as *simplex-lattice* designs. [9]

### 2.1.2 Simplex-Lattice Designs

The response in a mixture experiment can be described by a polynomial function. This function represents how specific combinations of the components impact the response(s). To best study the shape of the response surface, the most common choices for designs are those whose points are spread evenly over the simplex space. An ordered arrangement consisting of uniformly distributed points on a simplex is known as a lattice.

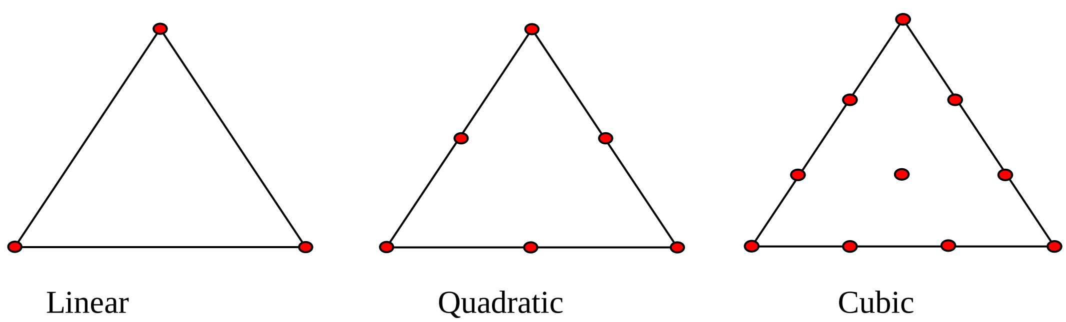



Figure 1. Three component simplex-lattice designs.

A simplex-lattice design for q components consists of points defined by their coordinate settings. The standard selections for each component take on m+1 equally spaced values from 0 to 1 and the design space consists of all the reasonable combinations of the values for each factor. Additionally, m is referred to as the degree of the lattice.

$$x_i = 0, \frac{1}{m}, \frac{2}{m}, ...., 1 \ i = 1, 2, ...., q$$

For the three component simplex-lattice design depicted in Figure 1 above, the following polynomial functions apply.

Linear model:

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$$

Quadratic model:

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3$$

Cubic model:

$$\begin{aligned} &y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \\ &+ \delta_{12} x_1 x_2 (x_1 - x_2) + \delta_{13} x_1 x_3 (x_1 - x_3) + \delta_{23} x_2 x_3 (x_2 - x_3) \\ &+ \beta_{123} x_1 x_2 x_3 \end{aligned}$$

### 2.1.3 Constrained Mixture Design

For the purpose of this experiment, consideration was given as how to best evaluate the manner in which both discontinuous short chopped *S-2 Glass* fibers (X2) and carbon fibers (X3) enhance physical properties when intimately blended with Nylon 6/6 (X1). Since it is not possible to obtain meaningful composite results for a 100% blend of either fiber or a combination thereof, the design must be augmented to limit the fiber contents to a reasonable level. When it is not feasible to have 100% of one or more of the design components, the design is said to be constrained. The mixture components are still subject to the overall design constraint that they must sum to total of 1. In this case, basic mixture designs for fitting standard models are still appropriate based on shape of the constrained design space. For the purposes of this study, the maximum level of fiber content was constrained to 15 volume %. The volume % limit was chosen in order to minimize fiber on fiber abrasion and the associated intensification in fiber length degradation that results due to extruder based hot melt mixture dynamics.

The cubic model was chosen as the basis of this work since the four edge line points (along X1X2 and X1X3, respectively) could serve to determine conformance to other predictive models associated with glass and carbon fiber reinforcements in resin and the base line (X2X3) and other horizontally connected points could help define the relative interactions between the two input fibers at constant relative fiber loadings.

The cubic simplex-lattice mixture DOE depicted to the right in Figure 2 below was chosen as the preferred design and subsequently set up utilizing Statgraphics® Centurion XV software.

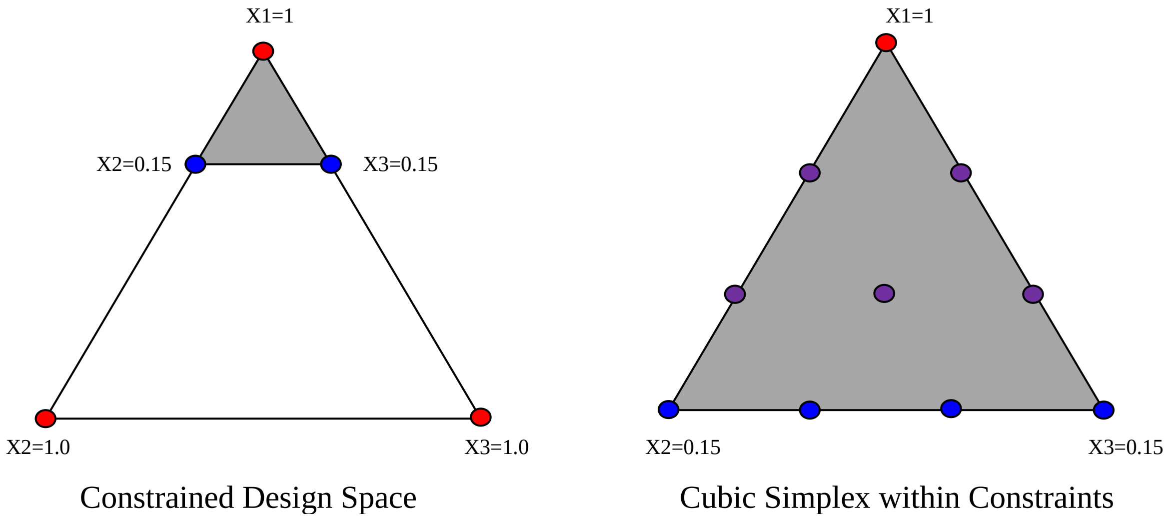



Figure 2. The cubic simplex-lattice mixture DOE.

**2.2 Materials**

The *S-2 Glass* fiber was produced by AGY in Aiken, SC and surface treated with a direct sizing system known as 544. Carbon fiber, PX-35 Type-45 was produced by Zoltek and Nylon 6/6 was produced by Ascend Performance Materials and sold under the trade name Vydyne® 50BW polyamide 66. Properties of the commercially available fibers and matrix are presented in Table 2.

Table 2. Properties of the fibers and matrix used in composite production.

| Material | Tensile Modulus (GPa) | Tensile Strength (MPa) | Density (g/cm$^3$) | Elongation to Break (%) | Diameter (µm) | Intitial Length (mm) |
|---|---|---|---|---|---|---|
| **Carbon Fiber** | 242 | 4137 | 1.81 | 1.4 | 7.2 | 6 |
| ***S-2 Glass* Fiber** | 90 | 4000 | 2.47 | 5.6 | 9 | 4 |
| **Nylon 6/6** | 3 | 80 | 1.14 | 22 | - | - |

**2.3 Composite Production**

The composite specimens were prepared by feeding a pre-blended glass, carbon fiber, and polymer mix into the throat of a Coperion (formerly Werner & Pfleiderer) co-rotating 27 mm twin-screw extruder at Plastics Analytical Laboratory, (PAL) Santa Ana, CA. The heating zones were set over a temperature range from 277 to 293 °C. The compounded extrudates were quenched in water and then cooled in air until ambient temperature was reached and immediately chopped into pellets and dried at 80 °C for 2 hours. All the specimens were injection molded at PAL into ASTM D638 Type I tensile specimens, ASTM D256 Izod impact bars and ASTM D790 flexural specimens using a 35 ton Van Dorn injection molding machine with a barrel temperature of between 282 and 299 °C. Specimens were conditioned for 24 hours at 22 °C and 50% relative humidity prior to mechanical testing.

### 2.4 Mechanical Properties

Mechanical properties were determined at ambient temperature in the tension and compression mode using an Instron Universal test machine with a 30,000 pound load capacity and equipped with an Epsilon Technology Corp. clip-on extensometer. Tensile strength and modulus were determined according to ASTM D 638, “Standard Test Method for Tensile Properties of Plastics”, on Type I tensile specimens. Flexural strength and modulus were determined according to ASTM D790, “Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials,” by the 3-point bending mode. Glass roving strength and modulus were determined by ASTM D2343, “Tensile properties of glass fiber strands, yarns and roving used in reinforced plastics.” Impact resistance of the composite systems was determined by ASTM D256 “Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics,” using notched specimens according to procedure A. All mechanical properties except fiberglass roving strength by ASTM D2343 were conducted at PAL and AGY to verify reproducibility.

### 2.5 Physical Properties

Composite density was determined according to ASTM D 792, “Density and Specific Gravity (Relative Density) of Plastics by Displacement." Fiber, resin and void volume fractions were determined according to ASTM D 2584, “Standard Test Method for Ignition Loss of Cured Reinforced Resins,” and ASTM D 3171, “Standard Test Methods for Constituent Content of Composite Materials.”

### 2.6 Measurement of Fiber Length

Short glass and carbon fibers were first isolated from the composite specimens via combustion at 650 °C for glass fibers and 475 °C for any sample containing carbon. Fibers were extracted from the remaining material and dispersed onto the surface of a rectangular glass slide and investigated by optical microscopy. A mineral oil with an index of refraction near that of *S-2 Glass* was applied to the surface of hybrid fiber systems resulting in a translucent glass fiber that was easily distinguishable from carbon. Magnified fiber images were acquired and the lengths were determined using software associated with the imaging device.

## 3. RESULTS & DISCUSSION

### 3.1 Composite Physical Properties

The constituent content and density for all composites were determined according to previously noted standard techniques. Table 3 presents the physical properties for all compositions evaluated during this program. Entry number 1 is unfilled Nylon 6/6. Entries 2, 3, and 4 are controls composed only of varying amounts of carbon fiber. Entries 8, 9 and 10 are also controls containing only *S-2 Glass* fiber and finally numbers 5, 6 and 7 are the hybrid compositions.

### 3.2 Fiber Lengths

The effect of increasing fiber volume fraction ($V_f$) upon mean fiber lengths is shown in Table 4 for the carbon only, *S-2 Glass* only fiber reinforced Nylon 6/6 controls as well as the three hybrid compositions. The reduction in mean glass and carbon fiber lengths as a function of increasing $V_f$ has been previously reported. [10, 11]

Table 3. The physical properties for all composites.

| Entry No. | Weight Percent Carbon Fiber | Weight Percent *S-2 Glass* Fiber | Volume Fraction Carbon Fiber | Volume Fraction *S-2 Glass* Fiber | Total Volume Fraction fiber | Volume Fraction Nylon 6/6 | Composite Density, ($g/cm^3$) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1.14 |
| 2 | 22.00 | 0 | 0.152 | 0 | 0.152 | 0.848 | 1.24 |
| 3 | 14.00 | 0 | 0.093 | 0 | 0.093 | 0.907 | 1.20 |
| 4 | 7.50 | 0 | 0.049 | 0 | 0.049 | 0.951 | 1.17 |
| 5 | 12.25 | 12.80 | 0.088 | 0.067 | 0.154 | 0.846 | 1.29 |
| 6 | 4.50 | 22.80 | 0.033 | 0.122 | 0.155 | 0.845 | 1.32 |
| 7 | 6.75 | 10.70 | 0.047 | 0.054 | 0.100 | 0.900 | 1.24 |
| 8 | 0 | 11.00 | 0 | 0.054 | 0.054 | 0.946 | 1.21 |
| 9 | 0 | 19.60 | 0 | 0.101 | 0.101 | 0.899 | 1.27 |
| 10 | 0 | 28.50 | 0 | 0.155 | 0.155 | 0.845 | 1.34 |

The lower mean carbon fiber length is also not unusual and is a likely consequence of carbons brittleness and susceptibility to fracture during compounding. It appears that the addition of carbon fiber to *S-2 Glass* in the hybrid compounds also results in reduced fiber lengths for the glass fiber as previously described for hybrid compounds of E-Glass and carbon fiber reinforced polycarbonate.[2]

Table 4. Mean fiber lengths for all compositions.

| **Controls** | | | | | | **Hybrids** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Entry No.** | **Volume Fraction Carbon Fiber** | **Volume Fraction *S-2 Glass* Fiber** | **Mean Fiber Length, (µm)** | **Aspect Ratio, (L/d)** | | **Entry No.** | **Volume Fraction Carbon Fiber** | **Volume Fraction *S-2 Glass* Fiber** | **Mean Fiber Length, (µm) *S-2 Glass* Fiber** | **Mean Fiber Length, (µm) Carbon Fiber** | **Aspect Ratio Carbon Fiber, (L/d)** | **Aspect Ratio *S-2 Glass* Fiber, (L/d)** |
| 2 | 0.152 | 0 | 53 | 7 | | | | | | | | |
| 3 | 0.093 | 0 | 62 | 9 | | 5 | 0.088 | 0.067 | 92 | 72 | 10 | 10 |
| 4 | 0.049 | 0 | 88 | 12 | | 6 | 0.033 | 0.122 | 64 | 43 | 6 | 7 |
| 8 | 0 | 0.054 | 191 | 21 | | 7 | 0.047 | 0.054 | 55 | 43 | 6 | 6 |
| 9 | 0 | 0.101 | 128 | 14 | | L = Mean fiber length, d = fiber diameter | | | | | | |
| 10 | 0 | 0.155 | 149 | 17 | | | | | | | | |

## 3.3 DOE Contour Plot Analysis

### 3.3.1 Strength Contour Plots

The mixture DOE was analyzed and contour plots were generated utilizing Statgraphics software. The contour plots for each response are shown in Figure 3 below:

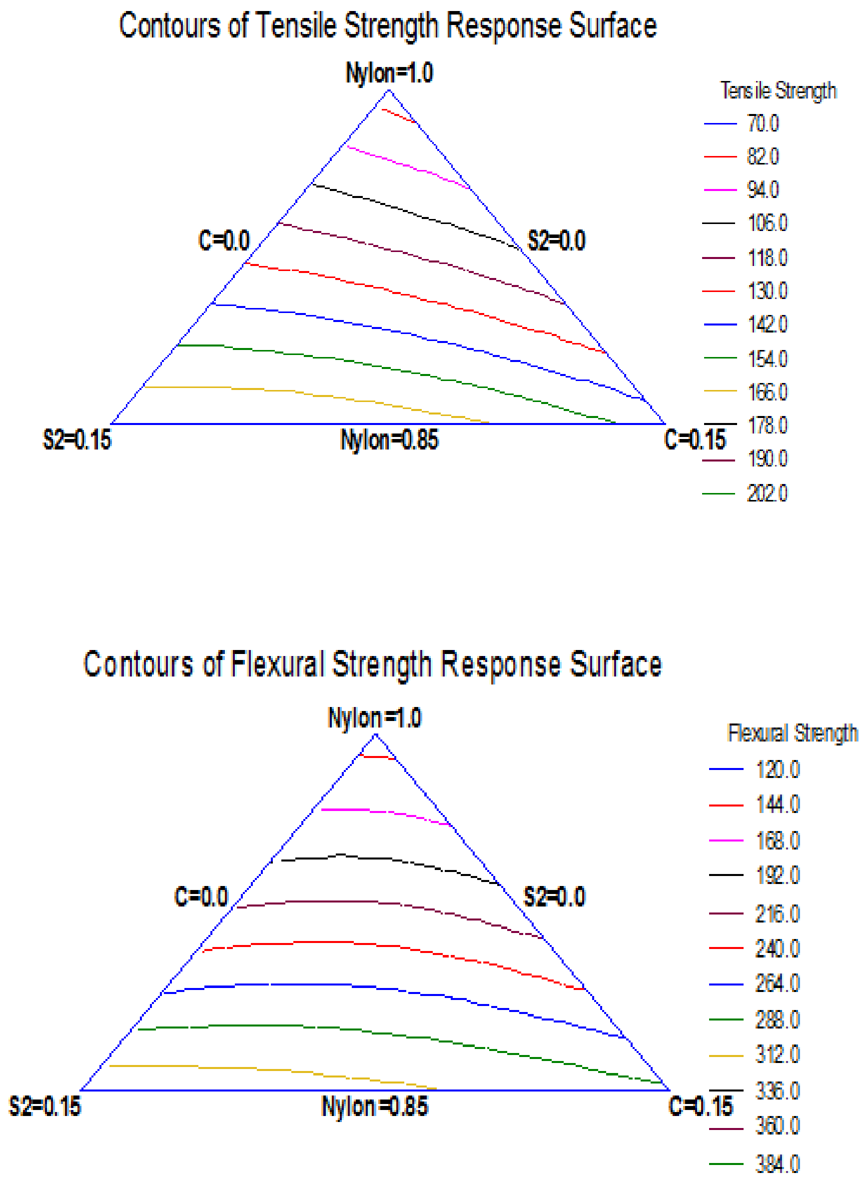
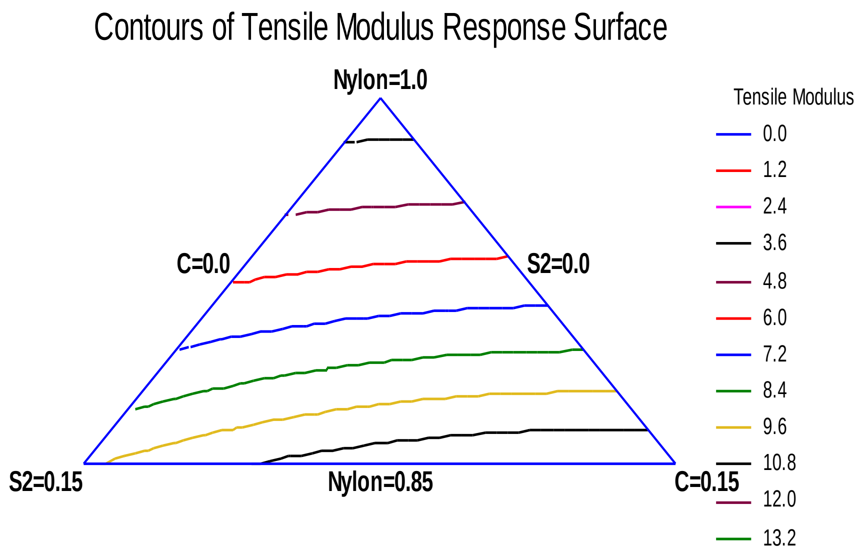



Figure 3. Contour plots of tensile and flexural strength.

The contour plots show that both tensile and flexural strength rise slightly more rapidly with the addition of *S-2 Glass fibers* vs. carbon fibers. For tensile, the composite strength at 15% carbon fiber is achieved with a 10.3% loading of *S-2 Glass*. Similarly, for flexural performance, the composite strength at 15% carbon fiber is achieved with a 12.7% loading of *S-2 Glass*.

### 3.3.2 Modulus Contour Plots

Conversely, the contour plots (Figure 4) show that both tensile modulus and flexural modulus rise slightly more rapidly with the addition of carbon fibers versus *S-2 Glass* fibers. For tensile modulus, the composite strength at 15% *S-2 Glass* is achieved with an 11.5% loading of carbon fiber. Similarly, for flexural modulus, the composite strength at 15% *S-2 Glass* is achieved with a 12.9% loading of carbon fiber.



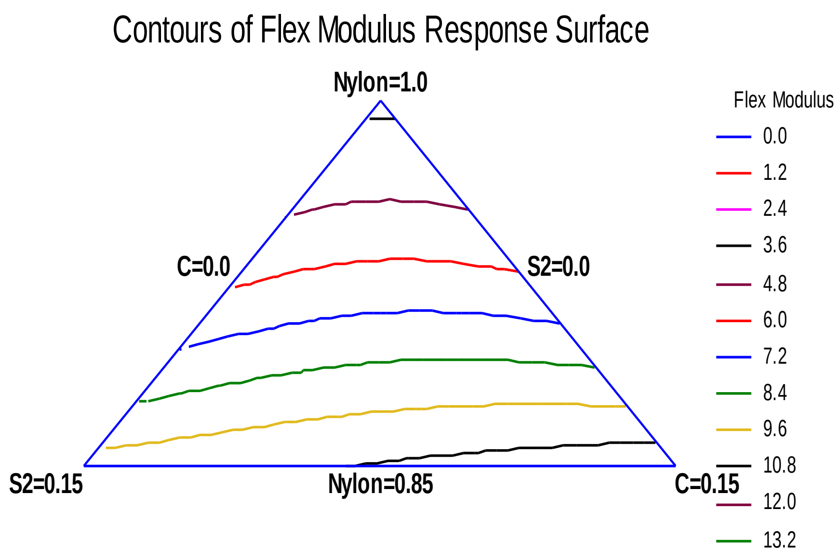




Figure 4. Contour plots of tensile and flexural modulus.

### 3.3.3 Impact Contour Plot

The contour plot (Figure 5) shows that the Izod impact strength rises much more pronouncedly with the addition of *S-2 Glass* fibers versus carbon fibers. In this instance, the impact strength at 15% carbon fiber is achieved with only a 7.8% loading of *S-2 Glass*.

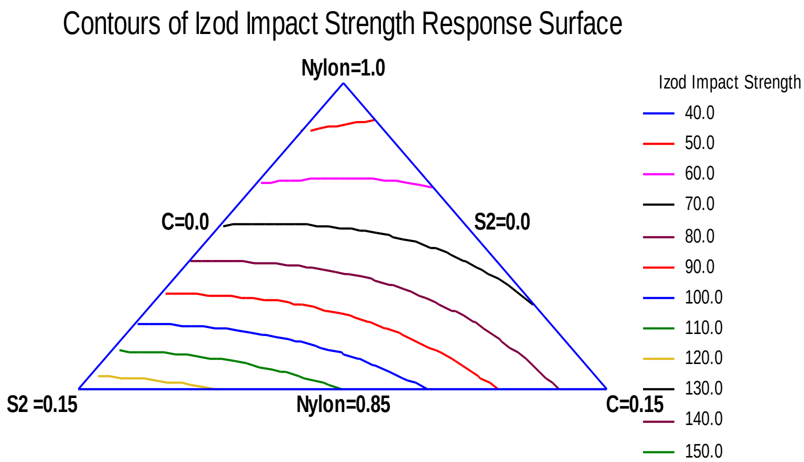



Figure 5. Contour plot for Izod impact strength.

## 3.4 Mechanical Properties

### 3.4.1 Typical Stress-Strain Curves

The tensile stress-strain curves for two short fiber reinforced Nylon 6/6 compounds, one with carbon fiber and the other containing only *S-2 Glass* fiber, entries 2 and 10 of Table 3 are shown in Figure 6.

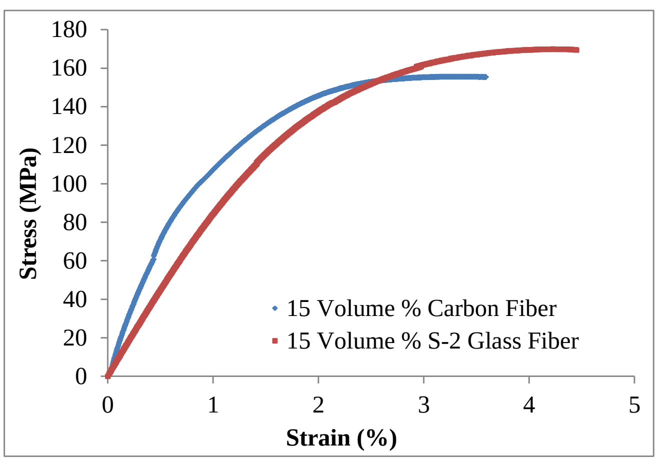



Figure 6. Typical stress-strain curves for carbon and *S-2 Glass* fiber reinforced Nylon 6/6.

The stress-strain curves clearly demonstrate the fundamental differences in the fiber properties where the increased modulus and reduced strain-to-failure are apparent for the carbon fiber reinforced specimen. The increased strain-to-failure and tensile strength of *S-2 Glass* fiber reinforced Nylon 6/6 are evident; ultimately leading to improved composite toughness. For example, the mean energy absorbed at rupture during tensile testing for the *S-2 Glass* fiber reinforced Nylon 6/6 (Figure 1) is 25% higher than the carbon fiber analogue.

### 3.4.2 Tensile Strength and Modulus

Figure 7 shows the variation in ultimate tensile strength as a function of $V_f$ for the carbon and *S-2 Glass* fiber controls, entries 1-3 and 8-10, respectively of Table 3.

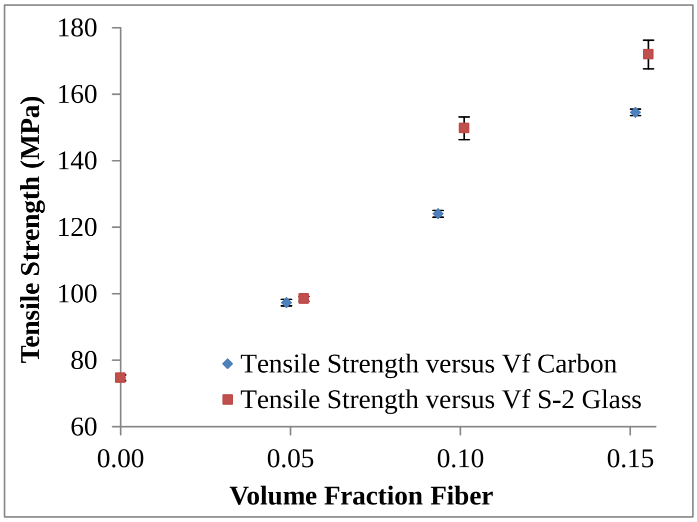



Figure 7. Tensile strength versus $V_f$.

The addition of glass or carbon fiber greatly improves the ultimate tensile strength of pure Nylon 6/6, also shown in Figure 7. The strength of the *S-2 Glass* fiber reinforced Nylon 6/6 is significantly greater at higher $V_f$ and is a direct consequence of reduced carbon fiber lengths at higher concentrations, see Table 4. The strength for both composite systems increases almost linearly with $V_f$. The variation in tensile modulus as a function of $V_f$ for the controls is presented in Figure 8.

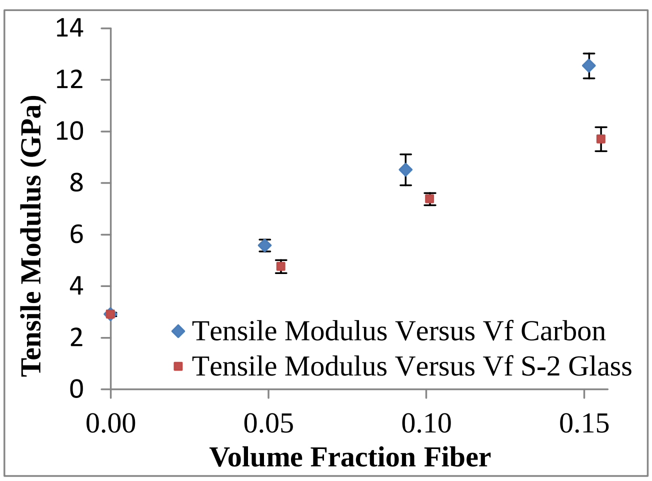



Figure 8. Tensile modulus versus $V_f$.

The modulus of Nylon 6/6 is improved dramatically by the addition of fibrous reinforcement. Carbon fiber increases the tensile modulus of Nylon 6/6 more significantly; especially at the highest $V_f$. Figure 9 shows the variation in tensile strength and modulus as a function of volume fraction *S-2 Glass* fiber in the two hybrid compositions (enclosed by the circle) entries 5 and 6 of Table 3. The two sets of data points bookending the hybrids represent the 100% carbon and 100% *S-2 Glass* fiber reinforced composites. All samples contain identical total $V_f = 0.15$.

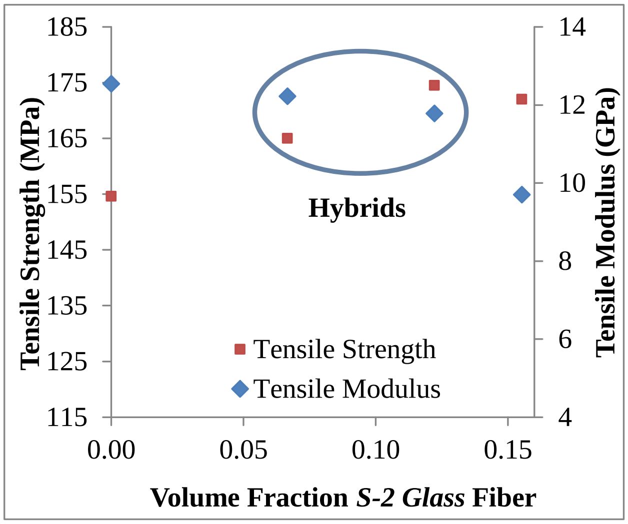



Figure 9. Tensile strength and modulus.

It is apparent from Figure 9 that increasing amounts of *S-2 Glass* fiber result in improved composite tensile strength with very little reduction in modulus. Based on Figure 9, the optimum composition for maximizing strength and modulus of the hybrid composite system is one containing approximately 12 volume % *S-2 Glass* fiber and 3 volume % carbon fiber. Or in other words, about 23 weight % *S-2 Glass* to 5 weight % carbon fiber.

**3.4.3 Flexural Properties**

Flexural strength and modulus were determined on all compositions given in Table 3. Figure 10 shows increasing fiber content results in a linear increase in both properties, for the carbon and *S-2 Glass* fiber controls.

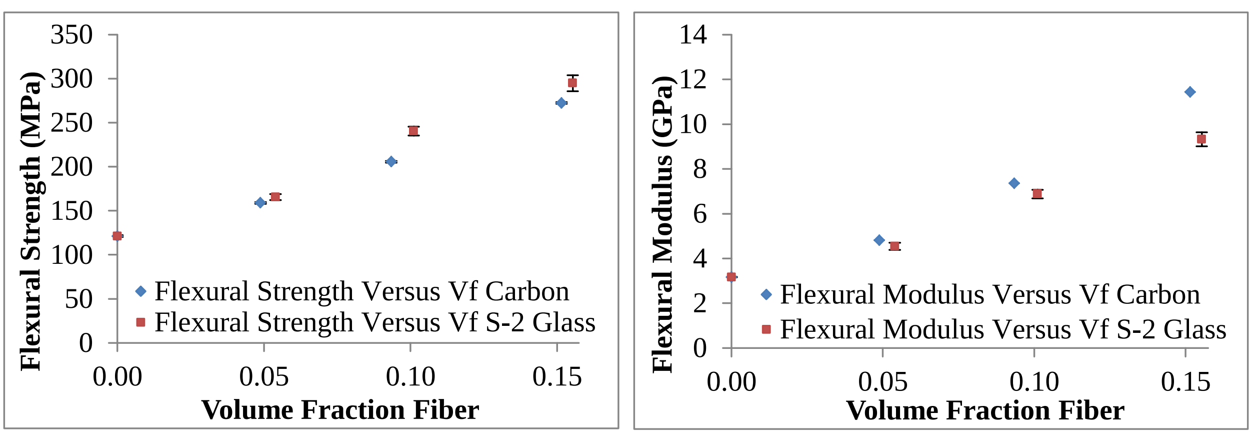



Figure 10. Flexural strength and modulus versus $V_f$.

Figure 11 shows the variation in flexural strength and modulus as a function of $V_f$ *S-2 Glass* fiber in two hybrid compositions (enclosed by the circle) entries 5 and 6 of Table 3. The trend in flexural strength and modulus matches the behavior shown for tensile properties (Figure 9) where increasing amounts of *S-2 Glass* fiber lead to improved composite flexural strength with little reduction in modulus.

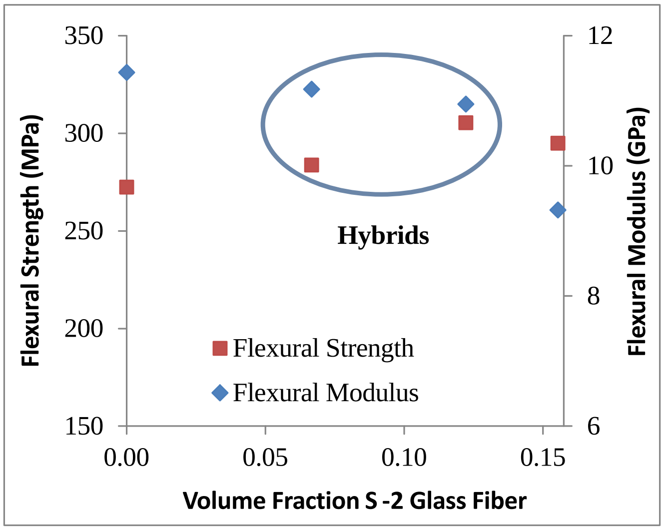



Figure 11. Flexural strength and modulus.

### 3.4.4 Izod Impact Resistance

Notched Izod impact tests were performed on all compositions shown in Table 3. It is reasonable to expect that *S-2 Glass* reinforced Nylon 6/6 composites would display improved impact resistance especially at higher $V_f$ when compared to the carbon fiber reinforced analogues and this is confirmed in Figure 12(a).

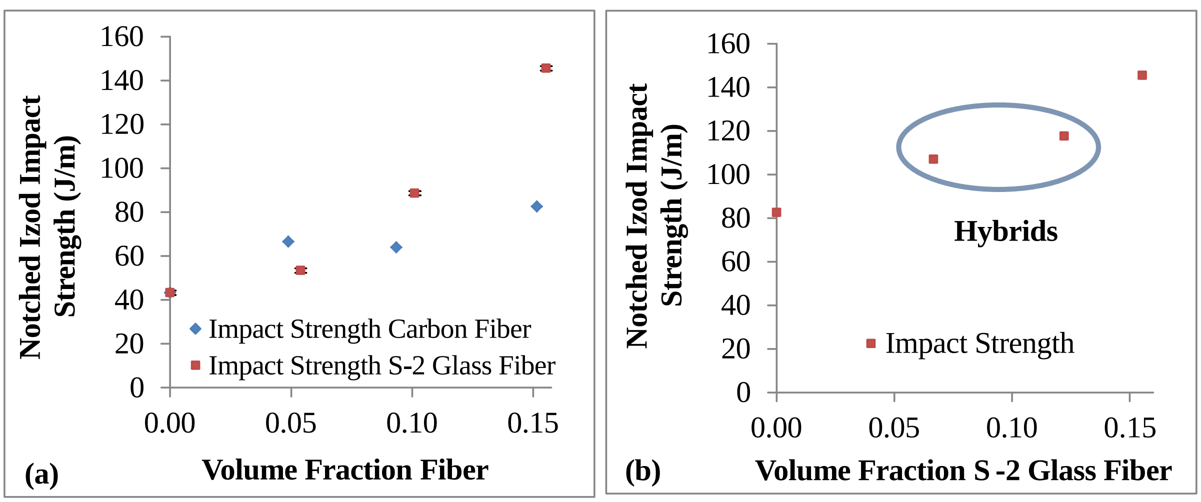



Figure 12. Notched Izod Impact strength for all composites.

The dramatically enhanced impact performance of glass fiber reinforced plastics at higher $V_f$ has been previously described [12] and attributed to a toughening mechanism that results from plasticity around fiber glass ends that leads to enhanced ductility of the thermoplastic especially when the fiber-end spacing reaches a critical value and the stress fields begin to overlap. Increasing amounts of *S-2 Glass* fiber dramatically improve the impact resistance of carbon fiber reinforced Nylon 6/6 as shown in Figure 12(b) for the hybrid composites. All compositions in Figure 12(b) contain the same amount of fiber at a total $V_f$ of 0.15. The data point at zero $V_f$ *S-2*

*Glass* fiber is the 100% carbon analogue. Hybrid composites based on *S-2 Glass* and carbon fiber reinforced thermoplastics provide new options for the reinforced plastics community. The increased modulus, strength and elongation to failure of *S-2 Glass* relative to standard E-Glass fiber results in hybrid compositions that exhibit dramatically improved impact performance with little reduction in tensile modulus, Figure 13.

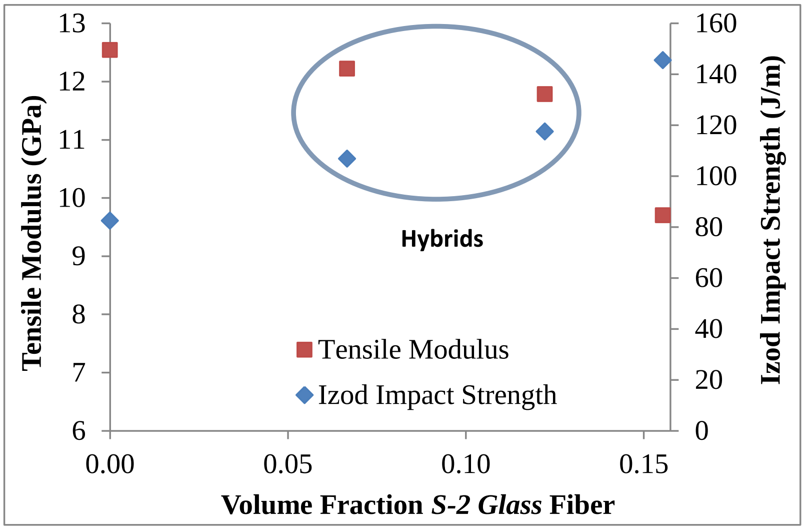



Figure 13. Tensile modulus and Izod impact strength as a function of $V_f$ *S-2 Glass* fiber.

Based on Figure 13 the optimum composition for maximizing tensile modulus and impact resistance of the current composite system is one containing approximately 12 volume % *S-2 Glass* fiber and 3 volume % carbon fiber. Or in other words, about 23 weight % *S-2 Glass* to 5 weight % carbon fiber.

## 4. CONCLUSIONS & RECOMENDATIONS

Mechanical properties normalized to density (specific properties) are a common metric used to compare a materials mass efficiency in strength or stiffness. The higher the ratio the more efficient the material property is per unit mass. Table 5 shows the specific strength, modulus and impact strength for all compositions evaluated during this program. It is obvious from the data shown in Table 5 and highlighted in green that reinforcing Nylon 6/6 with hybrid compositions of *S-2 Glass* and carbon fiber results in the best balance of mechancial properties per unit mass. These hybrid compositions could be useful for applications where strength and impact resistance are key design drivers but where stiffness cannot be sacrificed.


## 5. ACKNOWLEDGEMENTS

This work was completed by an AGY lead team with support from Don Jackson & Curt Schmuhl of Plastics Analytical Laboratory (PAL), Santa Ana, CA. The authors would also like to recognize Curtis Nappier & Brian Ruppell of AGY for the mechanical testing and fiber length measurements.

Table 5. Specific properties for all composites evaluated.

| Volume Fraction Carbon Fiber | Volume Fraction *S-2 Glass* Fiber | Izod Impact Strength (J/m) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Density ($kg/m^3$) | Specific Strength ($kPa{\cdot}m^3/kg$) | Specific Modulus ($kPa{\cdot}m^3/kg$) | Specific Impact Strength ($J{\cdot}m^2/kg$) |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 44.3 | 74.7 | 2.9 | 1140 | 66 | 2548 | 0.04 |
| 0.152 | 0 | 67.3 | 154.6 | 12.5 | 1239 | 125 | 10124 | 0.05 |
| 0.093 | 0 | 56.6 | 124.1 | 8.5 | 1202 | 103 | 7084 | 0.05 |
| 0.049 | 0 | 51.2 | 97.3 | 5.6 | 1172 | 83 | 4760 | 0.04 |
| **0.088** | **0.067** | **89.1** | **165.0** | **12.2** | **1286** | **128** | **9503** | **0.07** |
| **0.033** | **0.122** | **100.9** | **174.5** | **11.8** | **1324** | **132** | **8899** | **0.08** |
| **0.047** | **0.054** | **61.4** | **141.4** | **8.1** | **1242** | **114** | **6516** | **0.05** |
| 0 | 0.054 | 56.6 | 98.5 | 4.8 | 1210 | 81 | 3937 | 0.05 |
| 0 | 0.101 | 74.2 | 149.8 | 7.4 | 1274 | 118 | 5793 | 0.06 |
| 0 | 0.155 | 114.8 | 173.1 | 9.7 | 1341 | 129 | 7233 | 0.09 |

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