Composites Basics: Materials

Introduction

Fiber Reinforced Polymer (FRP) composites is defined as a polymer (plastic) matrix, either thermoset or thermoplastic, that is reinforced (combined) with a fiber or other reinforcing material with a sufficient aspect ratio (length to thickness) to provide a discernable reinforcing function in one or more directions. FRP composites are different from traditional construction materials such as steel or aluminum. FRP composites are anisotropic (properties only apparent in the direction of the applied load) whereas steel or aluminum is isotropic (uniform properties in all directions, independent of applied load). Therefore, FRP composite properties are directional, meaning that the best mechanical properties are in the direction of the fiber placement. Composites are similar to reinforced concrete where the rebar is embedded in an isotropic matrix called concrete.

Many terms have been used to define FRP composites. Modifiers have been used to identify a specific fiber such as Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), and Aramid Fiber Reinforced Polymer (AFRP). Another familiar term used is Fiber Reinforced Plastics. In addition, other acronyms were developed over the years and its use depended on geographical location or market use. For example, Fiber Reinforced Composites (FRC), Glass Reinforced Plastics (GRP), and Polymer Matrix Composites (PMC) can be found in many references. Although different, each of aforementioned terms mean the same thing; FRP composites.

Benefits

FRP composites have many benefits to their selection and use. The selection of the materials depends on the performance and intended use of the product. The composites designer can tailor the performance of the end product with proper selection of materials. It is important for the end-user to understand the application environment, load performance and durability requirements of the product and convey this information to the composites industry professional. A summary of composite material benefits include:

- Light weight

- High strength-to-weight ratio
- Directional strength
- Corrosion resistance
- Weather resistance
- Dimensional stability
    - low thermal conductivity
    - low coefficient of thermal expansion
- Radar transparency
- Non-magnetic
- High impact strength
- High dielectric strength (insulator)
- Low maintenance
- Long term durability
- Part consolidation
- Small to large part geometry possible
- Tailored surface finish

Composition

Composites are composed of resins, reinforcements, fillers, and additives. Each of these constituent materials or ingredients play an important role in the processing and final performance of the end product. The resin or polymer is the “glue” that holds the composite together and influences the physical properties of the end product. The reinforcement provides the mechanical strength. The fillers and additives are used as process or performance aids to impart special properties to the end product.

The mechanical properties and composition of FRP composites can be tailored for their intended use. The type and quantity of materials selected in addition to the manufacturing process to fabricate the product, will affect the mechanical properties and performance. Important considerations for the design of composite products include:

- Type of fiber reinforcement
- Percentage of fiber or fiber volume
- Orientation of fiber (0^o, 90^o, +/- 45 ^{o}or a combination of these)
- Type of resin
- Cost of product
- Volume of production (to help determine the best manufacturing method)
- Manufacturing process
- Service conditions

Resins

The primary functions of the resin are to transfer stress between the reinforcing fibers, act as a glue to hold the fibers together, and protect the fibers from mechanical and environmental damage. Resins are divided into two major groups known as thermoset and thermoplastic. Thermoplastic resins become soft when heated, and may be shaped or molded while in a heated semi-fluid state and become rigid when cooled. Thermoset resins, on the other hand, are usually liquids or low melting point solids in their initial form. When used to produce finished goods, these thermosetting resins are “cured” by the use of a catalyst, heat or a combination of the two. Once cured, solid thermoset resins cannot be converted back to their original liquid form. Unlike thermoplastic resins, cured thermosets will not melt and flow but will soften when heated (and lose hardness) and once formed they cannot be reshaped. Heat Distortion Temperature (HDT) and the Glass Transition Temperature (Tg) is used to measure the softening of a cured resin. Both test methods (HDT and Tg) measure the approximate temperature where the cured resin will soften significantly to yield (bend or sag) under load.

The most common thermosetting resins used in the composites industry are unsaturated polyesters, epoxies, vinyl esters and phenolics. There are differences between these groups that must be understood to choose the proper material for a specific application.

Polyester

Unsaturated polyester resins (UPR) are the workhorse of the composites industry and represent approximately 75% of the total resins used. To avoid any confusion in terms, readers should be aware that there is a family of thermoplastic polyesters that are best known for their use as fibers for textiles and clothing. Thermoset polyesters are produced by the condensation polymerization of dicarboxylic acids and difunctional alcohols (glycols). In addition, unsaturated polyesters contain an unsaturated material, such as maleic anhydride or fumaric acid, as part of the dicarboxylic acid component. The finished polymer is dissolved in a reactive monomer such as styrene to give a low viscosity liquid. When this resin is cured, the monomer reacts with the unsaturated sites on the polymer converting it to a solid thermoset structure.

A range of raw materials and processing techniques are available to achieve the desired properties in the formulated or processed polyester resin. Polyesters are versatile because of their capacity to be modified or tailored during the building of the polymer chains. They have been found to have almost unlimited usefulness in all segments of the composites industry. The principal advantage of these resins is a balance of properties (including mechanical, chemical, electrical) dimensional stability, cost and ease of handling or processing.

Unsaturated polyesters are divided into classes depending upon the structures of their basic building blocks. Some common examples would be orthophthalic (“ortho”), isophthalic (“iso”), dicyclopentadiene (“DCPD”) and bisphenol A fumarate resins. In addition, polyester resins are classified according to end use application as either general purpose (GP) or specialty polyesters.

Polyester producers have proved willing and capable of supplying resins with the necessary properties to meet the requirements of specific end use applications. These resins can be formulated and chemically tailored to provide properties and process compatibility.

Epoxy

Epoxy resins have a well-established record in a wide range of composite parts, structures and concrete repair. The structure of the resin can be engineered to yield a number of different products with varying levels of performance. A major benefit of epoxy resins over unsaturated polyester resins is their lower shrinkage. Epoxy resins can also be formulated with different materials or blended with other epoxy resins to achieve specific performance features. Cure rates can be controlled to match process requirements through the proper selection of hardeners and/or catalyst systems. Generally, epoxies are cured by addition of an anhydride or an amine hardener as a 2-part system. Different hardeners, as well as quantity of a hardener produce a different cure profile and give different properties to the finished composite.

Epoxies are used primarily for fabricating high performance composites with superior mechanical properties, resistance to corrosive liquids and environments, superior electrical properties, good performance at elevated temperatures, good adhesion to a substrate, or a combination of these benefits. Epoxy resins do not however, have particularly good UV resistance. Since the viscosity of epoxy is much higher than most polyester resin, requires a post-cure (elevated heat) to obtain ultimate mechanical properties making epoxies more difficult to use. However, epoxies emit little odor as compared to polyesters.

Epoxy resins are used with a number of fibrous reinforcing materials, including glass, carbon and aramid. This latter group is of small in volume, comparatively high cost and is usually used to meet high strength and/or high stiffness requirements. Epoxies are compatible with most composite manufacturing processes, particularly vacuum-bag molding, autoclave molding, pressure-bag molding, compression molding, filament winding and hand lay-up.

Vinyl Ester

Vinyl esters were developed to combine the advantages of epoxy resins with the better handling/faster cure, which are typical for unsaturated polyester resins. These resins are produced by reacting epoxy resin with acrylic or methacrylic acid. This provides an unsaturated site, much like that produced in polyester resins when maleic anhydride is used. The resulting material is dissolved in styrene to yield a liquid that is similar to polyester resin. Vinyl esters are also cured with the conventional organic peroxides used with polyester resins. Vinyl esters offer mechanical toughness and excellent corrosion resistance. These enhanced properties are obtained without complex processing, handling or special shop fabricating practices that are typical with epoxy resins.

Phenolic

Phenolics are a class of resins commonly based on phenol (carbolic acid) and formaldehyde. Phenolics are a thermosetting resin that cure through a condensation reaction producing water that should be removed during processing. Pigmented applications are limited to red, brown or black. Phenolic composites have many desirable performance qualities including high temperature resistance, creep resistance, excellent thermal insulation and sound damping properties, corrosion resistance and excellent fire/smoke/smoke toxicity properties. Phenolics are applied as adhesives or matrix binders in engineered woods (plywood), brake linings, clutch plates, circuit boards, to name a few.

Polyurethane

Polyurethane is a family of polymers with widely ranging properties and uses, all based on the exothermic reaction of an organic polyisocyanates with a polyols (an alcohol containing more than one hydroxl group). A few basic constituents of different molecular weights and functionalities are used to produce the whole spectrum of polyurethane materials. The versatility of polyurethane chemistry enables the polyurethane chemist to engineer polyurethane resin to achieve the desired properties.

Polyurethanes appear in an amazing variety of forms. These materials are all around us, playing important roles in more facets of our daily life than perhaps any other single polymer. They are used as a coating, elastomer, foam, or adhesive. When used as a coating in exterior or interior finishes, polyurethane's are tough, flexible, chemical resistant, and fast curing. Polyurethanes as an elastomer have superior toughness and abrasion is such applications as solid tires, wheels, bumper components or insulation. There are many formulations of polyurethane foam to optimize the density for insulation, structural sandwich panels, and architectural components. Polyurethanes are often used to bond composite structures together. Benefits of polyurethane adhesive bonds are that they have good impact resistance, the resin cures rapidly and the resin bonds well to a variety of different surfaces such as concrete.

Summary of Resins

The resins in thermoset composites are an important source of properties and process characteristics. One of the great design strengths of composites is the multiple choice of resins. In order to make effective use of these choices, designers and product specifiers should be familiar with the properties, advantages and limitations of each of the common composite resins. It is common to use the resources of the resin manufacturers laboratories to determine the best resin or an application.

Reinforcements

The primary function of fibers or reinforcements is to carry load along the length of the fiber to provide strength and stiffness in one direction. Reinforcements can be oriented to provide tailored properties in the direction of the loads imparted on the end product. Reinforcements can be both natural and man-made. Many materials are capable of reinforcing polymers. Some materials, such as the cellulose in wood, are naturally occurring products. Most commercial reinforcements, however, are man-made. Of these, by far the largest volume reinforcement measured either in quantity consumed or in product sales, is glass fiber. Other composite reinforcing materials include carbon, aramid, UHMW (ultra high molecular weight) polyethylene, polypropylene, polyester and nylon. Carbon fiber is sometimes referred to as graphite fiber. The distinction is not important in an introductory text, but the difference has to do with the raw material and temperature at which the fiber is formed. More specialized reinforcements for high strength and high temperature use include metals and metal oxides such as those used in aircraft or aerospace applications.

Development of Reinforcements- Fibers

Early in the development of composites, the only reinforcements available were derived from traditional textiles and fabrics. Particularly in the case of glass fibers, experience showed that the chemical surface treatments or “sizings” required to process these materials into fabrics and other sheet goods were detrimental to the adhesion of composite polymers to the fiber surface. Techniques to remove these materials were developed, primarily by continuous or batch heat cleaning. It was then necessary to apply new “coupling agents” (also known as finishes or surface treatments), an important ingredient in sizing systems, to facilitate adhesion of polymers to fibers, particularly under wet conditions and fiber processing.

Most reinforcements for either thermosetting or thermoplastic resins receive some form of surface treatments, either during fiber manufacture or as a subsequent treatment. Other materials applied to fibers as they are produced include resinous binders to hold fibers together in bundles and lubricants to protect fibers from degradation caused by process abrasion.

Glass Fibers

Based on an alumina-lime-borosilicate composition, “E” glass produced fibers are considered the predominant reinforcement for polymer matrix composites due to their high electrical insulating properties, low susceptibility to moisture and high mechanical properties. Other commercial compositions include “S” glass, with higher strength, heat resistance and modulus, as well as some specialized glass reinforcements with improved chemical resistance, such as AR glass (alkali resistant).

Glass fibers used for reinforcing composites generally range in diameter from 0.00035” to 0.00090” (9 to 23 microns). Fibers are drawn at high speeds, approaching 200 miles per hour, through small holes in electrically heated bushings. These bushings form the individual filaments. The filaments are gathered into groups or bundles called “strands.” The filaments are attenuated from the bushing, water and air cooled, and then coated with a proprietary chemical binder or sizing to protect the filaments and enhance the composite laminate properties. The sizing also determines the processing characteristics of the glass fiber and the conditions at the fiber-matrix interface in the composite.

Glass is generally a good impact resistant fiber but weighs more than carbon or aramid. Glass fibers have excellent characteristics, equal to or better than steel in certain forms. The lower modulus requires special design treatment where stiffness is critical. Composites made from this material exhibit very good electrical and thermal insulation properties. Glass fibers are also transparent to radio frequency radiation and are used in radar antenna applications.

Carbon Fibers

Carbon fiber is created using polyacrylonitrile (PAN), pitch or rayon fiber precursors. PAN based fibers offer good strength and modulus values up to 85-90 Msi. They also offer excellent compression strength for structural applications up to 1000 ksi. Pitch fibers are made from petroleum or coal tar pitch. Pitch fibers extremely high modulus values (up to 140 Msi) and favorable coefficient of thermal expansion make them the material used in space/satellite applications. Carbon fibers are more expensive than glass fibers, however carbon fibers offer an excellent combination of strength, low weight and high modulus. The tensile strength of carbon fiber is equal to glass while its modulus is about three to four times higher than glass.

Carbon fibers are supplied in a number of different forms, from continuous filament tows to chopped fibers and mats. The highest strength and modulus are obtained by using unidirectional continuous reinforcement. Twist-free tows of continuous filament carbon contain 1,000 to 75,000 individual filaments, which can be woven or knitted into woven roving and hybrid fabrics with glass fibers and aramid fibers.

Carbon fiber composites are more brittle (less strain at break) than glass or aramid. Carbon fibers can cause galvanic corrosion when used next to metals. A barrier material such as glass and resin is used to prevent this occurrence.

Aramid Fibers (Polyaramids)

Aramid fiber is an aromatic polyimid that is a man-made organic fiber for composite reinforcement. Aramid fibers offer good mechanical properties at a low density with the added advantage of toughness or damage/impact resistance. They are characterized as having reasonably high tensile strength, a medium modulus, and a very low density as compared to glass and carbon. The tensile strength of aramid fibers are higher than glass fibers and the modulus is about fifty percent higher than glass. These fibers increase the impact resistance of composites and provide products with higher tensile strengths. Aramid fibers are insulators of both electricity and heat. They are resistant to organic solvents, fuels and lubricants. Aramid composites are not as good in compressive strength as glass or carbon composites. Dry aramid fibers are tough and have been used as cables or ropes, and frequently used in ballistic applications.

Reinforcement Forms

Regardless of the material, reinforcements are available in forms to serve a wide range of processes and end-product requirements. Materials supplied as reinforcement include roving, milled fiber, chopped strands, continuous, chopped or thermoformable mat. Reinforcement materials can be designed with unique fiber architectures and be preformed (shaped) depending on the product requirements and manufacturing process.

Multi-End and Single-End Rovings

Rovings are utilized primarily in thermoset compounds, but can be utilized in thermoplastics. Multi-end rovings consist of many individual strands or bundles of filaments, which are then chopped and randomly deposited into the resin matrix. Processes such as sheet molding compound (SMC), preform and spray-up use the multi-end roving. Multi-end rovings can also be used in some filament winding and pultrusion applications. The single-end roving consists of many individual filaments wound into a single strand. The product is generally used in processes that utilize a unidirectional reinforcement such as filament winding or pultrusion.

Mats

Reinforcing mats are usually described by weight-per-unit-of-area. For instance, a 2 ounce chopped strand mat will weigh 2 ounces per square yard. The type and amount of binder that is used to hold the mat together dictate differences between mat products. In some processes such as hand lay-up, it is necessary for the binder to dissolve. In other processes, particularly in compression molding, the binder must withstand the hydraulic forces and the dissolving action of the matrix resin during molding. Therefore, two general categories of mats are produced and are known as soluble and insoluble.

Woven, Stitched, Braided & 3-D Fabrics

There are many types of fabrics that can be used to reinforce resins in a composite. Multidirectional reinforcements are produced by weaving, knitting, stitched or braiding continuous fibers into a fabric from twisted and plied yarn. Fabrics refer to all flat-sheet, roll goods, whether or not they are strictly fabrics. Fabrics can be manufactured utilizing almost any reinforcing fiber. The most common fabrics are constructed with fiberglass, carbon or aramid. Fabrics are available in several weave constructions and thickness (from 0.0010 to 0.40

inches). Fabrics offer oriented strengths and high reinforcement loadings often found in high performance applications.

Fabrics are typically supplied on rolls of 25 to 300 yards in length and 1 to 120 inches in width. The fabric must be inherently stable enough to be handled, cut and transported to the mold, but pliable enough to conform to the mold shape and contours. Properly designed, the fabric will allow for quick wet out and wet through of the resin and will stay in place once the resin is applied. Fabrics, like rovings and chopped strands, come with specific sizings or binder systems that promote adhesion to the resin system.

Fabrics allow for the precise placement of the reinforcement. This cannot be done with milled fibers or chopped strands and is only possible with continuous strands using relatively expensive fiber placement equipment. Due to the continuous nature of the fibers in most fabrics, the strength to weight ratio is much higher than that for the cut or chopped fiber versions. Stitched fabrics allow for customized fiber orientations within the fabric structure. This can be of great advantage when designing for shear or torsional stability.

Woven fabrics are fabricated on looms in a variety of weights, weaves, and widths. In a plain weave, each fill yarn or roving is alternately crosses over and under each warp fiber allowing the fabric to be more drapeable and conform to curved surfaces. Woven fabrics are manufactured where half of the strands of fiber are laid at right angles to the other half (0^o to 90^o). Woven fabrics are commonly used in boat manufacturing.

Stitched fabrics, also known as non-woven, non-crimped, stitched, or knitted fabrics have optimized strength properties because of the fiber architecture. Woven fabric is where two sets of interlaced continuous fibers are oriented in a 0^o and 90^o pattern where the fibers are crimped and not straight. Stitched fabrics are produced by assembling successive layers of aligned fibers. Typically, the available fiber orientations include the 0^o direction (warp), 90^o direction (weft or fill), and $\pm 45^o$ direction (bias). The assembly of each layer is then sewn together. This type of construction allows for load sharing between fibers so that a higher modulus, both tensile and flexural, is typically observed. The fiber architecture construction allows for optimum resin flow when composites are manufactured. These fabrics have been traditionally used in boat hulls for 50 years. Other applications include light poles, wind turbine blades, trucks, busses and underground tanks. These fabrics are currently used in bridge decks and column repair systems. Multiple orientations provide a quasi-isotropic reinforcement.

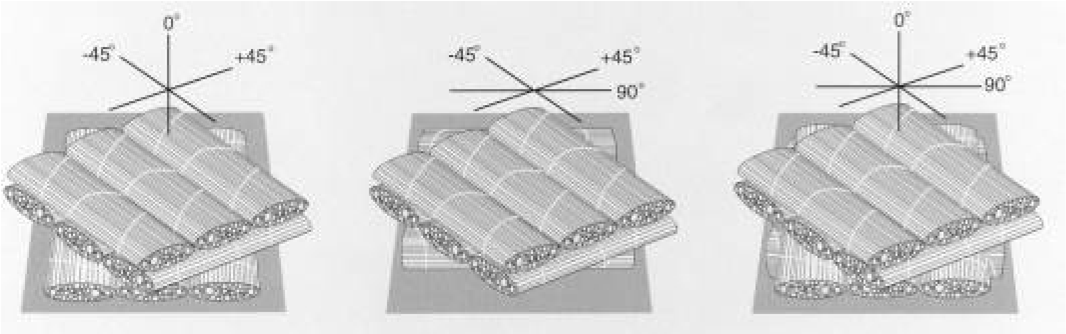
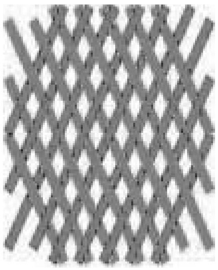
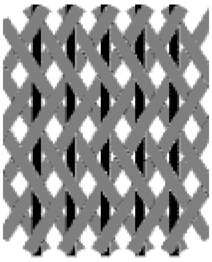


Diagram of Stitched Triaxial and Quadraxial Fabrics

Braided fabrics are engineered with a system of two or more yarns intertwined in such a way that all of the yarns are interlocked for optimum load distribution. Biaxial braids provide reinforcement in the bias direction only with fiber angles ranging from ± 15° to ± 95°. Triaxial braids provide reinforcement in the bias direction with fiber angles ranging from ± 10° to ± 80° and axial (0°) direction.



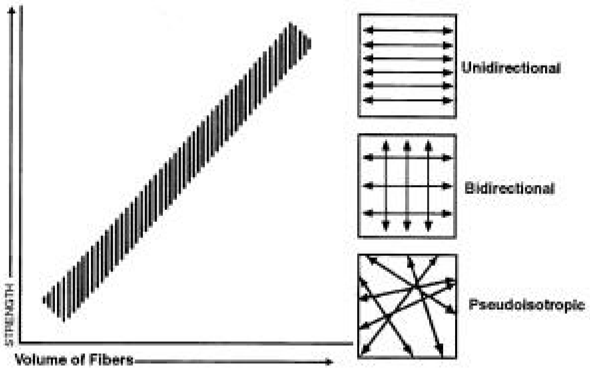
Biaxial Braided Fabric



Triaxial Braided Fabric

Unidirectional

Unidirectional reinforcements include tapes, tows, unidirectional tow sheets and rovings (which are collections of fibers or strands). Fibers in this form are all aligned parallel in one direction and uncrimped providing the highest mechanical properties. Composites using unidirectional tapes or sheets have high strength in the direction of the fiber. Unidirectional sheets are thin and multiple layers are required for most structural applications.



Strength Relation to Fiber Orientation [Schwarz (1992B)]

In some composite designs, it may be necessary to provide a corrosion or weather barrier to the surface of a product. A surface veil is a fabric made from nylon or polyester that acts as a very thin sponge that can absorb resin to 90% of its volume. This helps to provide an extra layer of protective resin on the surface of the product. Surface veils are used to improve the surface appearance and insure the presence of a corrosion resistance barrier for typical composites products such as pipes, tanks and other chemical process equipment. Other benefits include increased resistance to abrasion, UV and other weathering forces. Veils may be used in conjunction with gel coats to provide reinforcement to the resin.

Prepreg

Prepregs are a ready-made material made of a reinforcement form and polymer matrix. Passing reinforcing fibers or forms such as fabrics through a resin bath is used to make a prepreg. The resin is saturated (impregnated) into the fiber and then heated to advance the curing reaction to different curing stages. Thermoset or thermoplastic prepregs are available and can be either stored in a refrigerator or at room temperature depending on the constituent materials. Prepregs can be manually or mechanically applied at various directions based on the design requirements.

Summary of Reinforcements

The mechanical properties of FRP composites are dependent on the type, amount, and orientation of fiber that is selected for a particular service. There are many commercially available reinforcement forms to meet the design requirements of the user. The ability to tailor the fiber architecture allows for optmized performance of a product that translates to weight and cost savings.

Other Matrix Constituents

Fillers

Use of inorganic fillers in composites is increasing. Fillers not only reduce the cost of composites, but also frequently impart performance improvements that might not otherwise be achieved by the reinforcement and resin ingredients alone. Fillers can improve mechanical properties including fire and smoke performance by reducing organic content in composite laminates. Also, filled resins shrink less than unfilled resins, thereby improving the dimensional control of molded parts. Important properties, including water resistance, weathering, surface smoothness, stiffness, dimensional stability and temperature resistance, can all be improved through the proper use of fillers.

The thermosetting resin segment of the composite industry has taken advantage of the properties of fillers for many years. More recently, the thermoplastic industry has begun to make widespread use of inorganic fillers. Breakthroughs in chemical treatment of fillers that can provide higher filler loadings and improved laminate performance are accelerating this trend.

Filler Types

There are a number of inorganic filler materials that can be used with composites including:

- **Calcium carbonate** is the most widely used inorganic filler. It is available at low cost in a variety of particle sizes and treatments from well-established regional suppliers, especially for composite applications. Most common grades of calcium carbonate filler are derived from limestone or marble and very common in automobile parts.

- **Kaolin** (hydrous aluminum silicate) is the second most commonly used filler. It is known throughout the industry by its more common material name, clay. Mined clays are processed either by air flotation or by water washing to remove impurities and to classify the product for use in composites. A wide range of particle sizes is available.

- **Alumina trihydrate** is frequently used when improved fire/smoke performance is required. When exposed to high temperature, this filler gives off water (hydration), thereby reducing the flame spread and development of smoke. Composite plumbing fixture applications such as bathtubs, shower stalls and related building products often contain alumina trihydrate for this purpose.

- **Calcium sulfate** is a major flame/smoke retarding filler used by the tub/shower industry. It has fewer waters of hydration, and water is released at a lower temperature. This mineral filler offers a low cost flame/smoke retarding filler.

Other commonly used fillers include:

- Mica

- Feldspar

- Wollastonite

- Silica

- Talc
- Glass microspheres
- Flake glass
- Milled glass fibers
- Other microsphere product

Using Fillers in Composites

When used in composite laminates, inorganic fillers can account for 40 to 65% by weight. They perform a function similar to silica fume in concrete. In comparison to resins and reinforcements, fillers are the least expensive of the major ingredients. These materials are nevertheless very important in establishing the performance of the composite laminate for the following reasons:

- Fillers reduce the shrinkage of the composites part.
- Fillers influences the fire resistance of laminates.
- Fillers lower compound cost by diluting more expensive resin and may reduce the amount of reinforcement required.
- Fillers can influence the mechanical strengths of composites.
- Fillers serve to transfer stresses between the primary structural components of the laminate (i.e., resin and reinforcement), thereby improving mechanical and physical performance.
- Uniformity of the laminate can be enhanced by the effective use of fillers. Fillers help maintain fiber-loading uniformity by carrying reinforcing fibers along with the flow as resin is moved on the mold during compression molding.
- Crack resistance and crack prevention properties are improved with filled resin systems. This is particularly true in sharp corners and resin-rich areas where smaller particles in the filler help to reinforce the resin in these regions.
- The combination of small and medium filler particles helps control compound rheology at elevated temperatures and pressures, thereby helping to ensure that compression molded parts are uniform.

- Low-density fillers are used extensively in marine putty and the transportation industry. They offer the lowest cost of filled systems, without the increases of weight that affect the performance of the final product.

Surface Treatments Improve Some Fillers

Some fillers are chemically modified by treating the surface area of the particles with a coupling agent. These coupling agents help to improve the chemical bond between the resin and filler and can reduce resin demand.

Summary of Fillers

Effective use of fillers in composites can improve performance and reduce cost. In today’s market, many of the filler systems being sold are providing several different properties for the composite in one filler system. Flame/smoke, shrink control, weight management and physical properties are often modified by using a designed filler package that has a blend of specialty and commodity fillers. Product and technical information exists and is readily available to those interested in this very important composite ingredient that affects material, process and design and cost.

Additives and Modifiers

A wide variety of additives are used in composites to modify materials properties and tailor the laminate’s performance. Although these materials are generally used in relatively low quantity by weight compared to resins, reinforcements and fillers, they perform critical functions.

Additive Functions

Additive used in thermoset and thermoplastic composites include the following:

- **Low shrink/low profile**: when parts with smooth surfaces are required, a special thermoplastic resin, which moderates resin shrinkage, can be added to thermoset resins.

- **Fire resistance**: Combustion resistance is improved by proper choice of resin, use of fillers or flame retardant additives. Included in this category are materials containing antimony trioxide, bromine, chlorine, borate and phosphorus.

- **Air release**: most laminating resins, gel coats and other polyester resins might entrap air during processing and application. This can cause air voids and improper fiber wet-out. Air release additives are used to reduce such air entrapment and to enhance fiber wet-out.

- **Emission control**: in open mold applications, styrene emission suppressants are used to lower emissions for air quality compliance.
- **Viscosity control**: in many composite types, it is critical to have a low, workable viscosity during production. Lower viscosity in such filled systems is usually achieved by use of wetting and dispersing additives. These additives facilitate the wet-out and dispersion of fillers resulting in lower viscosity (and/or higher filler loading).
- **Electrical conductivity**: most composites do not conduct electricity. It is possible to obtain a degree of electrical conductivity by the addition of metal, carbon particles or conductive fibers. Electromagnetic interference shielding can be achieved by incorporating conductive materials.
- **Toughness**: can be enhanced by the addition of reinforcements. It can also be improved by special additives such as certain rubber or other elastomeric materials.
- **Antioxidants**: plastics are sometimes modified with antioxidants, which retard or inhibit polymer oxidation and the resulting degradation of the polymer.
- **Antistatic agents**: are added to polymers to reduce their tendency to attract electrical charge. Control of static electricity is essential in certain plastics processing and handling operations, as well as in finished products. Static charges on plastics can produce shocks, present fire hazard and attract dust. The effect of static charge in computer/data processing applications, for example, is particularly detrimental.
- **Foaming agents**: are chemicals that are added to polymers during processing to form minute cells throughout the resin. Foamed plastics exhibit lower density, decrease material costs, improve electrical and thermal insulation, increase strength-to-weight ratio and reduce shrinkage and part warping.
- **Plasticizers**: are added to compounds to improve processing characteristics and offer a wider range of physical and mechanical properties.
- **Slip and blocking agents** provide surface lubrication. This results in reduced coefficient of friction on part surfaces and enhances release of parts from the mold.

- **Heat stabilizers**: are used in thermoplastic systems to inhibit polymer degradation that results from exposure to heat.
- **Ultraviolet stabilizers**: both thermoset and thermoplastic composites may used special materials which are added to prevent loss of gloss, crazing, chalking, discoloration, changes in electrical characteristics, embrittlement and disintegration due to ultraviolet (UV) radiation. Additives, which protect composites by absorbing the UV, are called ultraviolet absorbers. Materials, which protect the polymer in some other manner, are known as ultraviolet stabilizers.

Catalysts, Promoters, Inhibitors

In polyesters, the most important additive is catalyst or initiator. Typically, organic peroxide such as methylethylketone peroxide (MEKP) is used for room temperature cured processes, or benzoyl peroxide is added to the resin for heat-cured molding. When triggered by heat, or used in conjunction with a promoter (such as cobalt napthenate), peroxides convert to a reactive state (exhibiting free radicals), causing the unsaturated resin to react (cross-link) and become solid. Some additives such as TBC (tertiary butyl catechol) are used to slow the rate of reaction and are called inhibitors. Accelerators such as DMA (dimethyl aniline) speed curing.

Colorants

Colorants are often used in composites to provide color throughout the part. Additives can be mixed in as part of the resin or applied as part of the molding process (as a gel coat). Also, a wide range of coatings can be applied after molding.

Release Agents

Release agents facilitate removal of parts from molds. These products can be added to the resin, applied to molds, or both. Zinc stearate is a popular mold release agent that is mixed into resin for compression molding. Waxes, silicones and other release agents may be applied directly to the surface of molds.

Thixotropic agents

In some processes such as hand lay-up or spray-up, thixotropic agents may be used. When “at rest”, resins containing thixotropic agents remain at elevated viscosities. This reduces the tendency of the liquid resin to flow or drain from vertical surfaces. When the resin is subjected to shear, the viscosity is reduced and the resin can be easily sprayed or brushed on the mold. Fumed silica and certain clays are common thixotropic agents.

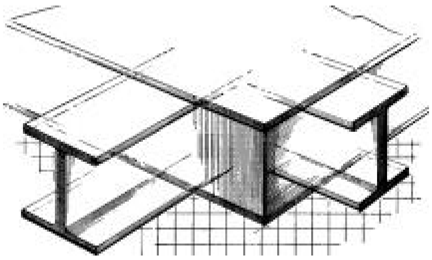
Summary

Additives and modifier ingredients expand the usefulness of polymers, enhance their processability or extend product durability. While additives and modifiers often increase the cost of the basic material system, these materials always improve cost/performance.

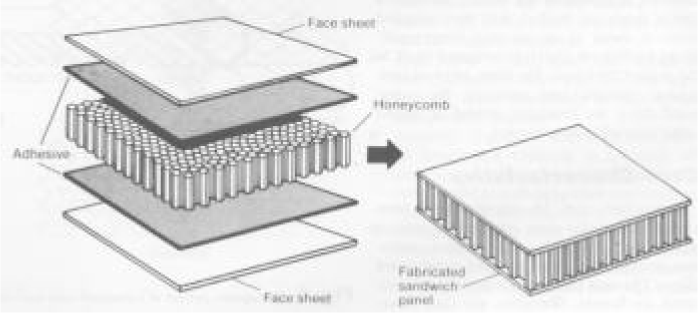
Core Materials for Sandwich Structures

Bonded sandwich structures have been a basic component of the composites industry for over 45 years. The concept of using relatively thin, strong face sheets bonded to thicker, lightweight core materials has allowed the industry to build strong, stiff, light and highly durable structures that otherwise would not be practical. This technology has been demonstrated in boats, trucks, and building panels. A 3% weight increase can increase the flexural strength and stiffness by a magnitude of 3.5 times and 7 times respectively if cores and skins are properly chosen. The structure then acts more or less monolithically.

The most common comparison made is that of a composite sandwich to an I-beam. The panel skins, like the flanges of the I-beam, carry the stresses imposed by use. The stresses are transferred between the top and bottom skins through shear stresses that run through the core or web of the I-beam. The purpose of an I-beam is to lessen the weight required to support a given load in bending. Since the highest stresses are carried at the extremities, both the top and bottom of the I-beam, the center section can be much narrower in width in relation to the flanges. In a sandwich structure, the core will generally have the same width and length dimensions as the skins, but can be much weaker than the skins since it primarily experiences shear stresses. Care must be taken in design to ensure that the shear carrying capability of the expected loads does not exceed both the core and the adhesive.

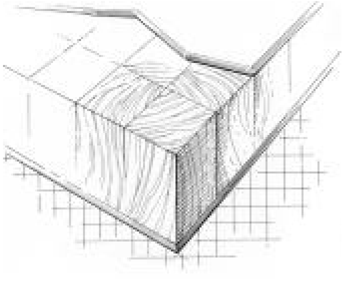


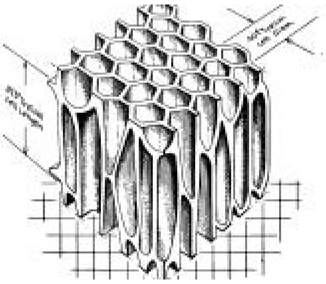
Face sheets can be of almost any material. In the composites industry, the most common face sheets are glass and carbon. The common core materials are foam, syntactic foam, honeycomb, and balsa wood. Some core materials can be shaped, such as a waffle pattern or corrugation to achieve the desired mechanical properties.



Honeycomb Sandwich Construction

A cost-effective and superior sandwich construction uses end-grain balsa wood. This material has exceptional bond, high impact and fatigue resistance with excellent strength/stiffness and lightweight properties. Balsa wood is "mother nature's" honeycomb material. Balsa has a high-aspect ratio and directionally aligned cells such that the grain is oriented in the direction of the maximum stress. Balsa has a proven track record in products such as pleasure boat hulls, military aircraft, vehicles, and corrosion-resistant industrial tanks.





Laminated Sandwich Construction with Balsa Wood

Adhesives

Adhesives are used to attach composites to themselves as well as to other surfaces. Adhesive bonding is the method of choice for bonding thermoset composites and is sometimes used for thermoplastic composites. There are several considerations involved in applying adhesives effectively. The joint or interface connection must be engineered to select the proper adhesive and application method to ensure bond strength. Careful surface preparation and cure are critical to bond performance.

Adhesives should be used in a joint design where the maximum load is transferred into the component using the loading characteristics of the adhesive and the composite material. The most common adhesives are acrylics, epoxies, and urethanes. A high-strength bond with high-temperature resistance would indicate the use of an epoxy, whereas a moderate temperature resistance with good strength and rapid cure might use an acrylic. For applications where toughness is needed, urethane might be selected.

Gel Coats

Gel coats are considered resins but have a very special purpose. A gel coat is a specially formulated polyester resin incorporating thixotropic agents to increase the gel coat's viscosity and non-sag properties, fillers for flow properties, pigments to give the desired color, and additives for specific application properties, such as gel time and cure. Gel coats are primarily used for contact molding (hand or spray lay-up). The gel coat, usually pigmented, provides a molded-in finished surface that is weather and wear resistant. The gel coat helps in hiding the glass reinforcement pattern that may show through from the inherent resin shrinkage around the glass fibers. Considerations used for the proper selection of a gel coat are compatibility of the underlying FRP materials to ensure good adhesion of the gel coat, as well as the operating environment.

The most common current usage of gel coats in "in-mold applications." That is, the gel coat is sprayed into the mold and the laminate is applied behind it. Adhesion of the laminating resin to the gel coat is a critical issue. Thickness of the gel coat can vary depending on the intended performance of the composite product. Gel coats are typically applied by spray application to approximately 16-20 mils wet film thickness. While gel coats do not add any structural strength to the FRP part, gel coats should be resilient. Gel coats should be able to bend without cracking. They should be resistant to thermal cracking (cracking that may occur with dramatic changes in temperature). The primary measurements of resilience are flexural modulus and elongation. Gel coats should be UV stable and pigmented sufficiently to provide good opacity.

Gel coats are used to improve weathering, filter out ultraviolet radiation, add flame retardancy, provide a thermal barrier, improve chemical resistance, improve abrasion resistance, and provide a moisture barrier. Gel coats are used to improve the product appearance such as the surface of a boat hull or golf cart. A unique benefit of gel coats is that they are supplied in many colors by the incorporation of pigments per the specification of the engineer.

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