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Introduction of Fibre-Reinforced Polymers – Polymers and Composites: Concepts, Properties and Processes

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1. Introduction

Fibre-reinforced polymer(FRP), also *Fibre-reinforced plastic*, is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually glass, carbon, or aramid, although other fibres such as paper or wood or asbestos have been sometimes used. The polymer is usually an epoxy, vinylester or polyester thermosetting plastic, and phenol formaldehyde resins are still in use. FRPs are commonly used in the aerospace, automotive, marine, and construction industries.

Composite materials are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct within the finished structure. Most composites have strong, stiff fibres in a matrix which is weaker and less stiff. The objective is usually to make a component which is strong and stiff, often with a low density. Commercial material commonly has glass or carbon fibres in matrices based on thermosetting polymers, such as epoxy or polyester resins. Sometimes, thermoplastic polymers may be preferred, since they are moldable after initial production. There are further classes of composite in which the matrix is a metal or a ceramic. For the most part, these are still in a developmental stage, with problems of high manufacturing costs yet to be overcome [1]. Furthermore, in these composites the reasons for adding the fibres (or, in some cases, particles) are often rather complex; for example, improvements may be sought in creep, wear, fracture toughness, thermal stability, etc [2].

Fibre reinforced polymer (FRP) are composites used in almost every type of advanced engineering structure, with their usage ranging from aircraft, helicopters and spacecraft through to boats, ships and offshore platforms and to automobiles, sports goods, chemical processing equipment and civil infrastructure such as bridges and buildings. The usage of FRP

composites continues to grow at an impressive rate as these materials are used more in their existing markets and become established in relatively new markets such as biomedical devices and civil structures. A key factor driving the increased applications of composites over the recent years is the development of new advanced forms of FRP materials. This includes developments in high performance resin systems and new styles of reinforcement, such as carbon nanotubes and nanoparticles. This book provides an up-to-date account of the fabrication, mechanical properties, delamination resistance, impact tolerance and applications of 3D FRP composites [3].

The fibre reinforced polymer composites (FRPs) are increasingly being considered as an enhancement to and/or substitute for infrastructure components or systems that are constructed of traditional civil engineering materials, namely concrete and steel. FRP composites are lightweight, no-corrosive, exhibit high specific strength and specific stiffness, are easily constructed, and can be tailored to satisfy performance requirements. Due to these advantageous characteristics, FRP composites have been included in new construction and rehabilitation of structures through its use as reinforcement in concrete, bridge decks, modular structures, formwork, and external reinforcement for strengthening and seismic upgrade [4].

The applicability of Fiber Reinforced Polymer (FRP) reinforcements to concrete structures as a substitute for steel bars or prestressing tendons has been actively studied in numerous research laboratories and professional organizations around the world. FRP reinforcements offer a number of advantages such as corrosion resistance, non-magnetic properties, high tensile strength, lightweight and ease of handling. However, they generally have a linear elastic response in tension up to failure (described as a brittle failure) and a relatively poor transverse or shear resistance. They also have poor resistance to fire and when exposed to high temperatures. They loose significant strength upon bending, and they are sensitive to stress-rupture effects. Moreover, their cost, whether considered per unit weight or on the basis of force carrying capacity, is high in comparison to conventional steel reinforcing bars or prestressing tendons. From a structural engineering viewpoint, the most serious problems with FRP reinforcements are the lack of plastic behavior and the very low shear strength in the transverse direction. Such characteristics may lead to premature tendon rupture, particularly when combined effects are present, such as at shear-cracking planes in reinforced concrete beams where dowel action exists. The dowel action reduces residual tensile and shear resistance in the tendon. Solutions and limitations of use have been offered and continuous improvements are expected in the future. The unit cost of FRP reinforcements is expected to decrease significantly with increased market share and demand. However, even today, there are applications where FRP reinforcements are cost effective and justifiable. Such cases include the use of bonded FRP sheets or plates in repair and strengthening of concrete structures, and the use of FRP meshes or textiles or fabrics in thin cement products. The cost of repair and rehabilitation of a structure is always, in relative terms, substantially higher than the cost of the initial structure. Repair generally requires a relatively small volume of repair materials but a relatively high commitment in labor. Moreover the cost of labor in developed countries is so high that the cost of material becomes secondary. Thus the

highest the performance and durability of the repair material is, the more cost-effective is the repair. This implies that material cost is not really an issue in repair and that the fact that FRP repair materials are costly is not a constraining drawback [5].

When considering only energy and material resources it appears, on the surface, the argument for FRP composites in a sustainable built environment is questionable. However, such a conclusion needs to be evaluated in terms of potential advantages present in use of FRP composites related to considerations such as:

- Higher strength

- Lighter weight

- Higher performance

- Longer lasting

- Rehabilitating existing structures and extending their life

- Seismic upgrades

- Defense systems

- Space systems

- Ocean environments

In the case of FRP composites, environmental concerns appear to be a barrier to its feasibility as a sustainable material especially when considering fossil fuel depletion, air pollution, smog, and acidification associated with its production. In addition, the ability to recycle FRP composites is limited and, unlike steel and timber, structural components cannot be reused to perform a similar function in another structure. However, evaluating the environmental impact of FRP composites in infrastructure applications, specifically through life cycle analysis, may reveal direct and indirect benefits that are more competitive than conventional materials.

Composite materials have developed greatly since they were first introduced. However, before composite materials can be used as an alternative to conventional materials as part of a sustainable environment a number of needs remain.

- Availability of standardized durability characterization data for FRP composite materials.

- Integration of durability data and methods for service life prediction of structural members utilizing FRP composites.

- Development of methods and techniques for materials selection based on life cycle assessments of structural components and systems.

Ultimately, in order for composites to truly be considered a viable alternative, they must be structurally and economically feasible. Numerous studies regarding the structural feasibility of composite materials are widely available in literature [6]. However, limited studies are available on the economic and environmental feasibility of these materials from the perspec-

tive of a life cycle approach, since short term data is available or only economic costs are considered in the comparison. Additionally, the long term affects of using composite materials needs to be determined. The byproducts of the production, the sustainability of the constituent materials, and the potential to recycle composite materials needs to be assessed in order to determine of composite materials can be part of a sustainable environment. Therefore in this chapter describe the physicochemical properties of polymers and composites more used in Civil Engineering. The theme will be addressed in a simple and basic for better understanding.

2. Manufactured process and basic concepts

The synthetic polymers are generally manufactured by polycondensation, polymerization or polyaddition. The polymers combined with various agents to enhance or in any way alter the material properties of polymers the result is referred to as a plastic. The Composite plastics can be of homogeneous or heterogeneous mix. Composite plastics refer to those types of plastics that result from bonding two or more homogeneous materials with different material properties to derive a final product with certain desired material and mechanical properties. The Fibre reinforced plastics (or fiber reinforced polymers) are a category of composite plastics that specifically use fibre materials (not mix with polymer) to mechanically enhance the strength and elasticity of plastics. The original plastic material without fibre reinforcement is known as the matrix. The matrix is a tough but relatively weak plastic that is reinforced by stronger stiffer reinforcing filaments or fibres. The extent that strength and elasticity are enhanced in a fibre reinforced plastic depends on the mechanical properties of the fibre and matrix, their volume relative to one another, and the fibre length and orientation within the matrix. Reinforcement of the matrix occurs by definition when the FRP material exhibits increased strength or elasticity relative to the strength and elasticity of the matrix alone.

Polymers are different from other construction materials like ceramics and metals, because of their macromolecular nature. The covalently bonded, long chain structure makes them macromolecules and determines, via the weight averaged molecular weight, Mw, their processability, like spin-, blow-, deep draw-, generally melt-formability. The number averaged molecular weight, Mn, determines the mechanical strength, and high molecular weights are beneficial for properties like strain-to-break, impact resistance, wear, etc. Thus, natural limits are met, since too high molecular weights yield too high shear and elongational viscosities that make polymers inprocessable. Prime examples are the very useful poly-tetra-fluor-ethylenes, PTFE's, and ultrahigh-molecular-weight-poly-ethylenes, UHMWPE's, and not only garbage bags are made of polyethylene, PE, but also high-performance fibers that are even used for bullet proof vests (alternatively made from, also inprocessable in the melt, rigid aromatic polyamides). The resulting mechanical properties of these high performance fibers, with moduli of 150 GPa and strengths of up to 4 GPa, represent the optimal use of what the potential of the molecular structure of polymers yields, combined with their low density. Thinking about polymers, it becomes clear why living nature used the polymeric

concept to build its structures, and not only in high strength applications like wood, silk or spider-webs [7].

2.1. Polymers

The linking of small molecules (monomers) to make larger molecules is a polymer. Polymerization requires that each small molecule have at least two reaction points or functional groups. There are two distinct major types of polymerization processes, condensation polymerization, in which the chain growth is accompanied by elimination of small molecules such as H_2O or CH_3OH, and addition polymerization, in which the polymer is formed without the loss of other materials. There are many variants and subclasses of polymerization reactions.

The polymer chains can be classified in linear polymer chain, branched polymer chain, and cross-linked polymer chain. The structure of the repeating unit is the difunctional monomeric unit, or "mer." In the presence of catalysts or initiators, the monomer yields a polymer by the joining together of n-mers. If n is a small number, 2–10, the products are dimers, trimers, tetramers, or oligomers, and the materials are usually gases, liquids, oils, or brittle solids. In most solid polymers, n has values ranging from a few score to several hundred thousand, and the corresponding molecular weights range from a few thousand to several million. The end groups of this example of addition polymers are shown to be fragments of the initiator. If only one monomer is polymerized, the product is called a homopolymer. The polymerization of a mixture of two monomers of suitable reactivity leads to the formation of a copolymer, a polymer in which the two types of mer units have entered the chain in a more or less random fashion. If chains of one homopolymer are chemically joined to chains of another, the product is called a block or graft copolymer.

Isotactic and syndiotactic (stereoregular) polymers are formed in the presence of complex catalysts, or by changing polymerization conditions, for example, by lowering the temperature. The groups attached to the chain in a stereoregular polymer are in a spatially ordered arrangement. The regular structures of the isotactic and syndiotactic forms make them often capable of crystallization. The crystalline melting points of isotactic polymers are often substantially higher than the softening points of the atactic product.

The spatially oriented polymers can be classified in atactic (random; dlldl or lddld, and so on), syndiotactic (alternating; dldl, and so on), and isotactic (right- or left-handed; dddd, or llll, and so on). For illustration, the heavily marked bonds are assumed to project up from the paper, and the dotted bonds down. Thus in a fully syndiotactic polymer, asymmetric carbons alternate in their left- or right-handedness (alternating d, l configurations), while in an isotactic polymer, successive carbons have the same steric configuration (d or l). Among the several kinds of polymerization catalysis, free-radical initiation has been most thoroughly studied and is most widely employed. Atactic polymers are readily formed by free-radical polymerization, at moderate temperatures, of vinyl and diene monomers and some of their derivatives. Some polymerizations can be initiated by materials, often called ionic catalysts, which contain highly polar reactive sites or complexes. The term heterogeneous catalyst is often applicable to these materials because many of the catalyst systems are insoluble

in monomers and other solvents. These polymerizations are usually carried out in solution from which the polymer can be obtained by evaporation of the solvent or by precipitation on the addition of a nonsolvent. A distinguishing feature of complex catalysts is the ability of some representatives of each type to initiate stereoregular polymerization at ordinary temperatures or to cause the formation of polymers which can be crystallized [1, 6].

2.1.1. Polymerization

Polymerization, emulsion polymerization any process in which relatively small molecules, called monomers, combine chemically to produce a very large chainlike or network molecule, called a polymer. The monomer molecules may be all alike, or they may represent two, three, or more different compounds. Usually at least 100 monomer molecules must be combined to make a product that has certain unique physical properties-such as elasticity, high tensile strength, or the ability to form fibres-that differentiate polymers from substances composed of smaller and simpler molecules; often, many thousands of monomer units are incorporated in a single molecule of a polymer. The formation of stable covalent chemical bonds between the monomers sets polymerization apart from other processes, such as crystallization, in which large numbers of molecules aggregate under the influence of weak intermolecular forces.

Two classes of polymerization usually are distinguished. In condensation polymerization, each step of the process is accompanied by formation of a molecule of some simple compound, often water. In addition polymerization, monomers react to form a polymer without the formation of by-products. Addition polymerizations usually are carried out in the presence of catalysts, which in certain cases exert control over structural details that have important effects on the properties of the polymer [8].

Linear polymers, which are composed of chainlike molecules, may be viscous liquids or solids with varying degrees of crystallinity; a number of them can be dissolved in certain liquids, and they soften or melt upon heating. Cross-linked polymers, in which the molecular structure is a network, are thermosetting resins (i.e., they form under the influence of heat but, once formed, do not melt or soften upon reheating) that do not dissolve in solvents. Both linear and cross-linked polymers can be made by either addition or condensation polymerization.

2.1.2. Polycondensation

The polycondensation a process for the production of polymers from bifunctional and polyfunctional compounds (monomers), accompanied by the elimination of low-molecular weight by-products (for example, water, alcohols, and hydrogen halides). A typical example of polycondensation is the synthesis of complex polyester.

The process is called homopolycondensation if the minimum possible number of monomer types for a given case participates, and this number is usually two. If at least one monomer more than the number required for the given reaction participates in polycondensation, the process is called copolycondensation. Polycondensation in which only bifunctional com-

pounds participate leads to the formation of linear macromolecules and is called linear poly-condensation. If molecules with three or more functional groups participate in polycondensation, three-dimensional structures are formed and the process is called three-dimensional polycondensation. In cases where the degree of completion of polycondensa-tion and the mean length of the macromolecules are limited by the equilibrium concentration of the reagents and reaction products, the process is called equilibrium (rever-sible) polycondensation. If the limiting factors are kinetic rather than thermodynamic, the process is called nonequilibrium (irreversible) polycondensation.

Polycondensation is often complicated by side reactions, in which both the original mono-mers and the polycondensation products (oligomers and polymers) may participate. Such reactions include the reaction of monomer or oligomer with a mono-functional compound (which may be present as an impurity), intramolecular cyclization (ring closure), and degra-dation of the macromolecules of the resultant polymer. The rate competition of polyconden-sation and the side reactions determines the molecular weight, yield, and molecular weight distribution of the polycondensation polymer.

Polycondensation is characterized by disappearance of the monomer in the early stages of the process and a sharp increase in molecular weight, in spite of a slight change in the extent of conversion in the region of greater than 95-percent conversion.

A necessary condition for the formation of macro-molecular polymers in linear polyconden-sation is the equivalence of the initial functional groups that react with one another.

Polycondensation is accomplished by one of three methods:

1. in a melt, when a mixture of the initial compounds is heated for a long period to 10°-20°C above the melting (softening) point of the resultant polymer;

2. in solution, when the monomers are present in the same phase in the solute state;

3. on the phase boundary between two immiscible liquids, in which one of the initial com-pounds is found in each of the liquid phases (interphase polycondensation).

Polycondensation processes play an important role in nature and technology. Polycondensa-tion or similar reactions are the basis for the biosynthesis of the most important biopoly-mers-proteins, nucleic acids, and cellulose. Polycondensation is widely used in industry for the production of polyesters (polyethylene terephthalate, polycarbonates, and alkyd resins), polyamides, phenol-formaldehyde resins, urea-formaldehyde resins, and certain silicones [9]. In the period 1965-70, polycondensation acquired great importance in connection with the development of industrial production of a series of new polymers, including heat-resist-ant polymers (polyarylates, aromatic polyimides, polyphe-nylene oxides, and polysulfones).

2.1.3. Polyaddition

The polyaddition reactions are similar to polycondensation reactions because they are also step reactions, however without splitting off low molecular weight by-products. The reac-tion is exothermic rather than endothermic and therefore cannot be stopped at will. Typical

for polyaddition reaction is that individual atoms, usually H-atoms, wander from one monomer to another as the two monomers combine through a covalent bond. The monomers, as in polycondensation reactions, have to be added in stoichiometric amounts. These reactions do not start spontaneously and they are slow.

Polyaddition does not play a significant role in the production of thermoplastics. It is commonly encountered with cross-linked polymers. Polyurethane, which can be either a thermoplastic or thermosets, is synthesized by the reaction of multi-functional isocyanates with multifunctional amines or alcohol. Thermosetting epoxy resins are formed by polyaddition of epoxides with curing agents, such as amines and acid anhydrides.

In comparing chain reaction polymerization with the other two types of polymerization the following principal differences should be noted: Chain reaction polymerization, or simply called polymerization, is a chain reaction as the name implies. Only individual monomer molecules add to a reactive growing chain end, except for recombination of two radical chain ends or reactions of a reactive chain end with an added modifier molecule. The activation energy for chain initiation is much grater than for the subsequent growth reaction and growth, therefore, occurs very rapidly.

2.2. Composites

Composite is any material made of more than one component. There are a lot of composites around you. Concrete is a composite. It's made of cement, gravel, and sand, and often has steel rods inside to reinforce it. Those shiny balloons you get in the hospital when you're sick are made of a composite, which consists of a polyester sheet and an aluminum foil sheet, made into a sandwich. The polymer composites made from polymers, or from polymers along with other kinds of materials [7]. But specifically the fiber-reinforced composites are materials in which a fiber made of one material is embedded in another material.

2.2.1. Polymer composites

The polymer composites are any of the combinations or compositions that comprise two or more materials as separate phases, at least one of which is a polymer. By combining a polymer with another material, such as glass, carbon, or another polymer, it is often possible to obtain unique combinations or levels of properties. Typical examples of synthetic polymeric composites include glass-, carbon-, or polymer-fiber-reinforced, thermoplastic or thermosetting resins, carbon-reinforced rubber, polymer blends, silica- or mica-reinforced resins, and polymer-bonded or -impregnated concrete or wood. It is also often useful to consider as composites such materials as coatings (pigment-binder combinations) and crystalline polymers (crystallites in a polymer matrix). Typical naturally occurring composites include wood (cellulosic fibers bonded with lignin) and bone (minerals bonded with collagen). On the other hand, polymeric compositions compounded with a plasticizer or very low proportions of pigments or processing aids are not ordinarily considered as composites.

Typically, the goal is to improve strength, stiffness, or toughness, or dimensional stability by embedding particles or fibers in a matrix or binding phase. A second goal is to use inexpen-

sive, readily available fillers to extend a more expensive or scarce resin; this goal is increasingly important as petroleum supplies become costlier and less reliable. Still other applications include the use of some filler such as glass spheres to improve processability, the incorporation of dry-lubricant particles such as molybdenum sulfide to make a self-lubricating bearing, and the use of fillers to reduce permeability.

The most common fiber-reinforced polymer composites are based on glass fibers, cloth, mat, or roving embedded in a matrix of an epoxy or polyester resin. Reinforced thermosetting resins containing boron, polyaramids, and especially carbon fibers confer especially high levels of strength and stiffness. Carbon-fiber composites have a relative stiffness five times that of steel. Because of these excellent properties, many applications are uniquely suited for epoxy and polyester composites, such as components in new jet aircraft, parts for automobiles, boat hulls, rocket motor cases, and chemical reaction vessels.

Although the most dramatic properties are found with reinforced thermosetting resins such as epoxy and polyester resins, significant improvements can be obtained with many reinforced thermoplastic resins as well. Polycarbonates, polyethylene, and polyesters are among the resins available as glass-reinforced composition. The combination of inexpensive, one-step fabrication by injection molding, with improved properties has made it possible for reinforced thermoplastics to replace metals in many applications in appliances, instruments, automobiles, and tools.

In the development of other composite systems, various matrices are possible; for example, polyimide resins are excellent matrices for glass fibers, and give a high- performance composite. Different fibers are of potential interest, including polymers [such as poly(vinyl alcohol)], single-crystal ceramic whiskers (such as sapphire), and various metallic fibers.

Long ago, people living in South and Central America had used natural rubber latex, polyisoprene, to make things like gloves and boots, as well as rubber balls which they used to play games that were a lot like modern basketball. He took two layers of cotton fabric and embedded them in natural rubber, also known as polyisoprene, making a three-layered sandwich like the one you see on your right (Remember, cotton is made up of a natural polymer called cellulose). This made for good raincoats because, while the rubber made it waterproof, the cotton layers made it comfortable to wear, to make a material that has the properties of both its components. In this case, we combine the water-resistance of polyisoprene and the comfort of cotton.

Modern composites are usually made of two components, a fiber and matrix. The fiber is most often glass, but sometimes Kevlar, carbon fiber, or polyethylene. The matrix is usually a thermoset like an epoxy resin, polydicyclopentadiene, or a polyimide. The fiber is embedded in the matrix in order to make the matrix stronger. Fiber-reinforced composites have two things going for them. They are strong and light. They are often stronger than steel, but weigh much less. This means that composites can be used to make automobiles lighter, and thus much more fuel efficient.

A common fiber-reinforced composite is Fiberglas™. Its matrix is made by reacting polyester with carbon-carbon double bonds in its backbone, and styrene. We pour a mix of the styrene and polyester over a mass of glass fibers.

The styrene and the double bonds in the polyester react by free radical vinyl polymerization to form a crosslinked resin. The glass fibers are trapped inside, where they act as a reinforcement. In Fiberglas™ the fibers are not lined up in any particular direction. They are just a tangled mass, like you see on the right. But we can make the composite stronger by lining up all the fibers in the same direction. Oriented fibers do some weird things to the composite. When you pull on the composite in the direction of the fibers, the composite is very strong. But if you pull on it at right angles to the fiber direction, it is not very strong at all [8-9]. This is not always bad, because sometimes we only need the composite to be strong in one direction. Sometimes the item you are making will only be under stress in one direction. But sometimes we need strength in more than one direction. So we simply point the fibers in more than one direction. We often do this by using a woven fabric of the fibers to reinforce the composite. The woven fibers give a composite good strength in many directions.

The polymeric matrix holds the fibers together. A loose bundle of fibers would not be of much use. Also, though fibers are strong, they can be brittle. The matrix can absorb energy by deforming under stress. This is to say, the matrix adds toughness to the composite. And finally, while fibers have good tensile strength (that is, they are strong when you pull on them), they usually have awful compressional strength. That is, they buckle when you squash them. The matrix gives compressional strength to the composite.

Not all fibers are the same. Now it may seem strange that glass is used as reinforcement, as glass is really easy to break. But for some reason, when glass is spun into really tiny fibers, it acts very different. Glass fibers are strong, and flexible.

Still, there are stronger fibers out there. This is a good thing, because sometimes glass just isn't strong and tough enough. For some things, like airplane parts, that undergo a lot of stress, you need to break out the fancy fibers. When cost is no object, you can use stronger, but more expensive fibers, like Kevlar™, carbon fiber. Carbon fiber (Spectra™) is usually stronger than Kevlar™, that is, it can withstand more force without breaking. But Kevlar™ tends to be tougher. This means it can absorb more energy without breaking. It can stretch a little to keep from breaking, more so than carbon fiber can. But Spectra™, which is a kind of polyethylene, is stronger and tougher than both carbon fiber and Kevlar™.

Different jobs call for different matrices. The unsaturated polyester/styrene systems at are one example. They are fine for everyday applications. Chevrolet Corvette bodies are made from composites using unsaturated polyester matrices and glass fibers. But they have some drawbacks. They shrink a good deal when they're cured, they can absorb water very easily, and their impact strength is low.

2.2.2. Biocomposites

For many decades, the residential construction field has used timber as its main source of building material for the frames of modern American homes. The American timber industry

produced a record 49.5 billion board feet of lumber in 1999, and another 48.0 billion board feet in 2002. At the same time that lumber production is peaking, the home ownership rate reached a record high of 69.2%, with over 977,000 homes being sold in 2002. Because residential construction accounts for one-third of the total softwood lumber use in the United States, there is an increasing demand for alternate materials. Use of sawdust not only provides an alternative but also increases the use of the by product efficiently. Wood plastic composites (WPC) is a relatively new category of materials that covers a broad range of composite materials utilizing an organic resin binder (matrix) and fillers composed of cellulose materials. The new and rapidly developing biocomposite materials are high technology products, which have one unique advantage – the wood filler can include sawdust and scrap wood products. Consequently, no additional wood resources are needed to manufacture biocomposites. Waste products that would traditraditionally cost money for proper disposal, now become a beneficial resource, allowing recycling to be both profitable and environmentally conscious. The use of biocomposites and WPC has increased rapidly all over the world, with the end users for these composites in the construction, motor vehicle, and furniture industries. One of the primary problems related to the use of biocomposites is the flammability of the two main components (binder and filler). If a flame retardant were added, this would require the adhesion of the fiber and the matrix not to be disturbed by the retardant. The challenge is to develop a composite that will not burn and will maintain its level of mechanical performance. In lieu of organic matrix compounds, inorganic matrices can be utilized to improve the fire resistance. Inorganic-based wood composites are those that consist of a mineral mix as the binder system. Such inorganic binder systems include gypsum and Portland cement, both of which are highly resistant to fire and insects. The main disadvantage with these systems is the maximum amount of sawdust or fibers than can be incorporated is low. One relatively new type of inorganic matrix is potassium aluminosilicate, an environmentally friendly compound made from naturally occurring materials. The Federal Aviation Administration has investigated the feasibility of using this matrix in commercial aircraft due to its ability to resist temperatures of up to 1000 ºC without generating smoke, and its ability to enable carbon composites to withstand temperatures of 800 ºC and maintain 63% of its original flexural strength. Potassium aluminosilicate matrices are compatible with many common building material including clay brick, masonry, concrete, steel, titanium, balsa, oak, pine, and particleboard [10].

2.3. Fiberglass

Fiberglass refers to a group of products made from individual glass fibers combined into a variety of forms. Glass fibers can be divided into two major groups according to their geometry: continuous fibers used in yarns and textiles, and the discontinuous (short) fibers used as batts, blankets, or boards for insulation and filtration. Fiberglass can be formed into yarn much like wool or cotton, and woven into fabric which is sometimes used for draperies. Fiberglass textiles are commonly used as a reinforcement material for molded and laminated plastics. Fiberglass wool, a thick, fluffy material made from discontinuous fibers, is used for thermal insulation and sound absorption. It is commonly found in ship and submarine bulkheads and hulls; automobile engine compartments and body panel liners; in furnaces and

air conditioning units; acoustical wall and ceiling panels; and architectural partitions. Fiberglass can be tailored for specific applications such as Type E (electrical), used as electrical insulation tape, textiles and reinforcement; Type C (chemical), which has superior acid resistance, and Type T, for thermal insulation [11].

Though commercial use of glass fiber is relatively recent, artisans created glass strands for decorating goblets and vases during the Renaissance. A French physicist, Rene-Antoine Ferchault de Reaumur, produced textiles decorated with fine glass strands in 1713. Glass wool, a fluffy mass of discontinuous fiber in random lengths, was first produced in Europe in 1900, using a process that involved drawing fibers from rods horizontally to a revolving drum [12].

The basic raw materials for fiberglass products are a variety of natural minerals and manufactured chemicals. The major ingredients are silica sand, limestone, and soda ash. Other ingredients may include calcined alumina, borax, feldspar, nepheline syenite, magnesite, and kaolin clay, among others. Silica sand is used as the glass former, and soda ash and limestone help primarily to lower the melting temperature. Other ingredients are used to improve certain properties, such as borax for chemical resistance. Waste glass, also called cullet, is also used as a raw material. The raw materials must be carefully weighed in exact quantities and thoroughly mixed together (called batching) before being melted into glass.

2.3.1. The manufacturing process

2.3.1.1. Melting

Once the batch is prepared, it is fed into a furnace for melting. The furnace may be heated by electricity, fossil fuel, or a combination of the two. Temperature must be precisely controlled to maintain a smooth, steady flow of glass. The molten glass must be kept at a higher temperature (about 1371 °C) than other types of glass in order to be formed into fiber. Once the glass becomes molten, it is transferred to the forming equipment via a channel (forehearth) located at the end of the furnace [13].

2.3.1.2. Forming into fibers

Several different processes are used to form fibers, depending on the type of fiber. Textile fibers may be formed from molten glass directly from the furnace, or the molten glass may be fed first to a machine that forms glass marbles of about 0.62 inch (1.6 cm) in diameter. These marbles allow the glass to be inspected visually for impurities. In both the direct melt and marble melt process, the glass or glass marbles are fed through electrically heated bushings (also called spinnerets). The bushing is made of platinum or metal alloy, with anywhere from 200 to 3,000 very fine orifices. The molten glass passes through the orifices and comes out as fine filaments [13].

2.3.1.3. Continuous-filament process

A long, continuous fiber can be produced through the continuous-filament process. After the glass flows through the holes in the bushing, multiple strands are caught up on a high-speed winder. The winder revolves at about 3 km a minute, much faster than the rate of flow from the bushings. The tension pulls out the filaments while still molten, forming strands a fraction of the diameter of the openings in the bushing. A chemical binder is applied, which helps keep the fiber from breaking during later processing. The filament is then wound onto tubes. It can now be twisted and plied into yarn [14].

2.3.1.4. Staple-fiber process

An alternative method is the staplefiber process. As the molten glass flows through the bushings, jets of air rapidly cool the filaments. The turbulent bursts of air also break the filaments into lengths of 20-38 cm. These filaments fall through a spray of lubricant onto a revolving drum, where they form a thin web. The web is drawn from the drum and pulled into a continuous strand of loosely assembled fibers [15]. This strand can be processed into yarn by the same processes used for wool and cotton.

2.3.1.5. Chopped fiber

Instead of being formed into yarn, the continuous or long-staple strand may be chopped into short lengths. The strand is mounted on a set of bobbins, called a creel, and pulled through a machine which chops it into short pieces. The chopped fiber is formed into mats to which a binder is added. After curing in an oven, the mat is rolled up. Various weights and thicknesses give products for shingles, built-up roofing, or decorative mats [16].

2.3.1.6. Glass wool

The rotary or spinner process is used to make glass wool. In this process, molten glass from the furnace flows into a cylindrical container having small holes. As the container spins rapidly, horizontal streams of glass flow out of the holes. The molten glass streams are converted into fibers by a downward blast of air, hot gas, or both. The fibers fall onto a conveyor belt, where they interlace with each other in a fleecy mass. This can be used for insulation, or the wool can be sprayed with a binder, compressed into the desired thickness, and cured in an oven. The heat sets the binder, and the resulting product may be a rigid or semi-rigid board, or a flexible bat [15-16].

2.3.1.7. Protective coatings

In addition to binders, other coatings are required for fiberglass products. Lubricants are used to reduce fiber abrasion and are either directly sprayed on the fiber or added into the binder. An anti-static composition is also sometimes sprayed onto the surface of fiberglass insulation mats during the cooling step. Cooling air drawn through the mat causes the anti-static agent to penetrate the entire thickness of the mat. The anti-static agent consists of two

ingredients a material that minimizes the generation of static electricity, and a material that serves as a corrosion inhibitor and stabilizer.

Sizing is any coating applied to textile fibers in the forming operation, and may contain one or more components (lubricants, binders, or coupling agents). Coupling agents are used on strands that will be used for reinforcing plastics, to strengthen the bond to the reinforced material. Sometimes a finishing operation is required to remove these coatings, or to add another coating. For plastic reinforcements, sizings may be removed with heat or chemicals and a coupling agent applied. For decorative applications, fabrics must be heat treated to remove sizings and to set the weave. Dye base coatings are then applied before dying or printing [15-16].

2.3.1.8. Forming into shapes

Fiberglass products come in a wide variety of shapes, made using several processes. For example, fiberglass pipe insulation is wound onto rod-like forms called mandrels directly from the forming units, prior to curing. The mold forms, in lengths of 91 cm or less, are then cured in an oven. The cured lengths are then de-molded lengthwise, and sawn into specified dimensions. Facings are applied if required, and the product is packaged for shipment [17].

2.4. Carbon fibre

Carbon-fiber-reinforced polymer or carbon-fiber-reinforced plastic (CFRP or CRP or often simply carbon fiber), is a very strong and light fiber-reinforced polymer which contains carbon fibers. Carbon fibres are created when polyacrylonitrile fibres (PAN), Pitch resins, or Rayon are carbonized (through oxidation and thermal pyrolysis) at high temperatures. Through further processes of graphitizing or stretching the fibres strength or elasticity can be enhanced respectively. Carbon fibres are manufactured in diameters analogous to glass fibres with diameters ranging from 9 to 17 μm. These fibres wound into larger threads for transportation and further production processes. Further production processes include weaving or braiding into carbon fabrics, cloths and mats analogous to those described for glass that can then be used in actual reinforcement processes. Carbon fibers are a new breed of high-strength materials. Carbon fiber has been described as a fiber containing at least 90% carbon obtained by the controlled pyrolysis of appropriate fibers. The existence of carbon fiber came into being in 1879 when Edison took out a patent for the manufacture of carbon filaments suitable for use in electric lamps [18].

2.4.1. Classification and types

Based on modulus, strength, and final heat treatment temperature, carbon fibers can be classified into the following categories:

1. Based on carbon fiber properties, carbon fibers can be grouped into:

• Ultra-high-modulus, type UHM (modulus >450Gpa)

- High-modulus, type HM (modulus between 350-450Gpa)

- Intermediate-modulus, type IM (modulus between 200-350Gpa)

- Low modulus and high-tensile, type HT (modulus < 100Gpa, tensile strength > 3.0Gpa)

- Super high-tensile, type SHT (tensile strength > 4.5Gpa)

2.   Based on precursor fiber materials, carbon fibers are classified into;

- PAN-based carbon fibers

- Pitch-based carbon fibers

- Mesophase pitch-based carbon fibers

- Isotropic pitch-based carbon fibers

- Rayon-based carbon fibers

- Gas-phase-grown carbon fibers

3.   Based on final heat treatment temperature, carbon fibers are classified into:

- Type-I, high-heat-treatment carbon fibers (HTT), where final heat treatment temperature should be above 2000°C and can be associated with high-modulus type fiber.

- Type-II, intermediate-heat-treatment carbon fibers (IHT), where final heat treatment temperature should be around or above 1500 °C and can be associated with high-strength type fiber.

- Type-III, low-heat-treatment carbon fibers, where final heat treatment temperatures not greater than 1000 °C. These are low modulus and low strength materials [19].

2.4.2. Manufacture

In Textile Terms and Definitions, carbon fiber has been described as a fiber containing at least 90% carbon obtained by the controlled pyrolysis of appropriate fibers. The term "graphite fiber" is used to describe fibers that have carbon in excess of 99%. Large varieties of fibers called precursors are used to produce carbon fibers of different morphologies and different specific characteristics. The most prevalent precursors are polyacrylonitrile (PAN), cellulosic fibers (viscose rayon, cotton), petroleum or coal tar pitch and certain phenolic fibers.

Carbon fibers are manufactured by the controlled pyrolysis of organic precursors in fibrous form. It is a heat treatment of the precursor that removes the oxygen, nitrogen and hydrogen to form carbon fibers. It is well established in carbon fiber literature that the mechanical properties of the carbon fibers are improved by increasing the crystallinity and orientation, and by reducing defects in the fiber. The best way to achieve this is to start with a highly oriented precursor and then maintain the initial high orientation during the process of stabilization and carbonization through tension [18-19].

2.4.2.1. Carbon fibers from polyacrylonitrile (PAN)

There are three successive stages in the conversion of PAN precursor into high-performance carbon fibers. Oxidative stabilization: The polyacrylonitrile precursor is first stretched and simultaneously oxidized in a temperature range of 200-300 °C. This treatment converts thermoplastic PAN to a non-plastic cyclic or ladder compound. Carbonization: After oxidation, the fibers are carbonized at about 1000 °C without tension in an inert atmosphere (normally nitrogen) for a few hours. During this process the non-carbon elements are removed as volatiles to give carbon fibers with a yield of about 50% of the mass of the original PAN. Graphitization: Depending on the type of fiber required, the fibers are treated at temperatures between 1500-3000 °C, which improves the ordering, and orientation of the crystallites in the direction of the fiber axis.

2.4.2.2. Carbon fibers from rayon

a- The conversion of rayon fibers into carbon fibers is three phase process

Stabilization: Stabilization is an oxidative process that occurs through steps. In the first step, between 25-150 °C, there is physical desorption of water. The next step is a dehydration of the cellulosic unit between 150-240 °C. Finally, thermal cleavage of the cyclosidic linkage and scission of ether bonds and some C-C bonds via free radical reaction (240-400 °C) and, thereafter, aromatization takes place.

Carbonization: Between 400 and 700 °C, the carbonaceous residue is converted into a graphite-like layer.

Graphitization: Graphitization is carried out under strain at 700-2700 °C to obtain high modulus fiber through longitudinal orientation of the planes.

b- The carbon fiber fabrication from pitch generally consists of the following four steps:

Pitch preparation: It is an adjustment in the molecular weight, viscosity, and crystal orientation for spinning and further heating.

Spinning and drawing: In this stage, pitch is converted into filaments, with some alignment in the crystallites to achieve the directional characteristics.

Stabilization: In this step, some kind of thermosetting to maintain the filament shape during pyrolysis. The stabilization temperature is between 250 and 400 °C.

Carbonization: The carbonization temperature is between 1000-1500 °C.

2.4.2.3. Carbon fibers in meltblown nonwovens

Carbon fibers made from the spinning of molten pitches are of interest because of the high carbon yield from the precursors and the relatively low cost of the starting materials. Stabilization in air and carbonization in nitrogen can follow the formation of melt-blown pitch webs. Processes have been developed with isotropic pitches and with anisotropic mesophase pitches. The mesophase pitch based and melt blown discontinuous carbon fibers have

a peculiar structure. These fibers are characterized in that a large number of small domains, each domain having an average equivalent diameter from 0.03 mm to 1mm and a nearly unidirectional orientation of folded carbon layers, assemble to form a mosaic structure on the cross-section of the carbon fibers. The folded carbon layers of each domain are oriented at an angle to the direction of the folded carbon layers of the neighboring domains on the boundary [20].

2.4.2.4. Carbon fibers from isotropic pitch

The isotropic pitch or pitch-like material, i.e., molten polyvinyl chloride, is melt spun at high strain rates to align the molecules parallel to the fiber axis. The thermoplastic fiber is then rapidly cooled and carefully oxidized at a low temperature (<100 °C). The oxidation process is rather slow, to ensure stabilization of the fiber by cross-linking and rendering it infusible. However, upon carbonization, relaxation of the molecules takes place, producing fibers with no significant preferred orientation. This process is not industrially attractive due to the lengthy oxidation step, and only low-quality carbon fibers with no graphitization are produced. These are used as fillers with various plastics as thermal insulation materials [20].

2.4.2.5. Carbon fibers from anisotropic mesophase pitch

High molecular weight aromatic pitches, mainly anisotropic in nature, are referred to as mesophase pitches. The pitch precursor is thermally treated above 350°C to convert it to mesophase pitch, which contains both isotropic and anisotropic phases. Due to the shear stress occurring during spinning, the mesophase molecules orient parallel to the fiber axis. After spinning, the isotropic part of the pitch is made infusible by thermosetting in air at a temperature below it's softening point. The fiber is then carbonized at temperatures up to 1000 °C. The main advantage of this process is that no tension is required during the stabilization or the graphitization, unlike the case of rayon or PANs precursors [21].

2.4.2.6. Structure

The characterization of carbon fiber microstructure has been mainly been performed by x-ray scattering and electron microscopy techniques. In contrast to graphite, the structure of carbon fiber lacks any three dimensional order. In PAN-based fibers, the linear chain structure is transformed to a planar structure during oxidative stabilization and subsequent carbonization. Basal planes oriented along the fiber axis are formed during the carbonization stage. Wide-angle x-ray data suggests an increase in stack height and orientation of basal planes with an increase in heat treatment temperature. A difference in structure between the sheath and the core was noticed in a fully stabilized fiber. The skin has a high axial preferred orientation and thick crystallite stacking. However, the core shows a lower preferred orientation and a lower crystallite height [22].

2.4.2.7. Properties

In general, it is seen that the higher the tensile strength of the precursor the higher is the tenacity of the carbon fiber. Tensile strength and modulus are significantly improved by carbonization under strain when moderate stabilization is used. X-ray and electron diffraction studies have shown that in high modulus type fibers, the crystallites are arranged around the longitudinal axis of the fiber with layer planes highly oriented parallel to the axis. Overall, the strength of a carbon fiber depends on the type of precursor, the processing conditions, heat treatment temperature and the presence of flaws and defects. With PAN based carbon fibers, the strength increases up to a maximum of 1300 ºC and then gradually decreases. The modulus has been shown to increase with increasing temperature. PAN based fibers typically buckle on compression and form kink bands at the innermost surface of the fiber. However, similar high modulus type pitch-based fibers deform by a shear mechanism with kink bands formed at 45° to the fiber axis. Carbon fibers are very brittle. The layers in the fibers are formed by strong covalent bonds. The sheet-like aggregations allow easy crack propagation. On bending, the fiber fails at very low strain [23].

2.4.2.8. Applications

The two main applications of carbon fibers are in specialized technology, which includes aerospace and nuclear engineering, and in general engineering and transportation, which includes engineering components such as bearings, gears, cams, fan blades and automobile bodies. Recently, some new applications of carbon fibers have been found. Others include: decoration in automotive, marine, general aviation interiors, general entertainment and musical instruments and after-market transportation products. Conductivity in electronics technology provides additional new application [24].

The production of highly effective fibrous carbon adsorbents with low diameter, excluding or minimizing external and intra-diffusion resistance to mass transfer, and therefore, exhibiting high sorption rates is a challenging task. These carbon adsorbents can be converted into a wide variety of textile forms and nonwoven materials. Cheaper and newer versions of carbon fibers are being produced from new raw materials. Newer applications are also being developed for protective clothing (used in various chemical industries for work in extremely hostile environments), electromagnetic shielding and various other novel applications. The use of carbon fibers in Nonwovens is in a new possible application for high temperature fire-retardant insulation (eg: furnace material) [25].

2.5. Aramid-definition

Aliphatic polyamides are macromolecules whose structural units are characteristically interlinked by the amide linkage -NH-CO-. The nature of the structural unit constitutes a basis for classification. Aliphatic polyamides with structural units derived predominantly from aliphatic monomers are members of the generic class of nylons, whereas aromatic polyamides in which at least 85% of the amide linkages are directly adjacent to aromatic structures have been designated aramids. The U.S. Federal Trade Commission defines nylon

fibers as ''a manufactured fiber in which the fiber forming substance is a long chain synthetic polyamide in which less than 85% of the amide linkages (-CO-NH-) are attached directly to two aliphatic groups.'' Polyamides that contain recurring amide groups as integral parts of the polymer backbone have been classified as condensation polymers regardless of the principal mechanisms entailed in the polymerization process. Though many reactions suitable for polyamide formation are known, commercially important nylons are obtained by processes related to either of two basic approaches: one entails the polycondensation of difunctional monomers utilizing either amino acids or stoichiometric pairs of dicarboxylic acids and diamines, and the other entails the ring-opening polymerization of lactams. The polyamides formed from diacids and diamines are generally described to be of the AABB format, whereas those derived from either amino acids or lactams are of the AB format.

The structure of polyamide fibers is defined by both chemical and physical parameters. The chemical parameters are related mainly to the constitution of the polyamide molecule and are concerned primarily with its monomeric units, end-groups, and molecular weight. The physical parameters are related essentially to chain conformation, orientation of both polymer molecule segments and aggregates, and to crystallinity [26]. This characteristic for single-chain aliphatic polyamides is determined by the structure of the monomeric units and the nature of end groups of the polymer molecules. The most important structural parameter of the noncrystalline (amorphous) phase is the glass transition temperature (T_g) since it has a considerable effect on both processing and properties of the polyamide fibers. It relates to a type of a glass–rubber transition and is defined as the temperature, or temperature range, at which mobility of chain segments or structural units commences. Thus it is a function of the chemical structure; in case of the linear aliphatic polyamides, it is a function of the number of CH_2 units (mean spacing) between the amide groups. As the number of CH_2 unit's increases, T_g decreases. Although T_g is further affected by the nature of the crystalline phase, orientation, and molecular weight, it is associated only with what may be considered the amorphous phase.

Any process affecting this phase exerts a corresponding effect on the glass transition temperature. This is particularly evident in its response to the concentration of water absorbed in polyamides. An increase in water content results in a steady decrease of T_g toward a limiting value. This phenomenon may be explained by a mechanism that entails successive replacement of intercatenary hydrogen bonds in the amorphous phase with water. It may involve a sorption mechanism, according to which 3 mol of water interact with two neighboring amide groups [27].

The properties of aromatic polyamides differ significantly from those of their aliphatic counterparts. This led the U.S. Federal Trade Commission to adopt the term ''aramid'' to designate fibers of the aromatic polyamide type in which at least 85% of the amide linkages are attached directly to two aromatic rings.

The search for materials with very good thermal properties was the original reason for research into aromatic polyamides. Bond dissociation energies of C-C and C-N bonds in aromatic polyamides are ~20% higher than those in aliphatic polyamides. This is the reason why the decomposition temperature of poly(m-phenylene isophthalamide) MPDI exceeds

450 ºC. Conjugation between the amide group and the aromatic ring in poly(p-phenylene terephthalamide) "PPTA" increases chain rigidity as well as the decomposition temperature, which exceeds 550 ºC.

Obviously, hydrogen bonding and chain rigidity of these polymers translates to very high glass transition temperatures. Using low-molecular-weight polymers, Aharoni [19] measured glass transition temperatures of 272 ºC for MPDI and over 295 ºC for PPTA (which in this case had low crystallinity). Others have reported values as high as 4928 ºC. In most cases the measurement of T_g is difficult because PPTA is essentially 100% crystalline. As one would expect, these values are not strongly dependent on the molecular weight of the polymer above a DP of ~10 [22].

The same structural characteristics that are responsible for the excellent thermal properties of these materials are responsible for their limited solubility as well as good chemical resistance. PPTA is soluble only in strong acids like H_2SO_4, HF, and methanesulfonic acid. Preparation of this polymer via solution polymerization in amide solvents is accompanied by polymer precipitation. As expected, based on its structure, MPDI is easier to solubilize then PPTA. It is soluble in neat amide solvents like N-methyl-2-pyrrolidone (NMP) and dimethylacetamide (DMAc), but adding salts like $CaCl_2$ or LiCl significantly enhances its solubility. The significant rigidity of the PPTA chain (as discussed above) leads to the formation of anisotropic solutions when the solvent is good enough to reach critical minimum solids concentration. The implications of this are discussed in greater detail later in this chapter. It is well known that chemical properties differ significantly between crystalline and noncrystalline materials of the same composition. In general, aramids have very good chemical resistance. Obviously, the amide bond is subject to a hydrolytic attack by acids and bases. Exposure to very strong oxidizing agents results in a significant strength loss of these fibers. In addition to crystallinity, structure consolidation affects the rate of degradation of these materials. The hydrophilicity of the amide group leads to a significant absorption of water by all aramids. While the chemistry is the driving factor, fiber structure also plays a very important role; for example, Kevlar 29 absorbs ~7% water, Kevlar 49~4%, and Kevlar 149 only 1%. Fukuda explored the relationship between fiber crystallinity and equilibrium moisture in great detail. Because of their aromatic character, aramids absorb UV light, which results in an oxidative color change. Substantial exposure can lead to the loss of yarn tensile properties. UV absorption by p-aramids is more pronounced than with m-aramids. In this case a self-screening phenomenon is observed, which makes thin structures more susceptible to degradation than thick ones. Very frequently p-aramids are covered with another material in the final application to protect them. The high degree of aromaticity of these materials also provides significant flame resistance. All commercial aramids have a limited oxygen index in the range of 28-32%, which compares with ~20% for aliphatic polyamides.

Typical properties of commercial aramid fibers are while yarns of m-aramids have tensile properties that are no greater than those of aliphatic polyamides, they do retain useful mechanical properties at significantly higher temperatures. The high glass transition temperature leads to low (less than 1%) shrinkage at temperatures below 250 ºC. In general, mechanical properties of m-aramid fibers are developed on drawing. This process produces

fibers with a high degree of morphological homogeneity, which leads to very good fatigue properties. The mechanical properties of p-aramid fibers have been the subject of much study. This is because these fibers were the first examples of organic materials with a very high level of both strength and stiffness. These materials are practical confirmation that nearly perfect orientation and full chain extension are required to achieve mechanical properties approaching those predicted for chemical bonds. In general, the mechanical properties reflect a significant anisotropy of these fibers-covalent bonds in the direction of the fiber axis with hydrogen bonding and van der Waals forces in the lateral direction [26].

Aramid-based reinforcement has been viewed as a more specialty product for applications requiring high modulus and where the potential for electrical conductivity would preclude the use of carbon; for example, aramid sheet is used for all tunnel repairs. Product forms include dry fabrics or unidirectional sheets as well as pre-cured strips or bars. Fabrics or sheets are applied to a concrete surface that has been smoothed (by grinding or blasting) and wetted with a resin (usually epoxy). The composite materials used for concrete infrastructure repair that was initiated in the mid 1980s. After air pockets are removed using rollers or flat, flexible squeegees, a second resin coat might be applied. Reinforcement of concrete structures is important in earthquake prone areas, although steel plate is the primary material used to reinforce and repair concrete structures, higher priced fiber-based sheet structures offer advantages for small sites where ease of handling and corrosion resistance are important. The high strength, modulus, and damage tolerance of aramid-reinforced sheets makes the fiber especially suitable for protecting structures prone to seismic activity. The use of aramid sheet also simplifies the application process. Sheets are light in weight and can be easily handled without heavy machinery and can be applied in confined working spaces. Sheets are also flexible, so surface smoothing and corner rounding of columns are less critical than for carbon fiber sheets [28].

3. All process description

FRP involves two distinct processes, the first is the process whereby the fibrous material is manufactured and formed, and the second is the process whereby fibrous materials are bonded with the matrix during the molding process.

3.1. Fibre process

3.1.1. The manufacture of fibre fabric

Reinforcing Fibre is manufactured in both two dimensional and three dimensional orientations

1.   Two Dimensional Fibre Reinforced Polymer are characterized by a laminated structure in which the fibres are only aligned along the plane in x-direction and y-direction of the material. This means that no fibres are aligned in the through thickness or the z-direction, this lack of alignment in the through thickness can create a disadvantage in cost

and processing. Costs and labour increase because conventional processing techniques used to fabricate composites, such as wet hand lay-up, autoclave and resin transfer molding, require a high amount of skilled labour to cut, stack and consolidate into a preformed component.

2.   Three-dimensional Fibre Reinforced Polymer composites are materials with three dimensional fibre structures that incorporate fibres in the x-direction, y-direction and z-direction. The development of three-dimensional orientations arose from industry's need to reduce fabrication costs, to increase through-thickness mechanical properties, and to improve impact damage tolerance; all were problems associated with two dimensional fibre reinforced polymers [28].

3.1.2. The manufacture of fibre preforms

Fibre preforms are how the fibres are manufactured before being bonded to the matrix. Fibre preforms are often manufactured in sheets, continuous mats, or as continuous filaments for spray applications. The four major ways to manufacture the fibre preform is though the textile processing techniques of Weaving, knitting, braiding and stitching.

1.   Weaving can be done in a conventional manner to produce two-dimensional fibres as well in a multilayer weaving that can create three-dimensional fibres. However, multilayer weaving is required to have multiple layers of warp yarns to create fibres in the z-direction creating a few disadvantages in manufacturing, namely the time to set up all the warp yarns on the loom. Therefore most multilayer weaving is currently used to produce relatively narrow width products or high value products where the cost of the preform production is acceptable. Another Fibre-reinforced plastic 3D one of the main problems facing the use of multilayer woven fabrics is the difficulty in producing a fabric that contains fibres oriented with angles other than 0º and 90º to each other respectively.

2.   The second major way of manufacturing fibre preforms is braiding. Braiding is suited to the manufacture of narrow width flat or tubular fabric and is not as capable as weaving in the production of large volumes of wide fabrics. Braiding is done over top of mandrels that vary in cross-sectional shape or dimension along their length. Braiding is limited to objects about a brick in size. Unlike the standard weaving process, braiding can produce fabric that contains fibres at 45 degrees angles to one another. Braiding three-dimensional fibres can be done using four steps, two-step or Multilayer Interlock Braiding. Four step or row and column braiding utilizes a flat bed containing rows and columns of yarn carriers that form the shape of the desired preform. Additional carriers are added to the outside of the array, the precise location and quantity of which depends upon the exact preform shape and structure required. There are four separate sequences of row and column motion, which act to interlock the yarns and produce the braided preform. The yarns are mechanically forced into the structure between each step to consolidate the structure in a similar process to the use of a reed in weaving.Two-step braiding is unlike the four step process because the two-step includes a

large number of yarns fixed in the axial direction and a fewer number of braiding yarns. The process consists of two steps in which the braiding carriers move completely through the structure between the axial carriers. This relatively simple sequence of motions is capable of forming performs of essentially any shape, including circular and hollow shapes. Unlike the four steps process the two steps process does not require mechanical compaction the motions involved in the process allows the braid to be pulled tight by yarn tension alone. The last type of braiding is multi-layer interlocking braiding that consists of a number of standard circular braiders being joined together to form a cylindrical braiding frame. This frame has a number of parallel braiding tracks around the circumference of the cylinder but the mechanism allows the transfer of yarn carriers between adjacent tracks forming a multilayer braided fabric with yarns interlocking to adjacent layers.

The multilayer interlock braid differs from both the four step and two-step braids in that the interlocking yarns are primarily in the plane of the structure and thus do not significantly reduce the in-plane properties of the perform. The four step and two step processes produce a greater degree of interlinking as the braiding yarns travel through the thickness of the preform, but therefore contribute less to the in-plane performance of the preform. A disadvantage of the multilayer interlock equipment is that due to the conventional sinusoidal movement of the yarn carriers to form the preform, the equipment is not able to have the density of yarn carriers that is possible with the two step and four step machines.

3. Knitting fibre preforms can be done with the traditional methods of Warp and [Weft] Knitting, and the fabric produced is often regarded by many as two-dimensional fabric, but machines with two or more needle beds are capable of producing multilayer fabrics with yams that traverse between the layers. Developments in electronic controls for needle selection and knit loop transfer and in the sophisticated mechanisms that allow specific areas of the fabric to be held and their movement controlled. This has allowed the fabric to form itself into the required three-dimensional perform shape with a minimum of material wastage.

4. Stitching is arguably the simplest of the four main textile manufacturing techniques and one that can be performed with the smallest investment in specialized machinery. Basically the stitching process consists of inserting a needle, carrying the stitch thread, through a stack of fabric layers to form a 3D structure. The advantages of stitching are that it is possible to stitch both dry and prepreg fabric, although the tackiness of prepare makes the process difficult and generally creates more damage within the prepreg material than in the dry fabric. Stitching also utilizes the standard two-dimensional fabrics that are commonly in use within the composite industry therefore there is a sense of familiarity concerning the material systems. The use of standard fabric also allows a greater degree of flexibility in the fabric lay-up of the component than is possible with the other textile processes, which have restrictions on the fibre orientations that can be produced.

3.1.3. Molding processes

There are two distinct categories of molding processes using FRP plastics; this includes composite molding and wet molding. Composite molding uses Prepreg FRP, meaning the plastics are fibre reinforced before being put through further molding processes. Sheets of Prepreg FRP are heated or compressed in different ways to create geometric shapes. Wet molding combines fibre reinforcement and the matrix or resist during the molding process. The different forms of composite and wet molding, are listed below.

3.2. Composite molding

3.2.1. Bladder molding

Individual sheets of prepreg material are laid -up and placed in a female-style mould along with a balloon-like bladder. The mould is closed and placed in a heated press. Finally, the bladder is pressurized forcing the layers of material against the mould walls. The part is cured and removed from the hot mould. Bladder molding is a closed molding process with a relatively short cure cycle between 15 and 60 minutes making it ideal for making complex hollow geometric shapes at competitive costs.

3.2.2. Compression molding

A "preform" or "charge", of SMC, BMC or sometimes prepreg fabric, is placed into mould cavity. The mould is closed and the material is compacted & cured inside by pressure and heat. Compression molding offers excellent detailing for geometric shapes ranging from pattern and relief detailing to complex curves and creative forms, to precision engineering all within a maximum curing time of 20 minutes.

3.2.3. Autoclave – Vacuum bag

Individual sheets of prepreg material are laid-up and placed in an open mold. The material is covered with release film, bleeder/breather material and a vacuum bag. A vacuum is pulled on part and the entire mould is placed into an autoclave (heated pressure vessel). The part is cured with a continuous vacuum to extract entrapped gasses from laminate. This is a very common process in the aerospace industry because it affords precise control over the molding process due to a long slow cure cycle that is anywhere from one to two hours. This precise control creates the exact laminate geometric forms needed to ensure strength and safety in the aerospace industry, but it is also slow and lab our intensive, meaning costs often confine it to the aerospace industry.

3.2.4. Mandrel wrapping

Sheets of prepreg material are wrapped around a steel or aluminum mandrel. The prepreg material is compacted by nylon or polypropylene cello tape. Parts are typically batch cured by hanging in an oven. After cure the cello and mandrel are removed leaving a hollow carbon tube. This process creates strong and robust hollow carbon tubes.

3.2.5. Wet layup

Fibre reinforcing fabric is placed in an open mould and then saturated with a wet (resin) by pouring it over the fabric and working it into the fabric and mould. The mould is then left so that the resin will cure, usually at room temperature, though heat is sometimes used to en-sure a proper curing process. Glass fibres are most commonly used for this process, the re-sults are widely known as fibreglass, and are used to make common products like skis, canoes, kayaks and surf boards.

3.2.6. Chopper gun

Continuous strand of fibreglass are pushed through a hand-held gun that both chops the strands and combines them with a catalyzed resin such as polyester. The impregnated chop-ped glass is shot onto the mould surface in whatever thickness the design and human opera-tor think is appropriate. This process is good for large production runs at economical cost, but produces geometric shapes with less strength than other molding processes and has poor dimensional tolerance.

3.2.7. Filament winding

Machines pull fibre bundles through a wet bath of resin and wound over a rotating steel mandrel in specific orientations Parts are cured either room temperature or elevat-ed temperatures. Mandrel is extracted, leaving a final geometric shape but can be left in some cases.

3.2.8. Pultrusion

Fibre bundles and slit fabrics are pulled through a wet bath of resin and formed into the rough part shape. Saturated material is extruded from a heated closed die curing while be-ing continuously pulled through die. Some of the end products of the pultrusion process are structural shapes, i.e. beam, angle, channel and flat sheet. These materials can be used to cre-ate all sorts of fibreglass structures such as ladders, platforms, handrail systems tank, pipe, and pump supports.

3.3. Resin infusion

Fabrics are placed into a mould which wet resin is then injected into. Resin is typically pres-surized and forced into a cavity which is under vacuum in the RTM (Resin Transfer Mold-ing) process. Resin is entirely pulled into cavity under vacuum in the VARTM (Vacuum Assisted Resin Transfer Molding) process. This molding process allows precise tolerances and detailed shaping but can sometimes fail to fully saturate the fabric leading to weak spots in the final shape.

3.3.1. Advantages and limitations

FRP allows the alignment of the glass fibres of thermoplastics to suit specific design programs. Specifying the orientation of reinforcing fibres can increase the strength and resistance to deformation of the polymer. Glass reinforced polymers are strongest and most resistive to deforming forces when the polymers fibres are parallel to the force being exerted, and are weakest when the fibres are perpendicular. Thus this ability is at once both an advantage and a limitation depending on the context of use. Weak spots of perpendicular fibres can be used for natural hinges and connections, but can also lead to material failure when production processes fail to properly orient the fibres parallel to expected forces. When forces are exerted perpendicular to the orientation of fibres the strength and elasticity of the polymer is less than the matrix alone. In cast resin components made of glass reinforced polymers such as UP and EP, the orientation of fibres can be oriented in two-dimensional and three-dimensional weaves. This means that when forces are possibly perpendicular to one orientation, they are parallel to another orientation; this eliminates the potential for weak spots in the polymer.

3.3.2. Failure modes

Structural failure can occur in FRP materials when:

- Tensile forces stretch the matrix more than the fibres, causing the material to shear at the interface between matrix and fibres.

- Tensile forces near the end of the fibres exceed the tolerances of the matrix, separating the fibres from the matrix.

- Tensile forces can also exceed the tolerances of the fibres causing the fibres themselves to fracture leading to material failure [29].

3.3.3. Material requirements

The matrix must also meet certain requirements in order to first be suitable for the FRP process and ensure a successful reinforcement of it. The matrix must be able to properly saturate, and bond with the fibres within a suitable curing period. The matrix should preferably bond chemically with the fibre reinforcement for maximum adhesion. The matrix must also completely envelope the fibres to protect them from cuts and notches that would reduce their strength, and to transfer forces to the fibres. The fibres must also be kept separate from each other so that if failure occurs it is localized as much as possible, and if failure occurs the matrix must also debond from the fibre for similar reasons. Finally the matrix should be of a plastic that remains chemically and physically stable during and after reinforcement and molding processes. To be suitable for reinforcement material fibre additives must increase the tensile strength and modulus of elasticity of the matrix and meet the following conditions; fibres must exceed critical fibre content; the strength and rigidity of fibres itself must exceed the strength and rigidity of the matrix alone; and there must be optimum bonding between fibres and matrix.

3.4. Glass fibre material

FRPs use textile glass fibres; textile fibres are different from other forms of glass fibres used for insulating applications. Textile glass fibres begin as varying combinations of SiO_2, Al_2O_3, B_2O_3, CaO, or MgO in powder form. These mixtures are then heated through a direct melt process to temperatures around 1300 degrees Celsius, after which dies are used to extrude filaments of glass fibre in diameter ranging from 9 to 17 µm. These filaments are then wound into larger threads and spun onto bobbins for transportation and further processing. Glass fibre is by far the most popular means to reinforce plastic and thus enjoys a wealth of production processes, some of which are applicable to aramid and carbon fibres as well owing to their shared fibrous qualities. Roving is a process where filaments are spun into larger diameter threads. These threads are then commonly used for woven reinforcing glass fabrics and mats, and in spray applications. Fibre fabrics are web-form fabric reinforcing material that has both warped and weft directions. Fibre mats are web-form non-woven mats of glass fibres. Mats are manufactured in cut dimensions with chopped fibres, or in continuous mats using continuous fibres. Chopped fibre glass is used in processes where lengths of glass threads are cut between 3 and 26 mm, threads are then used in plastics most commonly intended for moulding processes. Glass fibre short strands are short 0.2–0.3 mm strands of glass fibres that are used to reinforce thermoplastics most commonly for injection moulding.

3.5. Aramid fibre material process

Aramid fibres are most commonly known Kevlar, Nomex and Technora. Aramids are generally prepared by the reaction between an amine group and a carboxylic acid halide group (aramid); commonly this occurs when an aromatic polyamide is spun from a liquid concentration of sulfuric acid into a crystallized fibre. Fibres are then spun into larger threads in order to weave into large ropes or woven fabrics (Aramid) [29]. Aramid fibres are manufactured with varying grades to base on varying qualities for strength and rigidity, so that the material can be somewhat tailored to specific design needs concerns, such as cutting the tough material during manufacture.

3.6. FRP, applications

Fibre-reinforced plastics are best suited for any design program that demands weight savings, precision engineering, finite tolerances, and the simplification of parts in both production and operation. A molded polymer artifact is cheaper, faster, and easier to manufacture than cast aluminum or steel artifact, and maintains similar and sometimes better tolerances and material strengths. The Mitsubishi Lancer Evolution IV also used FRP for its spoiler material [30-32].

3.6.1. Carbon fibre reinforced polymers

Rudder of commercial airplane

• Advantages over a traditional rudder made from sheet aluminum are:

- 25% reduction in weight

- 95% reduction in components by combining parts and forms into simpler molded parts.

- Overall reduction in production and operational costs, economy of parts results in lower production costs and the weight savings create fuel savings that lower the operational costs of flying the airplane.

3.6.2. Structural applications of FRP

FRP can be applied to strengthen the beams, columns and slabs in buildings. It is possible to increase strength of these structural members even after these have been severely damaged due to loading conditions. For strengthening beams, two techniques are adopted. First one is to paste FRP plates to the bottom (generally the tension face) of a beam. This increases the strength of beam, deflection capacity of beam and stiffness (load required to make unit deflection). Alternatively, FRP strips can be pasted in 'U' shape around the sides and bottom of a beam, resulting in higher shear resistance. Columns in building can be wrapped with FRP for achieving higher strength. This is called wrapping of columns. The technique works by restraining the lateral expansion of the column. Slabs may be strengthened by pasting FRP strips at their bottom (tension face). This will result in better performance, since the tensile resistance of slabs is supplemented by the tensile strength of FRP. In the case of beams and slabs, the effectiveness of FRP strengthening depends on the performance of the resin chosen for bonding [32].

3.6.3. Glass fibre reinforced polymers

Engine intake manifolds are made from glass fibre reinforced PA 66.

- Advantages this has over cast aluminum manifolds are:

- Up to a 60% reduction in weight

- Improved surface quality and aerodynamics

- Reduction in components by combining parts and forms into simpler molded shapes. Automotive gas and clutch pedals made from glass fibre reinforced PA 66 (DWP 12-13)

- Advantages over stamped aluminum are:

- Pedals can be molded as single units combining both pedals and mechanical linkages simplifying the production and operation of the design.

- Fibres can be oriented to reinforce against specific stresses, increasing the durability and safety.

3.6.4. Design considerations

FRP is used in designs that require a measure of strength or modulus of elasticity those non-reinforced plastics and other material choices are either ill suited for mechanically or eco-

nomically. This means that the primary design consideration for using FRP is to ensure that the material is used economically and in a manner that takes advantage of its structural enhancements specifically. This is however not always the case, the orientation of fibres also creates a material weakness perpendicular to the fibres. Thus the use of fibre reinforcement and their orientation affects the strength, rigidity, and elasticity of a final form and hence the operation of the final product itself. Orienting the direction of fibres either, unidirectional, 2-dimensionally, or 3-dimensionally during production affects the degree of strength, flexibility, and elasticity of the final product. Fibres oriented in the direction of forces display greater resistance to distortion from these forces and vice versa, thus areas of a product that must withstand forces will be reinforced with fibres in the same direction, and areas that require flexibility, such as natural hinges, will use fibres in a perpendicular direction to forces. Using more dimensions avoids this either or scenario and creates objects that seek to avoid any specific weak points due to the unidirectional orientation of fibres. The properties of strength, flexibility and elasticity can also be magnified or diminished through the geometric shape and design of the final product. These include such design consideration such as ensuring proper wall thickness and creating multifunctional geometric shapes that can be molding as single pieces, creating shapes that have more material and structural integrity by reducing joints, connections, and hardware [30].

3.6.5. Disposal and recycling concerns

As a subset of plastic FR plastics are liable to a number of the issues and concerns in plastic waste disposal and recycling. Plastics pose a particular challenge in recycling processes because they are derived from polymers and monomers that often cannot be separated and returned to their virgin states, for this reason not all plastics can be recycled for re-use, in fact some estimates claim only 20% to 30% of plastics can be material recycled at all. Fibre reinforced plastics and their matrices share these disposal and environmental concerns. In addition to these concerns, the fact that the fibres themselves are difficult to remove from the matrix and preserve for re-use means FRP amplify these challenges. FRP are inherently difficult to separate into base a material that is into fibre and matrix, and the Fibre-reinforced plastic matrix into separate usable plastic, polymers, and monomers. These are all concerns for environmentally informed design today, but plastics often offer savings in energy and economic savings in comparison to other materials, also with the advent of new more environmentally friendly matrices such as bioplastics and UV-degradable plastics, FRP will similarly gain environmental sensitivity [29].

4. Mechanical properties measurements

4.1. Strength

Strength is a mechanical property that you should be able to relate to, but you might not know exactly what we mean by the word "strong" when are talking about polymers. First, there is more than one kind of strength. There is tensile strength. A polymer has tensile

strength if it is strong when one pulls on it. Tensile strength is important for a material that is going to be stretched or under tension. Fibers need good tensile strength.

Then there is compressional strength. A polymer sample has compressional strength if it is strong when one tries to compress it. Concrete is an example of a material with good compressional strength. Anything that has to support weight from underneath has to have good compressional strength [32]. There is also flexural strength. A polymer sample has flexural strength if it is strong when one tries to bend it.

There are other kinds of strength we could talk about. A sample torsional strength if it is strong when one tries to twist it. Then there is impact strength. A sample has impact strength if it is strong when one hits it sharply and suddenly, as with a hammer.

To measure the tensile strength of a polymer sample, we take the sample and we try to stretch. We usually stretch it with a machine for these studies. This machine simply has clamps on each end of the sample, then, when you turn it on it stretches the sample. While it is stretching the sample, it measures the amount of force (F) that it is exerting. When we know the force being exerted on the sample, we then divide that number by the cross-sectional area (A) of our sample. The answer is the stress that our sample is experiencing. Then, using our machine, we continue to increase the amount of force, and stress naturally, on the sample until it breaks. The stress needed to break the sample is the tensile strength of the material. Likewise, one can imagine similar tests for compressional or flexural strength. In all cases, the strength is the stress needed to break the sample. Since tensile stress is the force placed on the sample divided by the cross-sectional area of the sample, tensile stress, and tensile strength as well, are both measured in units of force divided by units of area, usually N/cm^2. Stress and strength can also be measured in megapascals (MPa) or gigapascals (GPa). It is easy to convert between the different units, because 1 MPa = 100 N/cm^2, 1 GPa = 100,000 N/cm^2, and of course 1 GPa = 1,000 MPa. Other times, stress and strength are measured in the old English units of pounds per square inch, or psi. If you ever have to convert psi to N/cm^2, the conversion factor is 1 N/cm^2 = 1.45 psi.

4.2. Elongation

But there is more to understanding a polymer's mechanical properties than merely knowing how strong it is. All strength tells us is how much stress is needed to break something. It doesn't tell us anything about what happens to our sample while we're trying to break it. That's where it pays to study the elongation behavior of a polymer sample. Elongation is a type of deformation. Deformation is simply a change in shape that anything undergoes under stress. When we're talking about tensile stress, the sample deforms by stretching, becoming longer. We call this elongation, of course. Usually we talk about percent elongation, which is just the length the polymer sample is after it is stretched (L), divided by the original length of the sample (L_0), and then multiplied by 100.

There are a number of things we measure related to elongation. Which is most important depends on the type of material one is studying. Two important things we measure are ultimate elongation and elastic elongation. Ultimate elongation is important for any kind of ma-

terial. It is nothing more than the amount you can stretch the sample before it breaks. Elastic elongation is the percent elongation you can reach without permanently deforming your sample. That is, how much can you stretch it, and still have the sample snap back to its original length once you release the stress on it. This is important if your material is an elastomer. Elastomers have to be able to stretch a long distance and still bounce back. Most of them can stretch from 500 to 1000 % elongation and return to their original lengths without any trouble [32].

4.3. Modulus

In the elastomers are need show the high elastic elongation. But for some other types of materials, like plastics, it usually they not stretch or deform so easily. If we want to know how well a material resists deformation, we measure something called modulus. To measure tensile modulus, we do the same thing as we did to measure strength and ultimate elongation. This time we measure the stress we're exerting on the material, just like we did when we were measuring tensile strength. First, is slowly increasing the amount of stress, and then we measure the elongation the sample undergoes at each stress level. We keep doing this until the sample breaks. This plot is called a stress-strain curve. (Strain is any kind of deformation, including elongation. Elongation is the word we use if we're talking specifically about tensile strain.) The height of the curve when the sample breaks is the tensile strength, of course, and the tensile modulus is the slope of this plot. If the slope is steep, the sample has a high tensile modulus, which means it resists deformation. If the slope is gentle, then the sample has a low tensile modulus, which means it is easily deformed. There are times when the stress-strain curve is not nice and straight, like we saw above. The slope isn't constant as stress increases. The slope, that is the modulus, is changing with stress. In a case like this we usually, the initial slope change as the modulus change [32].

In general, fibers have the highest tensile moduli, and elastomers have the lowest, and plastics have tensile moduli somewhere in between fibers and elastomers.

Modulus is measured by calculating stress and dividing by elongation, and would be measured in units of stress divided by units of elongation. But since elongation is dimensionless, it has no units by which we can divide. So modulus is expressed in the same units as strength, such as N/cm^2.

Intrinsic deformation is defined as the materials' true stress-strain response during homogeneous deformation. Since generally strain localization phenomena occur (like necking, shear banding, crazing and cracking), the measurement of the intrinsic materials' response requires a special experimental set-up, such as a video-controlled tensile or a uniaxial compression test. Although details of the intrinsic response differ per material, a general representation of the intrinsic deformation of polymers can be recognized [33], see Figure 1.
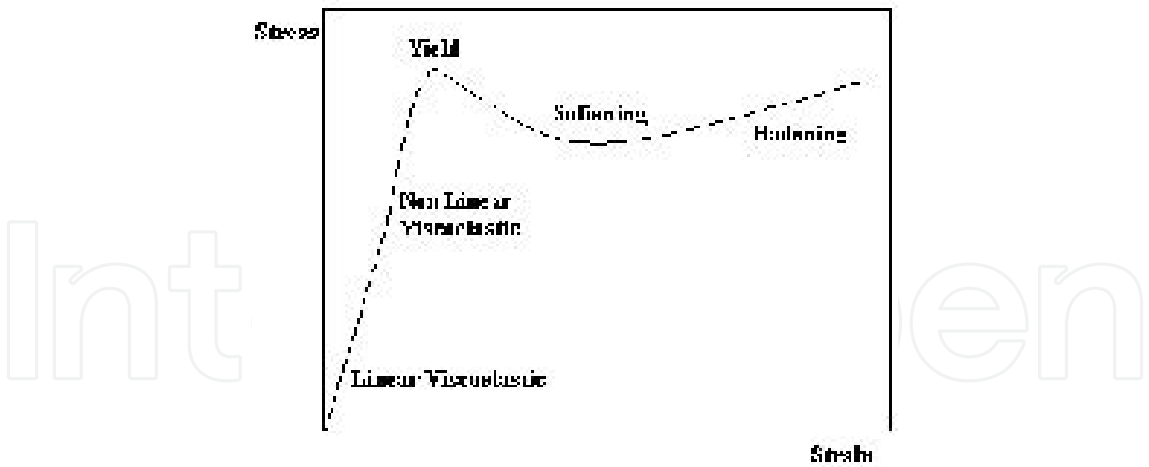
Figure 1. Schematic representation of the intrinsic deformation behavior of a polymer material [33].

4.4. Toughness

That plot of stress versus strain can give us another very valuable piece of information. If one measures the area underneath the stress-strain curve (figure 2), colored red in the graph below, the number you get is something we call toughness.
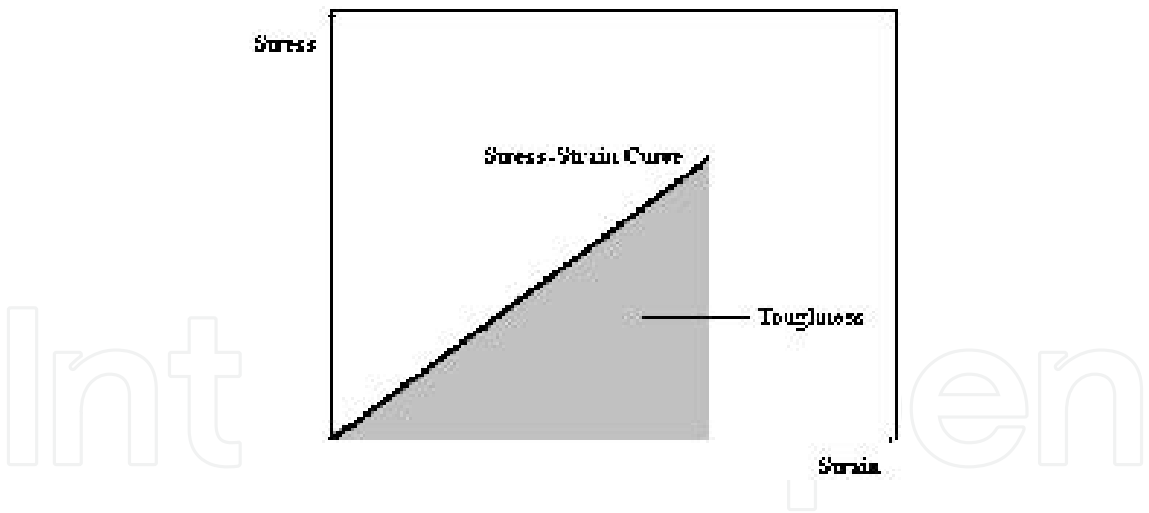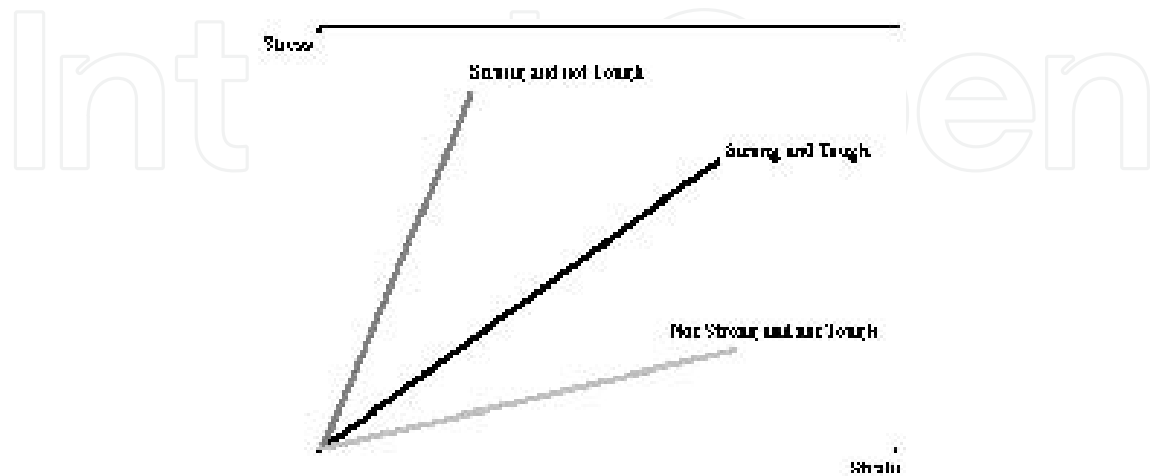

Figure 2. Plot of stress in function of strain.

Toughness is really a measure of the energy a sample can absorb before it breaks. Think about it, if the height of the triangle in the plot is strength, and the base of the triangle is strain, then the area is proportional to strength strain. Since strength is proportional to the force needed to break the sample, and strain is measured in units of distance (the distance the sample is stretched), then strength strain is proportional is force times distance, and as we remember from physics, force times distance is energy.

From a physics point of view the strength, is that strength tells how much force is needed to break a sample, and toughness tells how much energy is needed to break a sample. But that does not really tell you what the practical differences are. What is important knows that just because a material is strong, it isn't necessarily going to be tough as well [34-35].

Figure 3. Plot of stress in function of strain, strong and tough concepts.

The gray plot is the stress-strain curve for a sample that is strong, but not tough (figure 3). As you can see, it takes a lot of force to break this sample. Likewise, this sample ca not stretch very much before it breaks. A material like this which is strong, but can not deform very much before it breaks is called brittle [36].

The gray plot is a stress-strain curve for a sample that is both strong and tough. This material is not as strong as the sample in the gray plot, but the area underneath its curve is a lot larger than the area under the gray sample's curve. So it can absorb a lot more energy than the gray-black sample plot.

The gray-black sample elongates a lot more before breaking than the gray sample does. You see, deformation allows a sample to dissipate energy. If a sample can't deform, the energy won't be dissipated, and will cause the sample to break [37].

In real life, we usually want materials to be tough and strong. Ideally, it would be nice to have a material that would not bend or break, but this is the real world. The gray-black sample has a much higher modulus than the red sample. While it is good for materials in a lot of applications to have high moduli and resist deformation, in the real world it is a lot better for a material to bend than to break, and if bending, stretching or deforming in some other way prevents the material from breaking, all the better. So when we design new polymers, or new composites, we often sacrifice a little bit of strength in order to make the material tougher.

4.5. Mechanical properties
of real polymers

The rigid plastics such as polystyrene, poly(methyl methacrylate or polycarbonate can withstand a good deal of stress, but they won't withstand much elongation before breaking. There is not much area under the stress-strain curve at all. So we say that materials like this are strong, but not very tough. Also, the slope of the plot is very steep, which means that it takes a lot of force to deform a rigid plastic. So it is easy to see that rigid plastics have high moduli. In short, rigid plastics tend to be strong, at resist deformation, but they tend not to be very tough, that is, they are brittle.

Flexible plastics like polyethylene and polypropylene are different from rigid plastics in that they don not resist deformation as well, but they tend not to break. The ability to deform is what keeps them from breaking. Initial modulus is high, that is it will resist deformation for awhile, but if enough stress is put on a flexible plastic, it will eventually deform. If you try to stretch it a plastic bag, it will be very hard at first, but once you have stretched it far enough it will give way and stretch easily. The bottom line is that flexible plastics may not be as strong as rigid ones, but they are a lot tougher.

It is possible to alter the stress-strain behavior of a plastic with additives called plasticizers. A plasticizer is a small molecule that makes plastics more flexible. For example, without plasticizers, poly(vinyl chloride), or PVC for short, is a rigid plastic. Rigid unplasticized PVC is used for water pipes. But with plasticizers, PVC can be made flexible enough to use to make things like hoses.

Fibers like Kevlar™, carbon fiber and nylon tend to have stress-strain curves like the aqua-colored plot in the graph above. Like the rigid plastics, they are more strong than tough, and do not deform very much under tensile stress. But when strength is what you need, fibers have plenty of it. They are much stronger than plastics, even the rigid ones, and some polymeric fibers, like Kevlar™, carbon fiber and ultra-high molecular weight polyethylene have better tensile strength than steel.

Elastomers like polyisoprene, polybutadiene and polyisobutylene have completely different mechanical behavior from the other types of materials. Take a look at the pink plot in the graph above. Elastomers have very low moduli. You can see this from the very gentle slope of the pink plot, but you probably knew this already. You already knew that it is easy to stretch or bend a piece of rubber [34]. If elastomers did not have low moduli, they would not be very good elastomers.

But it takes more than just low modulus to make a polymer an elastomer. Being easily stretched is not much use unless the material can bounce back to its original size and shape once the stress is released. Rubber bands would be useless if they just stretched and did not bounce back. Of course, elastomers do bounce back, and that is what makes them so amazing. They have not just high elongation, but high reversible elongation.

4.6. Tensile properties

The discussion of which types of polymers have which mechanical properties has focused mostly on tensile properties. When we look at other properties, like compressional properties or flexural properties things can be completely different. For example, fibers have very high tensile strength and good flexural strength as well, but they usually have terrible compressional strength. They also only have good tensile strength in the direction of the fibers.

Some polymers are tough, while others are strong, and how one often has to make trade-offs when designing new materials; the design may have to sacrifice strength for toughness, but sometimes we can combine two polymers with different properties to get a new material with some of the properties of both. There are three main ways of doing this, and they are copolymerization, blending, and making composite materials.

The copolymer that combines the properties of two materials is spandex. It is a copolymer containing blocks of elastomeric polyoxyethylene and blocks of a rigid fiber-forming polyurethane. The result is a fiber that stretches. Spandex is used to make stretchy clothing like bicycle pants.

High-impact polystyrene, or HIPS for short, is an immiscible blend that combines the properties of two polymers, styrene and polybutadiene. Polystyrene is a rigid plastic. When mixed with polybutadiene, an elastomer, it forms a phase-separated mixture which has the strength of polystyrene along with toughness supplied by the polybutadiene. For this reason, HIPS is far less brittle than regular polystyrene [38].

In the case of a composite material, we are usually using a fiber to reinforce a thermoset. Thermosets are crosslinked materials whose stress-strain behavior is often similar to plastics. The fiber increases the tensile strength of the composite, while the thermoset gives it compressional strength and toughness.

5. Conclusions

This brief review of FRP has summarized the very broad range of unusual functionalities that these products bring (Polymers, Aramids, Composites, Carbon FRP, and Glass-FRP). While the chemistry plays an important role in defining the scope of applications for which these materials are suited, it is equally important that the final parts are designed to maximize the value of the inherent properties of these materials. Clearly exemplify the constant trade-off between functionality and processability that is an ongoing challenge with these advanced materials. The functionality that allows these materials to perform under extreme conditions has to be balanced against processability that allows them to be economically shaped into useful forms. The ability of a polymer material to deform is determined by the mobility of its molecules, characterized by specific molecular motions and relaxation mechanisms, which are accelerated by temperature and stress. Since these relaxation mechanisms are material specific and depend on the molecular structure, they are used here to establish the desired link with the intrinsic deformation behavior.

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References

[1] http://www.matter.org.uk/matscicdrom/manual/co.html.

[2] Hinton M.J., Soden P.D., Kaddour A.S. Failure Criteria in Fibre-Reinforced-Polymer Composites: The World-Wide Failure Exercise. Elsevier 2004.

[3] Tong L., Mouritz A.P., Bannister M. 3D Fibre Reinforced Polymer Composites. Elsevier 2002.

[4] Ravi Jain, Luke lee. Fiber Reinforced Polymer (FRP) Composites for Infrastructure Applications. Focusing on Innovation, Technology Implementation and Sustainability. Springer 2012.

[5] Kimg Hwee TAN. Fibre Reinforced Polymer. Reinforcement for Concrete Structures. Proceedings of the Sixth International Symposium on FRP Concrete Structures, volume 1-2 (FRPRCS-6). World Scientific 2003.

[6] Erki M.A., and Rizkalla S.H. FRP Reinforcement for Concrete Structures. Concrete International (1993) 48-53.

[7] Han E.H. Meijer, Govaert Leon E. Mechanical performance of polymer systems: The relation between structure and properties. Prog. Polym. Sci. 30 (2005) 915-938.

[8] McGraw-Hill Science & Technology Encyclopedia

[9] Entsiklopediia polimerov, vols. 1–3. Moscow, 1972-77. The Great Soviet Encyclopedia, 3rd Edition (1970-1979). 2010 The Gale Group, Inc.

[10] Giancaspro James, Papakonstantinou Christos, Balaguru P. Mechanical behavior of fire-resistant biocomposite. Composites: Part B 40 (2009) 206-211.

[11] Aubourg, P.F., Crall C., Hadley J., Kaverman R.D., and Miller D.M. Glass Fibers, Ceramics and Glasses. Engineered Materials Handbook, Vol. 4. ASM International, 1991, pp. 1027-31.

[12] McLellan, G.W. and Shand E.B. Glass Engineering Handbook. McGraw-Hill, 1984.

[13] Pfaender, H.G. Schott Guide To Glass. Van Nostrand Reinhold Company, 1983.

[14] Tooley, F.V. "Fiberglass, Ceramics and Glasses", in Engineered Materials 14- 14-14- Handbook, Vol. 4. ASM International, 1991, pp. 402-08.

[15] Hnat, J.G. "Recycling of Insulation Fiberglass Waste". Glass Production Technology International, Sterling Publications Ltd., pp. 81-84.

[16] Webb, R.O. "Major Forces Impacting the Fiberglass Insulation Industry in the 1990s". Ceramic Engineering and Science Proceedings, 1991, pp. 426-31.

[17] How fiberglass is made - material, used, processing, components, dimensions, composition, product, industry, machine, Raw Materials, The Manufacturing Process of fiberglass, Quality Control http://www.madehow.com/Volume-2/Fiberglass.html

[18] Carbon fibers Seen as Having Big Long Term Growth Infrastructure is Next Big Trend Driver, "Advanced Materials & Composites" News, No. 3, 1999.

[19] Structures, Advanced Materials & Composites News, No. 2, 1999.

[20] New Company Launches Carbon Fiber Fabrics for Decorative Applications, Advanced Materials & Composites News, No. 8, 1998

[21] Carbon fibers Electrical Conductivity Found to Offer New Uses, Composites News, No. 3, 1998, 9.

[22] Donnet Jean-Baptiste, Roop Chand Bansal, "Carbon Fibers", published by Marcel Dekker Inc., 1990, p370.

[23] Gullapalli Sravani; Wong Michael S. (2011). Nanotechnology: A Guide to Nano-Objects. Chemical Engineering Progress: 28–32.

[24] Zhao Z., and Gou J. (2009). Improved fire retardancy of thermoset composites modified with carbon nanofibers. Sci. Technol. Adv. Mater. 10: 015005. doi: 10.1088/1468-6996/10/1/015005.

[25] Japan Carbon Fiber Manufacturers Association (English) (http://www.carbonfiber.gr.jp/ english/)

[26] Handbook of Fiber Chemistry. International Fiber Science and Technology Series. Editor Menachem Lewin. Third Edition 2007 CRC Press, Taylor & Francis Group.

[27] Jassal M., Ghosh S. Aramid Fibres – An Overview. Indian Journal of Fibre & Textile Research 27 (2002) 290-306.

[28] José M. García, Félix C. García, Felipe Serna, José L. de la Peña. High-performance aromatic polyamides. Progress in Polymer Science 35 (2010) 623-686.

[29] Smallman, R.E., and Bishop R.J.. Modern Physical Metallurgy and Materials Engineering. 6th ed. Oxford. Butterworth-Heinemann, 1999.

[30] Erhard, Gunter. Designing with Plastics. Trans. Martin Thompson. Munich: Hanser Publishers, 2006.

[31] Rosato Donald V., Rosato Dominick V., Murphy John. Reinforced Plastics Handbook. Elsevier; 2004; page 586

[32] Composite moulding (http:/ / web. archive. org/ web/ 20080215010801/ http:/ / www. quatrocomposites. com/ comp101proc. htm).

[33] Klompen, Edwin T.J. Mechanical properties of solid polymers. Constitutive modelling of long and short term behaviour. Eindhoven: Technische Universiteit Eindhoven, 2005.

[34] FRP Library (http://www.compositepedia.com)

[35] Odian, George. Principles of Polymerization. 3rd ed., J. Wiley, New York, 1991.

[36] Jang, B.Z.; Advanced Polymer Composites: Principles and Applications, ASM International, Materials Park, OH, 1994.

[37] Bhowmick, Anil. Mechanical Properties of Polymers. Volume 1, Material Sciences Engineering. Enciclopedia of Life Support Systems – UNESCO, 2011.

[38] Hashim M.H.M., Sam A.R.M., Hussin M.W. The Future of External Application of Fibre Reinforced Polymer in Civil Infrastructure for Tropical Climates Region. International Journal of Mechanical and Materials Engineering (IJMME), 6, 2 (2011) 147-159.