

High Strength Glass Fibers

An Overview of Glass Fiber Technology

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Abstract

Continuous glass fibers, first conceived and manufactured around 1935 in Newark, Ohio, started a revolution in reinforced composite materials which by the year 2000 had led to a global annual glass fiber consumption of 2.6 million tons. During the early 1940's glass fiber reinforced composites were first used in structural aerospace parts. In the early 1960's high strength glass fibers, known as S Glass, were first used in joint work between Owens Corning Textile Products and the United States Air Force. Later in 1968 S-2 Glass fibers began evolving into a variety of commercial applications.

High strength glass fibers combine high temperature durability, mechanical stability, optical and radio frequency transparency, and resilience at a very reasonable cost-weight-performance. This document assesses the utility of high strength glass fiber compositions which are compared by physical, mechanical, electrical, thermal, acoustical, optical, and radiation properties.

Keywords: S-2 Glass, C Glass, AR Glass, D Glass, L-Glass, L-2 Glass, ECR glass, R Glass; E Glass; , S-3 HDI, S-1 HM, Fiberglass, Glass Reinforcements.

Introduction

Ancient Egyptians have been shown to have made containers of coarse fibers drawn from heat softened glasses. The French scientist, Reaumur, first considered the potential of forming fine glass fibers for woven glass articles as early as the 18th century. Continuous glass fibers were first manufactured in substantial quantities by Owens Corning Textile Products in the 1930's for high temperature electrical applications, this is where the "E" in E glass comes from. Revolutionary and evolutionary technology continues to improve manufacturing processes for continuous glass fiber production, an example of which is illustrated in Figure 1. Raw materials such as silicates, soda, clay, limestone, boric acid, fluorspar or various metallic oxides are blended to form a glass batch which is melted in a furnace and refined during lateral flow to the forehearth. The molten glass flows to platinum/rhodium alloy bushings and then through individual bushing tips and orifices ranging from 0.75 to 2.00mm (0.030 to 0.080 in) and is rapidly quenched and attenuated in air, (to prevent crystallization,) into fine fibers ranging from 4 to 24 μm . Mechanical winders pull the fibers at lineal velocities up to 61 m/s over an applicator which coats the fibers

with an appropriate chemical sizing to aid further processing and performance of the end products.

High strength glass fibers like S-2 Glass are compositions of aluminosilicates attenuated at higher temperatures into fine fibers ranging from 5 to 24 μm . Several other types of silicate glass fibers are manufactured for the textile and composite industry. Various glass chemical compositions described below from ASTM C 162 were developed to provide combinations of fiber properties directed at specific end use applications.

- **A glass:** Soda lime silicate glasses used where the strength, durability, and good electrical resistivity of E Glass are not required.
- **C glass:** Calcium borosilicate glasses used for their chemical stability in corrosive acid environments.
- **D glass:** Borosilicate glasses with a low dielectric constant and loss for electrical applications.
- **E glass:** Alumina-calcium-borosilicate glasses with a maximum alkali content of 2 wt.% used as general purpose fibers where strength and high electrical resistivity are required.
- **ECR glass:** Calcium aluminosilicate glasses with a maximum alkali content of 2 wt.% used where strength, electrical resistivity, and acid corrosion resistance are desired.
- **AR glass:** Alkali resistant glasses composed of alkali zirconium silicates used in cement substrates and concrete.
- **R glass:** Calcium aluminosilicate glasses used for reinforcement where added strength and acid corrosion resistance are required.
- **S-2 Glass:** Magnesium aluminosilicate glasses used for textile substrates or reinforcement in composite structural applications which require high strength, modulus, and stability under extreme temperature and corrosive environments.

Glass Fiber Chemical Compositions

Chemical composition variation within a glass type is typically company-specific and generally arises from differences in the available glass batch raw materials, or

in the melting and forming processes, or from different environmental constraints at the manufacturing site. These compositional fluctuations do not significantly alter the physical or chemical properties of the glass type. Very tight control is maintained within a given production facility to achieve consistency in the glass composition for production capability and efficiency. Table 1 provides the oxide components and their weight ranges for eight types of commercial glass fibers [1-6].

Glass Fiber Properties

Glass fiber properties, such as tensile strength, Young's modulus, and chemical durability, are measured on the fibers directly. Other properties, such as dielectric constant, dissipation factor, dielectric strength, volume/surface resistivities, and thermal expansion, are measured on glass that has been formed into a bulk sample and annealed (heat treated) to relieve forming stresses. Properties such as density and refractive index are measured on both fibers and bulk samples, in annealed or unannealed form. The properties presented in Tables 2 and 3 are representative of the compositional ranges in Table 1 and correspond to the following overview of glass fiber properties.

PHYSICAL PROPERTIES

Density of glass fibers is measured and reported either as formed or as bulk annealed samples. ASTM C 693 is one of the test methods used for density determinations [7]. The fiber density (in Table 3) is less than the bulk annealed value by approximately 0.04 g/cc at room temperature. The glass fiber densities used in composites range from approximately 2.3 g/cc for L Glass to 2.72 g/cc for ECR glass reinforcements.

Tensile strength of glass fibers is usually reported as the pristine single-filament or the multifilament strand measured in air at room temperatures. The respective impregnated strand strengths are normally 20 to 30% lower than the values reported in Table 2 due to surface defects introduced during the strand-forming process. ASTM D 2343 is the most common standard used to measure practical tensile strength and modulus. Moisture has a detrimental effect on the pristine strength of glass. This is best illustrated by measuring the pristine single-filament strength at liquid nitrogen temperatures where the influence of moisture is minimized. The result is an increase of 50 to 100% in strength over a measurement at room temperature in 50% relative humidity air. The maximum mea-

sured strength of S-2 Glass fibers at liquid nitrogen temperatures is 11.6 GPa for a 12.7 mm gauge length, 10 μm diameter fiber. The loss in strength of glass exposed to moisture while under an external load is known as static fatigue [4,8]. The pristine strength of glass fibers decreases as the fibers are exposed to increasing temperature. E Glass and S-2 Glass fibers have been found to retain approximately 50% of their pristine room-temperature strength at 538°C (1000°F) and are compared to organic reinforcement fibers in Figure 2.

The Young's modulus of elasticity of unannealed silicate glass fibers ranges from about 52 GPa to 87 GPa. As the fiber is heated, the modulus gradually increases. E Glass fibers that have been annealed to compact their atomic structure will increase in Young's modulus from 72 GPa to 84.7 GPa [4]. For most silicate glasses, Poisson's ratio falls between 0.15 and 0.26 [9]. The Poisson's ratio for E Glasses is 0.22 ± 0.02 and is reported not to change with temperature when measured up to 510°C [10].

High strength S-2 Glass fibers' annealed properties measured at 20°C are as follows:

- Young's Modulus 93.8 GPa
- Shear Modulus 38.1 GPa
- Poisson's Ratio 0.23
- Bulk Density 2.488 g/cc

CHEMICAL RESISTANCE

The chemical resistance of glass fibers to the corrosive and leaching actions of acids, bases, and water is expressed as a percent weight loss. The lower this value, the more resistant the glass is to the corrosive solution. The test procedure involves subjecting a given weight of 10 micron diameter glass fibers, without binders or sizes, to a known volume of corrosive solution held at 96°C. The fibers are held in the solution for the time desired and then are removed, washed, dried, and weighed to determine the weight loss. The results reported are for 24-hr (1 day) and 168-hr (1 week) exposures. As Table 3 shows, the chemical resistance of glass fibers depends on the composition of the fiber, the corrosive solution, and the exposure time.

It should be noted that glass corrosion in acidic environments is a complex process beginning with an initial fast corrosion rate. (Note the similarity in weight loss between the 1-day and 1-week samples treated with acid in Table 3.) With further time, an effective barrier of leached glass is established on the surface of the fiber and the corrosion rate of the remaining unleached fiber slows, being controlled

by the diffusion of compounds through the leached layer. Later, the corrosion rate slows to nearly zero as the non-silica compounds of the fiber are depleted.

For a given glass composition, the corrosion rate may be influenced by the acid concentration (Figure 3), temperature, fiber diameter, and the solution volume to glass mass ratio. In alkaline environments weight loss measurements are more subjective as the alkali affects the network and reprecipitates the metal oxides. Tensile strength after exposure is a better indicator of the residual glass fiber properties as shown in Figure 4 for 24-hour exposure at 96°C.

ELECTRICAL PROPERTIES

The electrical properties in Table 3 were measured on annealed bulk glass samples according to the testing procedures cited [11-13]. The dielectric constant or relative permittivity is the ratio of the capacitance of a system with the specimen as the dielectric to the capacitance of the system with a vacuum as the dielectric. Capacitance is the ability of the material to store an electrical charge. Permittivity values are affected by test frequency, temperature, voltage, relative humidity, water immersion, and weathering.

The dissipation factor of a dielectric is the ratio of the parallel reactance to the parallel resistance, or the tangent of the loss angle, which is usually called the loss tangent. It is also the reciprocal of the quality factor, and when the values are small, tangent of the loss angle is essentially equal to the power factor, or sine of the loss angle. The power factor is the ratio of power watts dissipated in the dielectric to the effective volt-amperes. The dissipation factor is dimensionless. In almost every electrical application, low value for the dissipation factor is desired. This reduces the internal heating of the material and keeps signal distortion low. The dissipation factor is generally measured simultaneously with permittivity measurements, and is greatly influenced by frequency, humidity, temperature, and water immersion. The loss factor, or loss index, as it is sometimes called, is occasionally confused with the dissipation factor, or loss tangent. The loss factor is simply the product of the dissipation factor and permittivity and is proportional to the energy loss in the dielectric.

The dielectric breakdown voltage, the voltage at which electrical failure occurs under prescribed test conditions in an electrical insulating material that is placed between two electrodes. When the thickness of the insulating material between the electrodes

can be accurately measured, the ratio of the dielectric breakdown voltage to the specimen thickness can be expressed as the dielectric strength kV/cm. Breakdown voltages are influenced by electrode geometry, specimen thickness (because dielectric strength varies approximately as the reciprocal of the square root of the thickness), temperature, voltage application time, voltage wave form, frequency, surrounding medium, relative humidity, water immersion, and directionality in laminated and inhomogeneous plastics.

THERMAL PROPERTIES

The viscosity of a glass decreases as the temperature increases. Figure 5 shows the viscosity-temperature plots for E Glass and S-2 Glass fibers. Note that the S-2 Glass fibers' temperature at viscosity is 150-260°C higher than that of E Glass, which is why S-2 Glass fibers have higher use temperatures than E Glass.

Several reference viscosity points are defined by the glass industry as used in Table 2. The softening point is the temperature at which a glass fiber of uniform diameter elongates at a specific rate under its own weight when measured by ASTM C 338 [14]. The softening point is defined as the temperature at which glass will deform under its own weight; it occurs at a viscosity of approximately 106.6 Pa.s (107.6 P). The annealing point is the temperature corresponding to either a specific rate of elongation of a glass fiber when measured by ASTM C 336 [15], or a specific rate of midpoint deflection of a glass beam when measured by ASTM C 598 [16]. At the annealing point of glass, internal stresses are substantially relieved in a matter of minutes. The viscosity at the annealing point is approximately 1012 Pa.s (1013 P). The strain point is measured following ASTM C 336 or C 598 as described above for annealing point. At the strain point of glass, internal stresses are substantially relieved in a matter of hours. The viscosity at the strain point is approximately 1013.5 Pa.s (1014.5 P).

The mean coefficient of thermal expansion over the temperature range from -30° to 250°C is provided in Table 3. The expansion measurements were made on annealed bars using ASTM D 696[17]. A lower coefficient of thermal expansion in the high strength glasses allows higher dimensional stability at temperature extremes.

The specific heat data in Table 3 was determined using high temperature differential scanning calorimetry techniques. In gen-

eral, the average specific heat values can be represented as follows: 0.94 kJ/kg·K at 200°C, 1.12 kJ/kg·K just below the transition point, and 1.40 kJ/kg·K in the liquid state above the transition. These values are accurate to about $\pm 5\%$. Above the transition temperature, no further increase in specific heat was observed. The transition temperature is nearly identical to the annealing temperature of bulk glass. Thermal conductivity characteristics in glasses differ considerably from those found in crystalline materials. For glasses, the conductivity is lower than that of the corresponding crystalline materials. Also, the conductivity of glasses drops steadily with temperature and reaches very low values, near absolute zero. For crystals, the conductivity continues to rise with decreasing temperature until very low temperatures are reached [18]. Thermal conductivity data for glass varies among investigators for materials which are normally identical [19]. In general fused silica glass and the alkali and alkaline earth silicate glasses have relatively similar conductivities at room temperature, whereas conductivities of borosilicate and glass that contain lead and barium are somewhat lower. Near room temperature, the thermal conductivity for glasses ranges from 0.55 W/m·K for lead silicate (80% lead oxide, 20% silicon dioxide) to 1.4 W/m·K for fused silica glass [20]. E. H. Ratcliffe developed property coefficients for predicting thermal conductivity from the percentage weight compositions of component oxides making up the glass [20]. Using this calculation, it is found that the approximate thermal conductivity of C Glass is 1.1 W/m·K, E Glass is 1.3 W/m·K, and S-2 Glass fibers is 1.45 W/m·K near room temperature.

OPTICAL PROPERTIES

Refractive index is measured on either unannealed or annealed glass fibers. The standard oil immersion techniques are used with monochromatic sodium D light at 25°C. In general, the corresponding annealed glass will exhibit an index that will range from approximately 0.003 to 0.006 higher than the as-formed glass fibers given in Table 2.

RADIATION PROPERTIES

E Glass and S-2 Glass fibers have excellent resistance to all types of nuclear radiation. Alpha and beta radiation have almost no effect, while gamma radiation and neutron bombardment produce a 5 to 10% decrease in tensile strength, a less than 1% decrease in density, and a slight discoloration of fibers. This data was true to 1020 NVT neutrons or gamma radiation up to 105 J/g. Glass fibers resist radiation because

the glass is amorphous, and the radiation does not distort the atomic ordering. Glass can also absorb a few percent of foreign material and maintain the same properties to a reasonable degree. Also, because the individual fibers have a small diameter, the heat of atomic distortion is easily transferred to a surface for dispersion.

E Glass and C Glass are not recommended for use inside atomic reactors because of their high boron content. S-2 Glass fibers are suitable for use inside atomic reactors. Because quite a wide variety of organic products are used in diverse radiation environments, it is usually necessary to try out most products in simulated conditions to determine whether the organics will be satisfactory.

Glass Fiber Size Treatments

The surface treatment chemistry of glass fiber follows the necessary product function. Textile size chemistries based on starch or polyvinyl alcohol film formers are capable in weaving, braiding, or knitting processes. Typically the weaver then scours or heat cleans the glass fabric and applies a finish compatible with the end product. Nonwoven size chemistries often include dispersants compatible with white water chemistry for wet formed mats or additives compatible with dry or wet binder chemistry for dry formed mats. Reinforcement size chemistries must be compatible with a multitude of processes and with the composite material end use performance criteria. Processes such as injection molding require chopped fibers with compatibility for thermoplastic compounds. Filament winding and pultrusion require continuous fibers with utility in thermoset and thermoplastic compounds. Typically three basic components are used with high strength glass size chemistries: a film former, lubricant, and coupling agent. Table 4 outlines evolutionary research for glass fiber size chemistry by each component's role.

Fiber Composite Utility

COMPOSITE PROPERTIES

Application of glass fiber composite materials depends on proper utilization of glass composition, size chemistry, fiber orientation, and fiber volume in the appropriate matrix for desired mechanical, electrical, thermal, and other properties. Table 5 gives typical mechanical properties for high strength S-2 Glass fibers epoxy with unidirectional fiber orientation. The elastic constants and strain allowables are used

for design input. The effect of glass composition and fiber volume in epoxy are shown in Figure 6 for the coefficient of thermal expansion and in Figure 7 for dielectric constant. The S-2 Glass fibers lower dielectric constant and therefore the potential for better radar transparency.

ENVIRONMENTAL DURABILITY

The durability of glass fiber composite materials is one of the features that attract users to them. Composites do not corrode like metals and are low maintenance materials. However, the durability and reliability in specific applications is often requested for design input. In load bearing structures, the long-term behavior of the material is needed to complete the design of the structure. How much load will the structure hold and survive for a given period of time? Or, how thick must the part be to handle a load for a given period of time?

These questions are usually addressed empirically, with accelerated testing. ASTM D 2992 and ASTM D 3681 for example are methods often incorporated in the practice of evaluating and designing composite pipe. In these methods, actual prototype products are manufactured and loaded in simulated environments for which the product is intended. To accelerate testing, the loads are significantly higher than operating conditions to induce failure in a relatively short period of time. The extrapolation of short-term data to the expected life of the product allows engineers to predict safe operating loads (stresses) for the purpose of design. This practice has served the composites industry well for over 30 years.

To demonstrate this process, the results of several test series are reported. Tests were conducted using pultruded rods made of glass fibers and thermoset resins. These tests are similar to those referenced in ASTM except the loading condition is pure tension and under a constant load. Figure 8 summarizes stress rupture testing using S-2 Glass fibers in epoxy with and without an adverse environment, a calcium hydroxide solution with a pH of 13. For reference, the initial tensile strength of the composite rod was 2070 MPa. The stress rupture behavior of an S-2 Glass fibers/epoxy rod in this test indicates a long-term stress capability of 65% of the initial ultimate tensile stress. As expected, the stress rupture behavior of the composite material affected by the presence of the environment. The long-term stress capability of this material in the high pH environment is roughly 50% of the initial ultimate tensile strength.

A second test series compared the stress rupture performance of E glass and S-2 Glass reinforcements in epoxy resin with the high pH environmental exposure. Figure 9 summarizes this data. The S-2 Glass fibers reinforced composite rod had higher initial tensile stress than the E Glass reinforced rod. The influence of the combined effects of stress and environment were similar for the two materials.

Recent Advancements

No industry remains static. Customer demand for improved performance has driven the industry to develop improved products by innovating new compositions that surpass the traditional offerings outlined in Table 1. Table 6 summarizes the key properties of some important new glass types. Just as D glass was an attempted improvement upon the electrical properties of E glass, even better dielectric performance has been achieved with a new glass fiber composition termed L-Glass. For applications where even lower dielectric loss is required, such as in 5G high speed telecommunication, L-2 Glass (an improvement upon L-Glass) was recently commercialized. An admirable overview of this technology space is given in reference [21].

S-3 HDI, standing for High Density Interconnect, was developed as a highly specialized PCB reinforcement for compatibility with FC-LGA (flip chip) processor applications. S-3 HDI is characterized by excellent mechanical and thermal stability, which are married with electrical performance that is superior to E glass.

Many cost sensitive applications that could benefit from a glass like S-2 Glass never adopted R glass due mainly to unreliable manufacturing. S-1 HM is a strong, high elastic modulus glass fiber that is easily manufactured in traditional glass melting furnaces. Designed specifically as a lower cost alternative to S-2 Glass, S-1 HM has found its way into numerous high performance applications that require superior mechanical performance at a non-specialty price point. An in depth review of this topic was published by Hausrath [22].

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Table 1 COMPOSITION RANGES FOR GLASS FIBERS

CHEMICAL PROPERTIES

	A glass	C glass	D glass	E glass	ECR glass	AR glass	R glass	S-2 Glass®
Oxide	%	%	%	%	%	%	%	%
SiO ₂	63–72	64–68	72–75	52–56	54–62	55–75	55–60	64–66
Al ₂ O ₃	0–6	3–5	0–1	12–16	9–15	0–5	23–28	24–25
B ₂ O ₃	0–6	4–6	21–24	5–10		0–8	0–0.35	
CaO	6–10	11–15	0–1	16–25	17–25	1–10	8–15	0–0.2
MgO	0–4	2–4		0–5	0–4		4–7	9.5–10
ZnO					2–5			
BaO		0–1						
Li ₂ O						0–1.5		
Na ₂ O + K ₂ O	14–16	7–10	0–4	0–2	0–2	11–21	0–1	0–0.2
TiO ₂	0–0.6			0–1.5	0–4	0–12		
ZrO ₂						1–18		
Fe ₂ O ₃	0–0.5	0–0.8	0–0.3	0–0.8	0–0.8	0–5	0–0.5	0–0.1
F ₂	0–0.4			0–1		0–5	0–0.3	

Table 2 PROPERTIES OF GLASS FIBERS

PHYSICAL PROPERTIES

	A glass	C glass	D glass	E glass	ECR glass	AR glass	R glass	S-2 Glass®
Density g/cc	2.44	2.52	2.11-2.14	2.58	2.72	2.70	2.54	2.46
Refractive Index	1.538	1.533	1.465	1.558	1.579	1.562	1.546	1.521
Softening Point °C (°F)	705 (1300)	750 (1382)	771 (1420)	846 (1555)	882 (1619)	773 (1424)	952 (1745)	1056 (1932)
Annealing Point °C (°F)		588 (1090)	521 (970)	657 (1215)			760 (1400)	816 (1500)
Strain Point °C (°F)		522 (1025)	477 (890)	615 (1140)			736 (1357)	766 (1410)
Tensile Strength MPa								
-196 °C		5380		5310	5310			8275
23 °C	3310	3310	2415	3445	3445	3241	4135	4890
371 °C				2620	2165		2930	4445
538 °C				1725	1725		2140	2415
Young's Modulus GPa								
23 °C	68.9	68.9	51.7	72.3	80.3	73.1	85.5	86.9
538 °C				81.3	81.3			88.9
Elongation at Break %	4.8	4.8	4.6	4.8	4.8	4.4	4.8	5.7

Table 3 PROPERTIES OF GLASS FIBERS

	A glass	C glass	D glass	E glass	ECR glass	AR glass	R glass	S-2 Glass®
CHEMICAL PROPERTIES								
Durability (% weight loss)								
H ₂ O: 24 hr	1.8	1.1	0.7	0.7	0.6	0.7	0.4	0.5
168 hr	4.7	2.9	5.7	0.9	0.7	1.4	0.6	0.7
10% HCl: 24 hr	1.4	4.1	21.6	42.0	5.4	2.5	9.5	3.8
168 hr		7.5	21.8	43.0	7.7	3.0	10.2	5.1
10% H ₂ SO ₄ : 24 hr	0.4	2.2	18.6	39.0	6.2	1.3	9.9	4.1
168 hr	2.3	4.9	19.5	42.0	10.4	5.4	10.9	5.7
10% Na ₂ CO ₃ : 24 hr		24.0	13.6	2.1		1.3	3.0	2.0
168 hr		31.0	36.3	2.1	1.8	1.5		2.1
ELECTRICAL PROPERTIES								
Dielectric Constant								
1MHz	6.2	6.9	3.8	6.6	6.9	8.1	6.4	5.3
10 GHz			4.0	6.1	7.0			5.2
Dissipation Factor								
1MHz		0.0085	0.0005	0.0025	0.0028		0.0034	0.0020
10GHz			0.0026	0.0038	0.0031		0.0051	0.0068
Volume Resistivity (ohm-cm)	1.0E + 10			4.02E+14	3.84E+14		2.03E+14	9.05E+12
Surface Resistivity (ohms)				4.20E+15	1.16E+16		6.74E+13	8.86E+12
Dielectric Strength (volts/mil)				262	250		274	330
THERMAL PROPERTIES								
Specific Heat J/g°C (BTU/lb°F)								
23°C	0.796 (0.190)	0.787 (0.188)	0.733 (0.176)	0.810 (0.193)			0.732 (0.175)	0.737 (0.176)
200°C		0.900 (0.215)		1.03 (0.247)	0.97 (0.232)		0.938 (0.224)	
Thermal Expansion								
Coefficient (x 10 ⁻⁷)	°C (°F)	°C (°F)	°C (°F)	°C (°F)	°C (°F)	°C (°F) °	C (°F)	°C (°F)
-30°C to 250°C	73 (41)	63 (35)	25 (14)	54 (30)	59 (33)	65 (36)	33 (18)	29 (16)

Table 4 GLASS FIBER SIZE CHEMISTRY SUMMARY

Nomenclature	Typical Chemistry	Role	Evolutionary Technology
Film Formers	Epoxies, polyesters, PVAc, EVAc, polyolefins, polyurethanes, etc.	Fiber protection, strand integrity, wetting and solubility.	Improved thermal stability, low surfactant, controlled solubility, etc
Lubricants	Imidazolines, tetraethylene amide, mineral oil/amide ester, acid amide, polyethylene glycols, etc.	Strand integrity, surface friction, improved fiber forming.	"Non-migrating" lubes, functionalized lubes.
Emulsifiers	EO/PO condensate polyoxyethylene octyphenyl glycol ether, etc.	Render file former and lubes water compatible.	Fugitive emulsifiers, functionalized emulsifiers.
Coupling Agents	Silanes, titanates, zirconates.	Resin/glass bonding.	Improved thermal stability, bonding to new materials.
Other Additives			
Antistats	Metal halides, quat. Ammonium, etc.	Increase conductivity.	Less-hygroscopic species.
pH Control	Organic acids/bases.	Control pH.	Improved coupling stability.
Nucleating Agents	See Patent literature.	Surface nucleation.	Encourage transcrystallinity.

Table 5 S-2 GLASS® FIBER UNIDIRECTIONAL EPOXY COMPOSITE PROPERTIES

Property (Test Standard)	ASTM Standard	Epoxy	
Elastic Constants (22°C/75°F)			
		GPa	Msi
Longitudinal Modulus, E_L	D3039	53–59	7.7–8.5
Transverse Modulus, E_T	D3039	16–20	2.3–2.9
Axial Shear Modulus, G_{LT}	D3518	6–9	0.9–1.3
Poisson's Ratio, ν_{LT}	D3039		0.26–0.28
Strength Properties			
		MPa	Ksi
Longitudinal Tension, F_L^{tu}	D3039	1540–2000	230–290
Longitudinal Compression, F_L^{cu}	D3410	690–1240	100–180
Transverse Tension, F_T^{tu}	D3039	41–82	6–12
Transverse Compression, F_T^{cu}	D3410	110–200	16–29
In-Plane Shear, F_{LT}^{su}	D3518	62–165	9–24
Interlaminar Shear, F^{isu}	D2344	55–103	8–15
Longitudinal Flexural	D790	1240–1720	180–250
Longitudinal Bearing	D953	469-552	68–80
Ultimate Strain			
Longitudinal Tension, ϵ_L^{tu}	D3039	2.7–3.5%	
Longitudinal Compression, ϵ_L^{cu}	D3410	1.1–1.8%	
Transverse Tension, ϵ_T^{tu}	D3039	0.25–0.50%	
Transverse Compression, ϵ_T^{cu}	D3410	1.1–2.0%	
In-Plane Shear, γ_{LT}^{su}	D3518	1.6–2.5%	
Physical Properties			
Fiber Volume (%)	D2734	57–63%	
Density g/cm ³ (lb/in ³)	D792	1.96–2.02 (0.071–0.073)	

Table 6 NEW PRODUCTS

PHYSICAL PROPERTIES

	L-Glass	L-2 Glass	S-3 HDI	S-1 HM
Density, g/cc	2.27–2.29	2.24–2.26	2.42–2.44	2.56–2.58
Refractive Index	1.496–1.500	1.488–1.5492	1.516–1.520	1.544–1.548
Softening Point, °C (°F)	861 (1582)	930 (1706)	940 (1724)	948 (1738)
Annealing Point, °C (°F)	622 (1152)	638 (1180)	715 (1319)	748 (1378)
Strain Point, °C (°F)	584 (1083)	586 (1087)	655 (1211)	693 (1279)
Coefficient of Thermal Expansion, $\times 10^{-7} / ^\circ\text{C}$	39	31	35	47
<hr/>				
Tensile Strength, MPa			4630	4300
Tensile Modulus, GPa	51	47	86	90
Impregnated Strand Tensile Strength, MPa			3270–3360	2900–3135
Impregnated Strand Tensile Modulus, GPa			85–86	89–91
Specific Tensile Strength, $\times 10^3 \text{ m}$			141	120
Specific Tensile Modulus, $\times 10^6 \text{ m}$			3.57	3.59
<hr/>				
Dielectric Constant, e' , 1 MHz	4.70		5.50	
Dielectric Constant, e' , 10 GHz	4.86	4.38	5.34	
Dielectric Loss, tan d, 1 MHz	<0.001		0.0050	
Dielectric Loss, tan d, 10 GHz	0.0029	0.0021	0.0075	
Volume Resistivity, r_v , $\times 10^{15}$ Ohms-cm, 500 V, 22°C	6.76		0.48	
Surface Resistivity, r_s , $\times 10^{15}$ Ohms, 500 V, 22°C	1.48		5.33	
Dielectric Breakdown, kV/m, 500 V/s	12.20		11.20	

Fig. 1 CONTINUOUS GLASS FIBER MANUFACTURING PROCESS

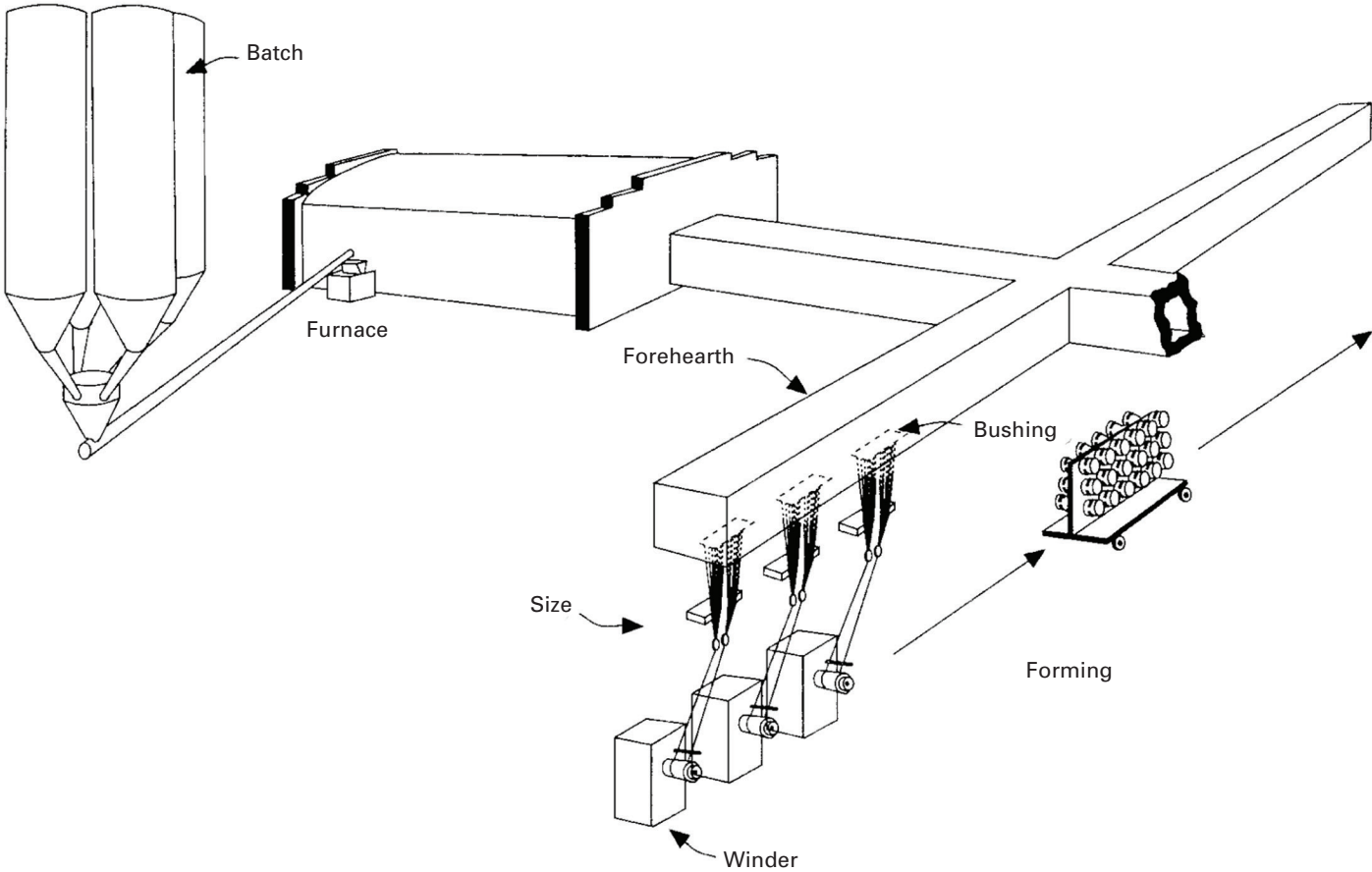


Fig. 2 FIBER TENSILE STRENGTH AT TEMPERATURE

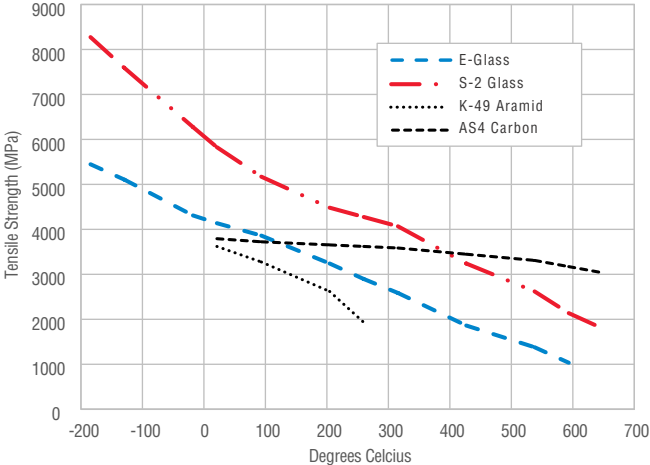


Fig. 3 FIBER WEIGHT RETENTION VS. PH EXPOSURE

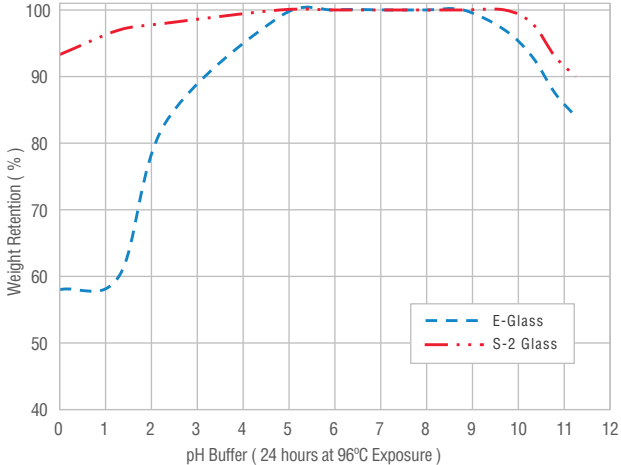


Fig. 4 FIBER STRENGTH VS. PH EXPOSURE

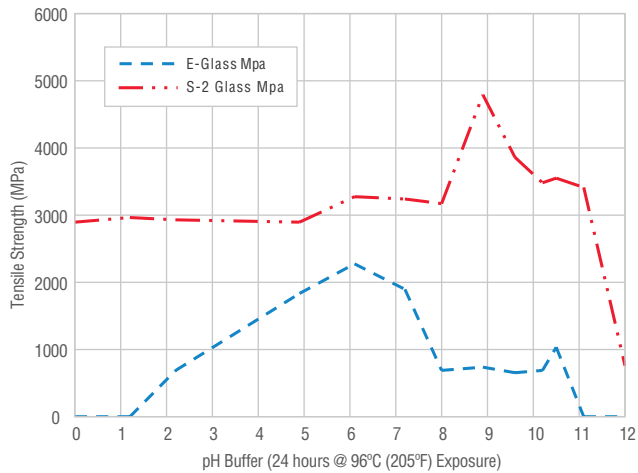


Fig. 5 GLASS VISCOSITY VS. TEMPERATURE

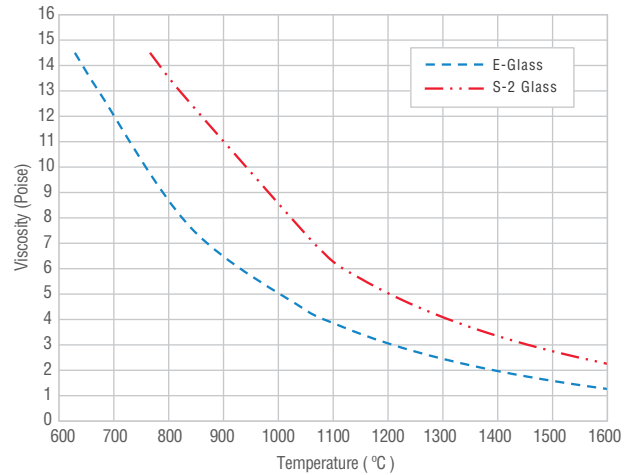


Fig. 6 DIMENSIONAL STABILITY

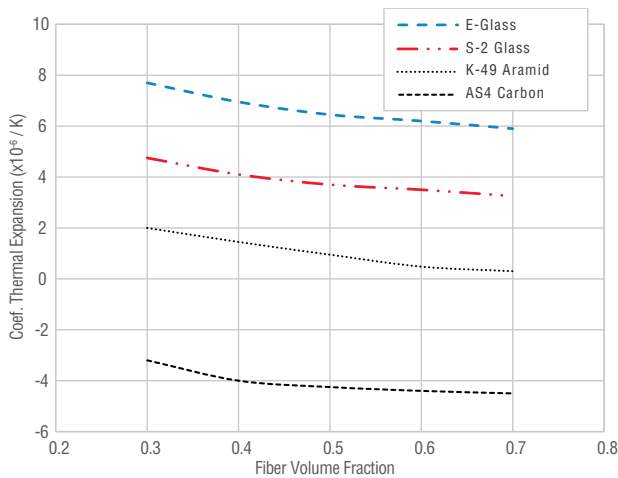


Fig. 7 DIELECTRIC TRANSPARENCY VS. FIBER VOLUME FRACTION IN EPOXY

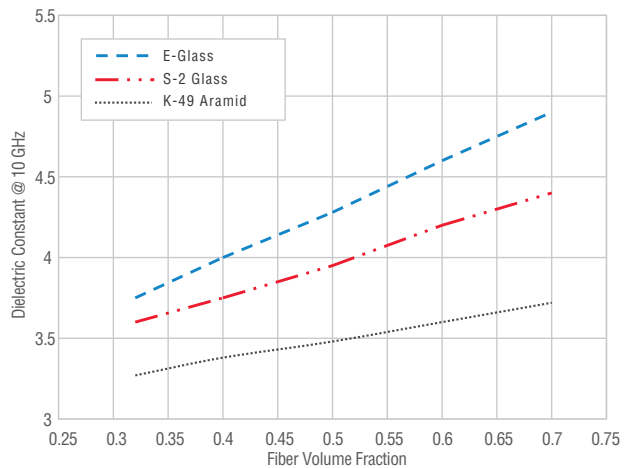


Fig. 8 ENVIRONMENTAL STRESS RUPTURE IN EPOXY

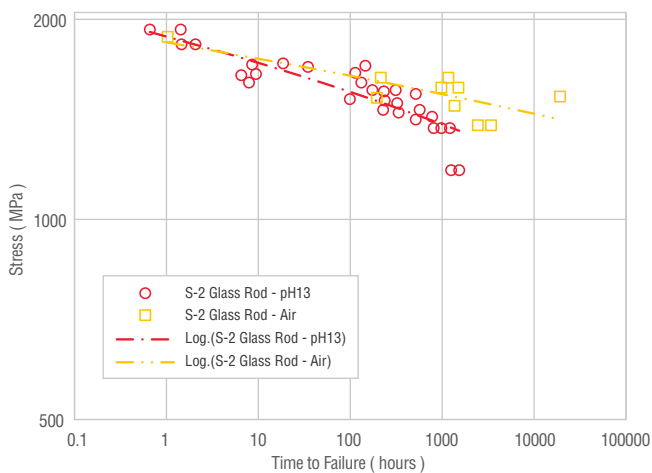
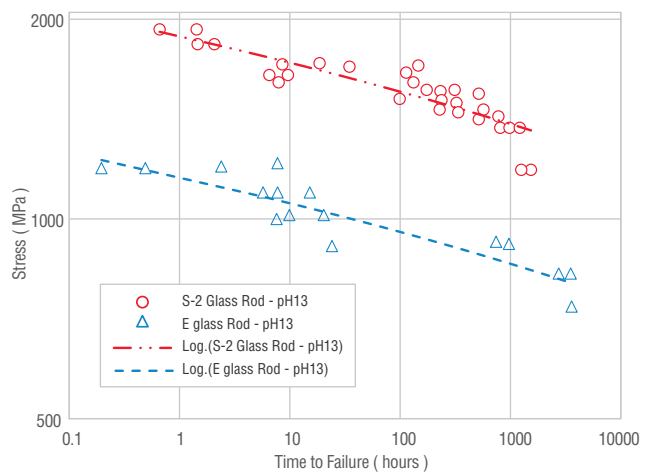


Fig. 9 ENVIRONMENTAL STRESS RUPTURE IN EPOXY



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For more information, visit us at www.agy.com



WORLD HEADQUARTERS

2556 Wagener Road
Aiken, South Carolina 29801 USA
Phone: +(1) 888.434.0945 (toll free)
T: +(1) 803.643.1501
Fax: +(1) 803.643.1180

EUROPE

Le Gemellyon Nord
57 Boulevard Marius Vivier Merle
69003 Lyon, France
Phone: +(33) 4727 81775
Fax: +(33) 4727 81780

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