This chapter presents the background studies of composites, definitions, types of composites, polymers, types and characteristics of different polymer composites like polyurethane, polyester and epoxy, advantages in applications over other materials, physical and mechanical properties as well as the properties of polyester, epoxy and other resin systems. Reinforced fibres like glass, aramid and carbon fibers are also explained in detail.

1.1 INTRODUCTION

Modern technologies require materials with unusual combination of properties that cannot be met with conventional metals, alloys and ceramic materials. This is especially true for materials that are needed for aerospace, underwater and transportation applications. For example, aircraft engineers are increasingly searching for structural materials that have low densities, are strong, stiff, abrasion and impact resistant and are not easily liable for corrosion. Material property combinations and ranges have been and are being extended by the development of composite materials.

A composite is considered any multiphase material that exhibits a significant proportion of the properties of both the constituent phases in such a way that a better combination of properties is realised. According to this principle of combined action, better property combinations are effected by the judicious combination of two or more distinct materials.
In practice, most of the composites consist of a bulk material (the 'matrix'), with some sort of reinforcement, added primarily to increase the strength and stiffness of the matrix. This reinforcement will usually be in fibre form.

In designing composite materials, scientists and engineers have ingeniously combined various metals, ceramics, and polymers to produce a new generation of extraordinary materials. Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, ambient and high-temperature strength.

Many composite materials are composed of just two phases; one is termed the matrix, which is continuous and surrounds the other phase, called the dispersed phase. The properties of composites are a combination of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. “Dispersed phase geometry” in this context means the shape of the particles their size, distribution and orientation.

1.2 CLASSIFICATION OF COMPOSITE MATERIALS

Today, the most common man-made composites can be classified into following three main groups:

1.2.1 Polymer matrix composites (PMC)

These are also known as Fibre Reinforced Polymers (or Plastics) (FRP). These materials use a polymer-based resin as the matrix, and a variety of fibres such as glass, carbon and aramid are used for reinforcement. These are the most commonly used composite materials.
1.2.2 Metal matrix composites (MMC)

Metal matrix composites are increasingly found in the automotive industry; these materials use a metal such as aluminum as the matrix and reinforce it with fibres such as silicon carbide.

1.2.3 Ceramic matrix composites (CMC)

Being used in very high temperature environments, these materials have a ceramic as the matrix reinforced with short fibres or whiskers, which are made from silicon carbide and boron nitride.

1.3 POLYMER MATRIX COMPOSITES

Resin systems such as epoxies and polyesters have limited use for the manufacture of structures on their own, since their mechanical properties are not very high when compared to most metals. However, they have other desirable properties, most notably their ability to be easily formed into complex shapes. Materials such as glass, aramid and boron have extremely high tensile and compressive strength but in ‘solid form’, these properties are not readily apparent. This is due to the fact that when stressed, random surface flaws will cause each material to crack and fail well below its theoretical ‘breaking point’. To overcome this problem, the material is produced in fibre form so that, although the same numbers of random flaws are present, they will be restricted to a small number of fibres with the remainder exhibiting the material’s theoretical strength. Therefore, a bundle of fibres will reflect more accurately the optimum
performance of the material. However, fibres alone can only exhibit tensile properties along the fibre’s length in the same way as fibres in a rope.

When the resin systems are combined with reinforcing fibres such as glass, carbon and aramid exceptional property can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and protects the fibres from damage caused by abrasion and impact. High strength and stiffness, ease of moulding into complex shapes, high environmental resistance all coupled with low density, make the resultant composite superior to metal for many applications.

Overall, the properties of the composite are determined by:

- The properties of the fibres.
- The properties of the resin.
- The ratio of fiber to resin in the composite [fibre volume fraction (FVF)].
- The geometry and orientation of the fibres in the composite.

1.4 RESIN SYSTEMS

Any resin system for use in a composite material need to have the following properties:

a) Good mechanical properties.
b) Good adhesive properties.
c) Good toughness properties.
d) Good resistance to environmental degradation [1].
1.5 RESIN TYPES

The resins that are used in fibre-reinforced composites are sometimes referred to as 'polymers'. All polymers exhibit an important common property in that they are composed of long chain-like molecules consisting of many simple repeating units. Manmade polymers are generally called 'synthetic resins' or simply 'resins'.

Polymers can be classified under two types, 'thermoplastic' and 'thermosetting', based on the effect of heat on their properties. Thermoplastics, like metals, soften with heating and eventually melt, but harden again on cooling. This process of softening or melting on heating can be repeated as often as desired without any appreciable effect on the material properties in either state. Typical thermoplastics include nylon, polypropylene and ABS, and these can be reinforced, although usually only with short, chopped fibres such as glass.

Thermosetting materials, or 'thermosets', are formed from a chemical reaction in situ, where the resin and hardener or resin and catalyst are mixed and then undergo an irreversible chemical reaction to form a hard, infusible product. In some thermosets, such as phenolic resins, volatile substances are produced as by-products (a 'condensation' reaction). Other thermosetting resins such as polyester and epoxy do not produce any volatile by-products and thus are much easier to process ('addition' reactions). Once cured, thermosets will not become liquid again when heated, although above a certain temperature their mechanical properties will change significantly. This temperature is known as the glass transition temperature (Tg), and varies widely according to the particular resin system used, its degree of cure and whether it was mixed correctly. Above the Tg, the molecular structure of the thermoset changes from that of a rigid crystalline polymer to a more flexible, amorphous polymer. This change is reversible on cooling back to below the Tg but above the Tg properties such as resin modulus (stiffness) drop sharply and as a result the compressive and shear strength of the composite also drop. Other properties such as water resistance and colour stability also reduce markedly above the resin's Tg.
are many different types of resins are in use in the composite industry, majority of the structural parts are made with three main types, namely polyester, vinyl ester and epoxy.

1.5.1 Polyester resins

Polyester resins are the most widely used resin systems, particularly in the marine industry. By far the majority of, yachts and workboats built in composites make use of this resin system. Polyester resins are of ‘unsaturated’ type. Unsaturated polyester resin is a thermoset, capable of being cured from a liquid or solid state when subject to the right conditions. Unsaturated polyester differs from saturated polyester such as terylene which cannot be cured in this way. It is usual, however, to refer to unsaturated polyester resins as ‘polyester resins’, or simply as ‘polyesters’. In chemistry, the reaction of a base with an acid produces a salt. Similarly, in organic chemistry the reaction of an alcohol with an organic acid produces an ester and water. By using special alcohols such as glycol reacts with di-basic acids, to provide a polyester and water. This reaction, together with the addition of compounds such as saturated di-basic acids and cross-linking monomers, forms the basic process of polyester manufacture. As a result, there is a whole range of polyesters made from different acids, glycols and monomers, all having varying properties.

1.5.2 Vinylester resins

Vinyl ester resins are similar to polyesters in their molecular structure, but differ primarily in the location of their reactive sites, these being positioned only at the ends of the molecular chains. As the whole length of the molecular chain is available to absorb shock loadings this makes vinyl ester resins tougher and more resilient than polyesters. The vinyl ester molecule also features fewer ester
groups. These ester groups are susceptible to water degradation by hydrolysis which means that vinyl esters exhibit better resistance to water and many other chemicals than their polyester counterparts, and are frequently found in applications such as pipelines and chemical storage tanks.

1.5.3 Epoxy resins

The large family of epoxy resins represents some of the highest performance resins of those available currently. Epoxies generally out-perform most other resin types in terms of mechanical properties and resistance to environmental degradation, which leads to their almost exclusive use in aircraft components. As a laminating resin their increased adhesive properties and resistance to water degradation make these resins ideal for use in applications such as boat building. Here epoxies are widely used as a primary construction material for high-performance boats or as a secondary application to sheath a hull or replace water-degraded polyester resins and gel coats. The material properties and cure rates can be formulated to meet the required performance [2].

1.6 POLYURETHRANES

Polyurethanes are an important and very versatile class of polymer materials with desirable properties, such as high abrasion resistance; tear strength, excellent shock absorption, flexibility and elasticity [3–4]. They are usually used as adhesives, coatings, foams and different kinds of plastics and elastomers, but also as matrix resins for composites. The importance given to polyurethane from the fact that their excellent processability (low viscosity), bonding to different substrates, absence of volatile organic compounds (VOC) and favourable economics.
1.7 REINFORCEMENTS

The role of reinforcement in a composite material is fundamentally one of increasing the mechanical properties of the resin system. Different fibers used in composites have varying properties and thus affect the properties of the composite in multiple ways. The mechanical properties of majority of the reinforcing fibres are considerably higher than those of non-reinforced resin systems.

1.7.1 Glass fibres

By blending quarry products (sand, kaolin, limestone, colemanite) at 1,600°C, liquid glass is formed. The liquid is passed through micro-fine bushings and simultaneously cooled to produce glass fibre filaments of 24gm in diameter. The filaments are drawn together into a strand (closely associated) or roving (loosely associated) and coated with a “size” to provide filament cohesion and protect the glass from abrasion. By varying the “recipe”, different types of glasses can be produced. The types of glasses used for structural reinforcements are as follows.

1.7.1.1 E-glass (Electrical)

Lower alkali content and stronger than A-glass (alkali). Good tensile and compressive strength and stiffness, good electrical properties and relatively low cost, but impact resistance is relatively poor. Depending on the type of E-glass the price ranges from £1-2/kg. E-glass is the most common form of reinforcing fibre used in polymer matrix composites.
1.7.1.2 **C-glass (Chemical)**

This has the best resistance to chemical attack. Mainly used as surface tissue in the outer layer of laminates in chemical and water pipes and tanks.

1.7.1.3 **R, S or T-glass**

These are manufacturers trade names for equivalent fibres having higher tensile strength and modulus than E-glass with better-wet strength retention. Higher ILSS (Inter laminar shear strength) and wet out properties are achieved through smaller filament diameter. S-glass is produced in the USA by OCF, R-glass in Europe by Vetrotex and T-glass by Nittobo in Japan. These are developed for aerospace and defence industries and used in some hard ballistic armour applications. This factor combined with low production volumes makes the cost relatively high. Glass fibre diameter is generally in the range of 10-20 μm. Finer fibres are more expensive but provide better reinforcement due to improved formability. Grades that are more robust may be preferred for filament winding and pultrusion processes. Glass fibres must always be protected by a size or finish to prevent degradation on exposure to damp environments. The finish usually incorporates polymers that control the handling characteristics of the roving and coupling agents to control adhesion and wetting to the matrix. The fibre making process has little influence on the stiffness of the glass but strength is increased by several orders of magnitude. Virgin glass fibres have strengths that exceed 5 GPa but the surface is extremely sensitive to damage from abrasion (including from other fibres) and from environmental attack by moist air. Since the enhanced strength depends largely on the elimination of minute surface flaws on the glass, it follows that any surface damage leads to a drastic strength reduction. The size is essential to protect the fibre. It also influences subsequent processing stages. In general, glass does not bond strongly to polymeric materials (either thermosetting or thermoplastic) and for the reason a
saline-coupling agent is usually incorporated into the size or applied later as a finish. This provides a link between the glass surface and the polymer. It has a strong influence on the strength that may be developed in the composite and on its retention of properties when exposed to water (humid air or immersion) [5].

1.7.2 Aramid fibres

Aramid fibers are high-strength, high-modulus materials that were introduced in the early 1970s. They are especially desirable because of their outstanding strength-to-weight ratios, which are superior to metals. Chemically, this group of materials is known as poly para-phenylene terephthalamide. There are a number of aramid materials; trade names for two of the most common are Kevlar and Nomex. The incorporation of short fibers with high thermal resistance and high strength, such as aramid fibers (i.e., Kevlar, Conex and Technora), to improve the dimensional stability of thermoplastic elastomers is, therefore, interesting [6].

The mechanical properties of short-fiber / elastomer composites depend on the fiber content, fiber aspect ratio, fiber dispersion, fiber orientation and fiber-matrix interactions. For Kevlar/thermoplastic polyurethane (TPU), many researchers have reported good fiber-matrix interactions [7-9].

1.7.3 Carbon fibres

Carbon fibre is produced by the controlled oxidation, carbonization and graphitisation of carbon-rich organic precursors, which are already in fibre form. The most common precursor is polyacrylonitrile (PAN), because it gives the best carbon fibre properties, but fibres can also be made from pitch or cellulose. Variation in the graphitization process produces either high strength fibres (@ ~2,600°C) or high modulus fibres (@ ~3,000°C) with other types in GTC-1-1098.
Once formed, the carbon fibre has a surface treatment applied to improve matrix bonding and chemical sizing which serves to protect it during handling.

1.8 PROCESSING OF POLYMERS

There are three fundamental processes used in the processing of different varieties of polymers. The three processes are as under:

1.8.1 Pultrusion process

Fibres are pulled from a creel through a resin bath and then on through a heated die as shown in Fig 1.1. The die completes the impregnation of the fibre, controls the resin content and cures the material into its final shape as it passes through the die. This cured profile is then automatically cut to length. Fabrics may also be introduced into the die to provide fibre direction other than at 0°. Although pultrusion is a continuous process, producing a profile of constant cross-section, a variant known as 'pullforming' allows some variation to be introduced into the cross-section. The process pulls the materials through the die for impregnation, and then clamps them in a mould for curing. This makes the process non-continuous, but accommodating small changes in cross-section.
1.8.2 Vacuum bagging process

This is an extension of the wet lay-up process where pressure is applied to the laminate once laid-up in order to improve its consolidation. This is achieved by sealing a plastic film over the wet laid-up laminate and onto the tool. The air under the bag is extracted by a vacuum pump and thus up to one atmosphere of pressure can be applied to the laminate to consolidate it as shown in Fig. 1.2.
1.8.3 Hand lay-up process

Resins are impregnated by hand into fibres, which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under normal atmospheric conditions as shown in Fig 1.3.

![Diagram of Hand lay-up process for processing polymers]

**Fig. 1.3 Hand lay-up process for processing polymers**

1.9 APPLICATIONS OF POLYMER COMPOSITES

The building industry provides perhaps the greatest challenge to organic polymers today; the organic polymers have gradually made progress. In this area, the organic polymers have made progress but at far too slow rate. Vinyl, epoxy and polyester pipes are just beginning to be accepted by the building construction industry.
Polyurethane composites are unique engineering materials, which enable the design of properties that are impossible to capture with other materials. They facilitate improved cost-performance and the ability to find new solutions to thousands of difficult engineering problems. Polyurethane composites are materials that combine many of the advantages of rigid plastics, metals and ceramics with the flexibility and resilience of rubber.

Polyurethanes due to their wide range of densities (40-400 kg/m³) and hardness ranging from softness of polyurethane foam used in refrigerators to hardness of castor wheels, high impact and wear resistance, resistance to chemicals, ability to bond with various reinforcements, machinability and castability with various colours have been attractive to designers worldwide where weight saving has been an important consideration. They are attractive materials for use in paints, aircrafts, defence, shape memory polyurethanes and other aerospace applications. Products made with polyurethane are stronger, tougher and more durable than products made with conventional elastomers and plastics. When compared to other elastomers polyurethanes have greater load bearing capability in both compression and shear. This load bearing capability is used to great advantage in the design and manufacture of wheels, rollers and other engineering parts. Conventional plastic materials tend to become brittle as they become harder, while polyurethanes remain elastic and resist fracture even in very hard formulations. Under repeated flexing, polyurethanes are highly resistant to cracking and they can be used in very thin sections because of their great strength and toughness. Glass fibre-reinforced composites are the most popular reinforced plastic materials used in the industry. Depending on formulation and use, they may be fabricated into products that are light in weight, transparent, translucent or opaque, colourless, coloured, flat, or shaped sheets, with no limit to the size of object that can be made.