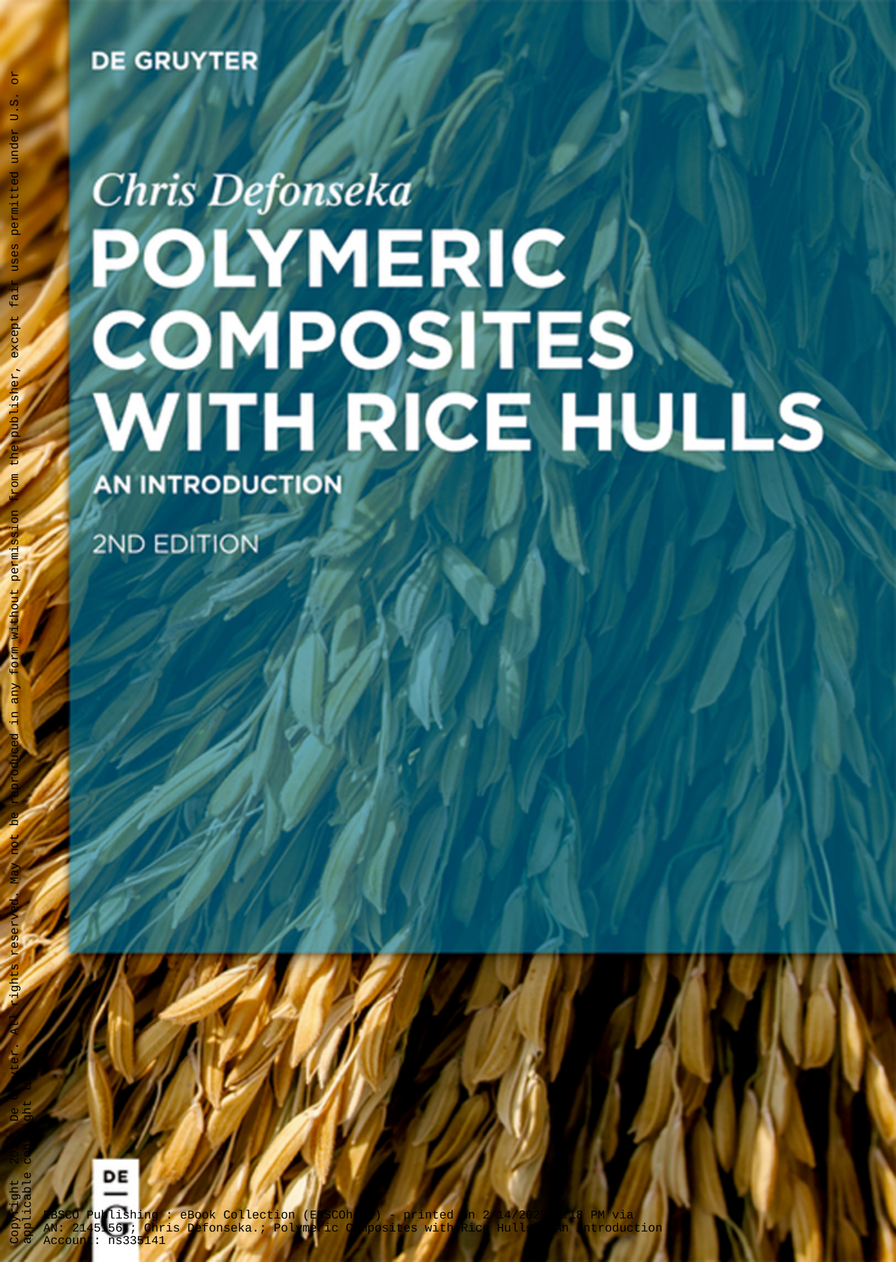

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Chris Defonseka

POLYMERIC COMPOSITES WITH RICE HULLS

AN INTRODUCTION

2ND EDITION

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Polymeric Composites with Rice Hulls

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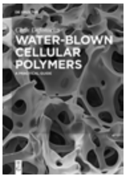

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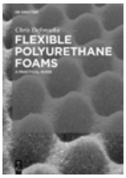

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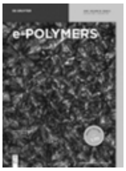

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Preface

The use of composites has been an integral part of everyday life of people for decades. Today, composites are playing a more significant part as issues such as increasing costs, environmental concerns, and global population growth necessitate cost-effective, quality materials. This book looks at the latest exciting new field of *polymer composites with rice hulls*.

Polymer composites with different biomasses are being used widely. Probably the most common and popular types are wood plastic composites (WPC). Although constant research has resulted in improvements in these composites, the end uses have been limited to more or less decking and fencing.

Polymeric composites with rice hulls are the latest addition to the composites 'family' and their potential is very exciting. These virtually new composites have greater possibilities for end uses than even WPC because silica in the rice hulls gives additional structural strength, versatility, durability along with lower costs. Moreover, it is possible to achieve aesthetically pleasing veneers that will be important as ideal substitutes for natural wood. With rice hulls available in abundance in most countries at very little cost and being cheaper than other biomasses, the possibilities are immense.

The standard process for converting polymer composites to end products such as for decking and fencing has been extrusion, but now polymer composites with rice hulls in pellet form are spreading into injection moulding, which forms >60% of the plastic processing industry and will soon spread to compression moulding and other processes. This will be a reality as newer resins with polymeric composites with rice hulls in pellet form are made available by resin manufacturers using modified polymers and combinations of additives.

Technology of polymer composites with rice hulls is virtually new and I present valuable information to producers and end users from the raw materials to the production processes of these composites resins to the manufacturing technology of the end products and recommendations for end applications.

It is hoped that this book will provide the necessary impetus to researchers, producers and end users to rapidly develop this challenging and exciting field. Such developments will help to ease global environmental concerns by the introduction of suitable substitutes for natural wood and also promote the use of freely available rice hulls as composite materials to manufacture polymeric composite resins suitable for the plastic processing industry so that we are less dependent upon petroleum sources.

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Acknowledgments

Polymeric composites with rice hulls is a virtually new technology and I have been researching and working closely for some time with companies based in Europe, North America and China to overcome technical problems in processing. I am happy to share this successful technology, which opens up vast possibilities and a wider range of applications, unlike wood plastic composites (WPC). Due to the highly technical nature of this book and to provide useful information for the reader as well as manufacturers, the author gratefully acknowledges the sources noted.

In this book, I offer all-round technical information which I hope will be greatly beneficial to producers, companies offering technical training programmes of processing of polymeric composites, authors of polymer books, as well as for entrepreneurs and product developers.

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1 Introduction

1.1 History of composite materials

In ancient times, natural wood from trees and plants (e.g., palms and bamboo) were the ‘natural’ composite materials used by mankind, followed by straw and mud in the production of bricks and wattle by the Egyptians for the construction of buildings. As the needs of humans widened, other composite materials (e.g., papyrus; plywood; volcanic sands; lime mortars; and combinations of paper and glues) were used. Concrete began to be used 25 BC and, as time progressed, the natural polymer shellac began to be employed until the birth of the first ‘plastic’: bakelite.

Many ‘developing’ countries produce huge quantities of agricultural residues and plastic wastes but their uses have been small compared with the large volumes produced, thus causing extensive pollution to the environment. Some of the major agricultural residues are rice husks (hulls); coffee husks; coir pith; jute sticks; bagasse; groundnut shells; mustard stalks; rice stalks; and sawdust. The major plastic wastes are films, bottles, parts and containers. Apart from the problems of collection, transport, storage and handling, the direct burning of loose biomass in conventional grates is associated with very low thermal efficiency and widespread pollution. To some extent, plastic wastes are recycled and re-used but two of the major constraints have been the limited number of times they can be recycled and the lack of bio-degradation in landfill sites.

Historically, agricultural biomass wastes have been used as important energy sources in industrial and domestic settings. These have been used for heating; cooking; lighting; insulation; composites; and fuel for steam boilers. Plastic wastes have been recycled and fed back into production on a limited basis. Agricultural wastes are being used ideally as briquettes; logs; chips; and ash. In the manufacture of versatile briquettes in various shapes and sizes, two main methods have been used: ram/piston press and extrusion screw press. Both processes have their merits and demerits but, over the years, it has become universally accepted that screw-pressed briquettes are far superior in terms of storability and combustibility. Worldwide, both technologies are being used for the briquetting of sawdust and other agricultural residues. The importance of biomass briquettes as a substitute fuel for wood, coal and lignite is well recognised, but numerous limitations with regard to machinery and production may be the reasons for the slow expansion in this sector.

Briquetting and composite technology is yet to get a strong foothold in many developing countries because of technical constraints and the lack of knowledge for obtaining higher efficiencies to match the end requirements. Overcoming the many operational problems associated with this technology and ensuring the quality of raw materials at the time of use are critical factors for determining its

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commercial success. In addition to this commercial aspect, the importance of composite technology lies in conserving wood, a commodity used in all countries extensively and which can lead to the widespread destruction of forests. The availability of wood plastic composites (WPC) with bio-wastes over the past few years has lessened the need for using natural wood. Also, the arrival of polymeric composites with rice hulls (PCRH) as ideal substitutes for natural wood with a greater range of applications will help to ease the need for wood but on a much larger scale.

1.2 What are composite materials?

Composites are materials made from two or more constituent materials with significantly different physical and chemical properties that, if combined, produce a material with characteristics different from the individual components while remaining separate and distinct within the structure. A composite material can also be described as a macroscopic combination of two or more distinct materials having recognisable interfaces between them, the properties of which can be optimised by the addition of additives to achieve a balance of properties to meet the requirements of a given range of applications. Composites are used not only for their superior structural strengths but, among others, for electric, thermal, biological and environmental applications.

Composites are formed by individual materials, which may occur naturally or be made artificially. There are two main categories of constituent materials: a matrix and reinforcements. At least one portion of each is required to make a composite. The matrix material surrounds and supports reinforcement materials by maintaining their relative positions. Reinforcement materials provide the special mechanical and physical properties to enhance the properties of the matrix. Synergism produces material properties that are not available from the individual constituent materials, whereas the wide variety of matrices and additives allow the designer/producer of composite products to choose the optimum combinations and to structure them to achieve the desired end result.

Several commercially produced composites use a polymer matrix material often called a ‘resin solution’. Many natural polymers and modified polymers are available for use and depend upon the planned composite. Selection is highly dependent upon the compatibility of the reinforcement materials to be used. There are several broad categories, each with numerous variations. Some of the most common polymers are polyester; vinyl ester; epoxy, phenols; polyimide; polypropylene (PP); polyethylene (PE); high-density polyethylene (HDPE); and polyvinyl chloride (PVC). Reinforcement materials are very often fibres but also ground minerals. In polymeric composites, the polymer matrix can also be considered a ‘carrier’ for processing an end product, as in extrusion.

The ratio of the resin matrix to reinforcements used is important to the end product and the targeted special properties. As a rule of thumb, a 60% resin and

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40% fibre may be considered a good starting point. The main aim is to reduce the resin content in the final product while achieving the special properties required, and additives go a long way in helping in this area. There is a limit to the reduction of resin content because the strength of the final product may be dependent upon the ratio of the constituents. Also, too little resin may also cause problems or completely prevent smooth processing of the composite. Polymeric composites can be made with a wide range of natural fibres, such as rice hulls, wood flour, palm-fibre wastes, flax, rice straw and other biomass wastes. This emerging ‘family’ of composites with such great possibilities can be categorised as ‘thermoplastic bio-composites’.

1.2.1 Engineered composites

Engineered composites are, in general, made to be shaped. The matrix material can be introduced before or after the reinforcement materials are placed into a mould cavity or onto a mould surface, as in the production of fibre-glass products. The matrix material undergoes melting and then the part shape is set. Depending on the nature of the matrix material, this melting phase can occur in various ways, such as chemical polymerisation or solidification from the melted state.

Various moulding methods can be used according to the design of the end-product. The principal factors affecting the methodology are the nature of the matrices chosen. Another important factor is the quantity of composite material to be produced. Large volumes may justify high capital investment for rapid and automated manufacturing. This chapter is mainly about the new technological field of PCRH and the methodology that can be used to produce composite resin pellets as well as how to process them to make composite profiled boards.

1.3 Types of composites

Many types of materials are suitable for combination with a range of polymers for making composites for different applications. Due to technological advances, polymers can be used singly, in combination, or as modified polymers, depending on the final objective in regard to a particular application(s).

1.3.1 Composite resins with rice hulls

Rapid developments are taking place in the production of composite resins in pellet form by combining a polymer matrix with rice hulls ground to a fine powder. These resins can be made in small volumes using manual operations but, for large-volume

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and quality resins, it is imperative that advanced technological equipment is employed. This process can be done in two stages: the rice hulls are ground, dried, compounded with the polymer matrix and then put through an extrusion process, resulting in a pellet form. Alternatively, this process can be set up with a continuous processing line, whereby the entire process is completed in one operation. These composite resins can be made with various plastics (e.g., PE, PP and polystyrene). Also, these WPC are just one category of an emerging family of materials termed thermoplastic bio-composite resins. Although these bio-composite resins can be made with fibres such as flax, palm-fibre wastes, wood flour, and rice-straw wastes, laboratory testing and practical applications have shown that PCRH elicit better overall properties (e.g., better structural strength) and capabilities.

These resins are slightly transparent to yellow in colour. Properties are decided by the types of constituents and additives used, whereas pellet sizes can be varied during pelletising. Colouring is an option but can also be carried out during conversion to the final product. The second option has benefits in that, whichever process is used, different finishes can be obtained by adding master-batches, dyes, pigments, or combinations of dyes/pigments to get the desired effects.

1.3.2 Composite profiles with rice hulls

A wide range of profiles can be produced using an extrusion process in which the composite resins of choice can be converted to profiled length boards. A specially designed die at the end/head of the extruder will determine the profile shape of the extrudate (i.e., whether the cross-section is round, rectangular, octagonal, or hollow). In general, the thicknesses of these boards can range from 15–25 mm and widths ≤1,000 mm and almost any desired lengths which are determined by a preset vertical cutting saw. Addition of extra additives during processing will enable a producer to achieve any special properties desired and incorporation of single colours or in combination to obtain aesthetically pleasing finishes.

1.3.3 Wood polymer composites

WPC have been available for some time and very popular for outdoor applications, especially for decking. The two main constituents are a polymer matrix and wood flour (finely ground wood waste). Some producers are also using other bio-mass wastes. These combinations produce strong boards, and have been replacing traditional materials used for outdoor applications such as decking, fencing, and park benches. These products are, in general, available in solid rectangular or hollow profiles and other pre-determined shapes with varying dimensions, and can be ≤5 m in length.

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1.3.4 High-density polyethylene resin composites with rice hulls

These eco-friendly composites are made from HDPE polymer resin with ground rice hull powder as the reinforcement fibre in the matrix. The mix can be 30–40% HDPE resin and 70–60% rice hull powder plus additives to achieve any special properties desired as required in the end application. An extrusion process is used to produce board lengths of desired profile sections. Additives are used singly but very often in combinations of two, three or more. Some of the common additives used are lubricants, binders, and crosslinking agents. It is also possible to use small percentages of other biomass wastes with rice hull content but this is dependent upon the producer.

1.3.5 Polymer composites with recycled plastics

This is a class of composites made with the wastes of recycled plastics, rice hull powder or other biomass and made into extruded profiled products. Here, the important factor is compatibility between the different grades of plastic wastes. Though most thermoplastic grades are compatible, a few grades may not be. A combination of thermoplastic and thermosetting grades is to be avoided because they will not be compatible and pose problems when being processed. With these composite mixtures, achieving the desired properties and finishes may be difficult unless they are used as a small percentage of the matrix comprising virgin polymers. However, products made from 100% recycled material may be suitable for certain low-end applications.

1.3.6 Fibre-reinforced polymers

Fibre-reinforced polymers include carbon-fibre reinforced plastics and glass-reinforced plastics (GRP). If classified by matrix, then they are termed ‘thermoplastic composites’, ‘short-fibre thermoplastics’, ‘long-fibre thermoplastics’ or ‘long fibre-reinforced thermoplastics’. There are several thermoplastic composites but advanced systems usually incorporate aramid fibre and carbon fibre in an epoxy resin matrix. Good examples of carbon-fibre composites are aircraft parts, whereas glass-reinforced composites include marine boats manufactured using a lay-down production method.

1.3.7 Concrete

Concrete is probably the most common artificial composite material and typically consists of loose stones (aggregate) mixed with a matrix of cement. Concrete is a

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very robust material (much more robust than cement) and will not shatter even under quite a large compressive force. However, concrete cannot survive tensile loading (will breakdown under stretching). Therefore, to give concrete the ability to resist stretching, steel bars (which can resist high stretching forces) are often added to concrete to form ‘reinforced concrete’.

1.3.8 Shape-polymer composites

Shape-polymer composites are high-performance composites formulated using fibre or fabric reinforcement and shape-memory polymer resin as the matrix. Because a shape-memory polymer is used as the matrix, these composites can be manipulated easily into various configurations if they are heated above their activation temperatures, and exhibit high strength and stiffness at lower temperatures. They can also be re-heated and re-heated repeatedly without losing their material properties. These composites are ideal for application as lightweight; rigid; deployable structures; rapid manufacturing processes; and dynamic reinforcement.

1.3.9 Metal fibre composites

Composites can also use metal fibers, reinforcing other metals. Ceramic matrix composites are built primarily for fracture toughness, not for strength. Organic matrix-ceramic aggregate composites include asphalt concrete, mastic asphalt, mastic roller hybrids, dental composites and syntactic foams. Certain types of composites are used in special military applications.

1.3.10 Thermoplastic composites with metal powders

Thermoplastic composites can also be formulated with specific metal powders, resulting in materials with high densities (e.g., composites with the same density as lead). The most common name for this type of material is ‘high-gravity compound’ (though ‘lead-replacement compound’ is also used). These materials can be used in place of traditional materials such as aluminium, stainless steel, brass, bronze, copper, lead and even tungsten in weighting and balancing, vibration damping and radiation-shielding applications. High-density composites are an economically viable option if certain materials are deemed hazardous and are banned (e.g., lead) or if secondary costs (e.g., machining, finishing, coating) are a factor.

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1.3.11 Structured composites

A sandwich-structured composite is a special class of composite material fabricated by attaching two thin (but stiff) skins to a lightweight (but thick) core. Usually, the core material is a low-strength material but its higher thickness provides the sandwich composite with high bending stiffness with overall low density. A very common sandwich composite involves the combination of two layers of cotton with a polymer or rubber. Cotton comprises a natural polymer called cellulose, whereas rubber is also known as ‘polyisoprene’. The two layers of cotton fabrics embedded in a polymer or rubber matrix makes an ideal material that can be used for rainwear or protective materials.

1.3.12 Natural composite – wood

Wood is a naturally occurring composite comprising cellulose fibre in a lignin and hemicellulose matrix. ‘Engineered wood’ includes a wide variety of products such as wood fibre board, plywood, oriented strand board, WPC with wood flour, WPC with sawdust powder- or plastic-impregnated paper or textiles as well as other laminated boards with brand names such as Aborite and Formica. Other engineered wood laminated composites such as Mallite use a central core of balsa wood bonded to the surface skin of a light alloy or GRP. These produce low-weight, highly rigid materials.

1.4 Uses for composites

The ever-increasing material, agricultural and other wastes (e.g., plastics) due to global population growth is causing environmental concerns because disposing of them is an enormous problem. Resin manufacturers are using bio-degradable additives to enable faster degradation in landfills but this is a slow process. Research has focused on finding solutions, and biomass wastes from different activities are being used in composites. Many types of composites are in use and continuing research and development are enabling the combination of plastic resins and biomass wastes. One of the most common and popular composites are WPC. New technology is enabling combination of plastic resins with rice hulls, which is opening up a wide range of possibilities with much better properties than the WPC available currently.

1.4.1 Polymeric composite resins in injection moulding

Wood fibre/thermoplastic blends are employed in extruded decking and fencing boards, but are now being used in injection moulding and compression moulding. Initially, some injection moulders were reluctant to accept this new concept.

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However, recent developments in the manufacture of composite resin compounds have vastly improved their quality, consistency and capabilities, and moulders are now using these environmentally friendly composite resins with more confidence, with cheaper costs playing a major part. The latest generation of WPC can be run smoothly through traditional injection-moulding equipment with minimal adjustments to process settings, and modifications to hardware are not needed. However, these composite materials have some processing characteristics that distinguish them from the standard moulding resins.

1.4.2 Polymeric composite resins in extrusion

WPC with wood flour have been in use for some years, but composites with rice hulls are comparatively new. WPC have been used in extrusion processes to make solid boards of different profiles, mainly for decking and fencing. With the emergence of composites with rice hulls, the possibilities have widened. Due to the unique presence of a high content of silica in rice hull wastes, products with higher strengths, very low maintenance and excellent finishes can be achieved. These products are emerging as ideal substitutes for natural wood, and their end uses are spreading from outdoor applications (e.g., decking, fencing and benches) to furniture and building construction.

1.4.3 Polymeric composites in compression moulding

Compression moulding is a simple and effective way to manufacture large plastic parts, especially for the automotive industry. This type of moulding involves heating of a plastic powder to remove moisture before introduction into one-half of a mould cavity, and then closing the mould and moulding under compression. Plastic raw materials used for this process are in powder form. They absorb moisture from the air during their shelf-life and must be heated before being moulded. Use of polymeric composite resins in pellet form will eliminate this stage and give the additional properties of strength and rigidity.

1.4.4 Some widely used applications for composites

Different types of composites are required for different end applications. The list below gives an idea of the variety of composites used:

- Polymer wood flour composites for WPC.
- Polymer biomass composites for WPC.
- Polymer rice husk composite pellets for plastic mouldings.

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- Carbon-fibre composites for aircraft applications.
- Polymer-fibre composites for automotive applications.
- Polymer-fibre composites for space-travel applications.
- Polymer rice straw composites for extruded board.
- Polymer (PVC)/cotton-fabric composites for artificial leather.
- Polymer/cotton-fabric composites for protective wear.
- Glass-fibre/epoxy matrix for fibre-glass products.
- PCRH for outdoor applications.

1.5 Why use thermoplastic bio-composites?

There are many compelling reasons to create products and components using thermoplastic bio-composites. Because they contain ≥50% of organic fibres, these materials offer processors a material option that is more environmentally friendly than typical petrochemical-derived polymers. In addition to ‘green’ factors, thermoplastic bio-composites reduce the processor’s exposure to increasing petroleum prices, and reduce the energy costs associated with production. Moreover, they can produce an end-product with great structural rigidity, an aesthetically pleasing finish, and new, highly marketable performance.

Wood flour/rice hulls with PP bio-composites tend to be lower in cost and weight than unfilled resins or glass-filled resins. They are competitive with calcium carbonate-filled or talc-filled PP resins in terms of cost, performance and processing. They also have the advantage of lower density, which reduces their effective cost and can be beneficial in transportation and other uses that put a premium on light weight. Applications can include automotive, construction, sports, toys and other consumer goods. Polymeric composite materials are especially suited for products with thick walls and those that require excellent rigidity and dimensional stability. PCRH offer the combined properties of wood and plastic: excellent moisture barriers, the ability to be screwed or nailed like wood, and an ‘organic’ look and feel. If products from PCRH are used outdoors, very little or no maintenance is required and, unlike wood, several pleasing profiles can be produced for many applications.

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2 Basic technology of plastics

2.1 Introduction to plastics

'*Plastic*' comes from the Greek word *plastikos*, which means a material that can be shaped by heat and pressure. A more sophisticated definition may be: a large and varied group of materials consisting wholly or in part of combinations of carbon with oxygen, nitrogen, hydrogen and other organic or inorganic elements which, while solid in the finished state is made liquid and thus capable of being formed into various shapes, most usually through the application (either singly or together) of heat or pressure.

Plastics are made from polymers and are, in general, available in the form of liquids, powders, and pellets. '*Polymer*' is derived from the Greek words, *poly* (meaning many) and *meros* (meaning a basic unit or part). Polymers are also known as 'resins' (incorrect but widely used) or 'macromolecules' from the Greek word *macros* (meaning long elastomers (which are polymers that can be stretched by >200% of their original length)). According to American Standards for Testing Methods, an elastomer is a polymeric material that at room temperature can be stretched at least twice its original length and, upon immediate release of stress, will return quickly to approximately its original length.

Plastics are considered 'wonder' materials and have replaced many traditional materials in all spheres of human activity. They have been used for a long time and have seen rapid growth in terms of quality and consumption. With research and development continuing in polymers and plastic resins, applications are spreading from traditional domestic and industrial uses to those in automobile and even to space travel.

2.2 Chemistry of plastics

Instead of highly technical and theoretical chemistry, the basics of the chemistry of plastics are described here in a simple and practical manner to help the reader understand polymeric materials relevant to this book.

'Chemistry' is a science that deals with the composition of matter and how that composition changes. The two broad classes of chemistry are *organic* and *inorganic*. Organic chemistry deals with matter that contains the element *carbon*, whereas inorganic chemistry deals with matter that is mineral in origin. The term 'organic' was used originally to mean compounds of plant or animal origin. However, now it also includes many synthetic materials that have been developed through research. Examples of such synthetic organic materials are plastics.

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Plastics are chemical compounds made up of polymers. Polymers are materials composed of molecules of very high molecular weight (MW). Polymers are formed by a process called polymerisation, in which many basic units (mers) or monomers are joined together. These large molecules are, in general, referred to as *macromolecules*. Polymers are macromolecular structures that are generated synthetically or through natural processes. Synthetic polymers are generated by addition (or chain growth polymerisation) and condensation (or radical-initiated) polymerisation. In addition polymerisation, the final molecule is a repeating sequence of blocks with the chemical formula of the monomers. Condensation polymerisation occurs if the resulting polymers have fewer atoms than those present in the monomers from which they are generated.

2.2.1 The atom

Matter is anything that has mass (weight) and occupies space. Matter may exist in the form of a solid, liquid or gas. According to chemical theory, the structures of matter are composed of atoms which form elements such as hydrogen, oxygen and nitrogen. These elements form molecules and, if two or molecules join together, they form compounds. The atom is the smallest particle to which an element can be reduced while retaining the properties of the element.

The atom may be broken down into basic subatomic particles known as *neutrons, protons* and *electrons*. The atoms of each element differ in the number of particles they contain. Thus, no two elements will have identical atoms. The neutron is a particle with no electrical charge. The proton is a positively charged particle. Both occupy a dense compact central area of the atom called the *nucleus*. Protons are very small particles. Electrons are negatively charged particles. They are located in orbit or shells around the nucleus. Electrons are nearly three-times as large in diameter as protons and are very much lighter.

The simplest atom is that of hydrogen. It has one proton (as its nucleus), one electron and no neutrons. For all elements, the atom itself is electrically neutral. The negative charge of the electrons moving around the nucleus is equal to the positive charge of the protons in the nucleus. If an atom gains an electron, it becomes electronegative (a negative ion). If it loses an electron, it becomes electropositive (a positive ion). An *ion* is an atom that has gained or lost one or more electron.

2.2.2 Molecular weight (Mass)

The mass of a molecule is determined by adding together the atomic masses of the various atoms making up the molecule. The atomic mass of hydrogen is 1 and the

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atomic mass of oxygen is 16. Thus, the molecular mass of a single molecule of water (H_2O) is 1 + 1 + 16 = 18.

The primary factor resulting from a polymerisation reaction is the size of the macromolecules. After such a reaction, a polymeric material will consist of polymer chains of various lengths or repeating units. Hence, the MW is determined by the average or mean MW, which is defined by $M = W/N$, where W is the weight of the sample and N the number of molecules in the sample. Methane, for example, would have a molecular mass (weight) of $12 + (4 \times 1.008) = 16.03$ g/mol.

The length (molecular mass) of a polymer chain would have a profound effect on the processing ('mouldability') and properties of the plastic. Increasing the chain length may increase toughness, melt temperature, melt viscosity, creep and stress resistance. With higher melt viscosities, it may also increase the difficulty of processing, material costs, and possible polymer degradation. Because the molecular structure may vary in shape and length, the molecular mass average is used. It is logical to expect polymers to contain molecular chains with a wide distribution of lengths (some short, some long) and the molecular mass average is the product of the average number of repeating units or mers in the polymer. If all molecules have the same mass, the polymer is said to have a narrow distribution of molecular mass. Polymers that do not have sufficient molecular mass (many long molecules) to cause some chain entanglements are generally weak, have lower melting points, and are readily attacked by appropriate reactants. The standard molecular mass required for good physical and mechanical properties is ≈20,000 g/mol.

2.2.3 Polymeric molecules

Molecules of organic materials are composed of carbon as a base element (most commonly joined to hydrogen by covalent bonds). These molecules are referred to as *hydrocarbons*. As the name suggests, hydrocarbons are composed of hydrogen and carbon. Because of the ability of the carbon atoms to link up with other atoms to form chains, rings and other complex molecules, thousands of hydrocarbons are known to organic chemistry.

At one time, all organic compounds came from plants or animals. However, today coal, oil and natural gas are good sources of carbon for the chemicals used in the manufacture of plastics. Many organic hydrocarbons are obtained directly from animal or plant sources. Oils such as cottonseed, linseed, soybean oils, and lard yield hydrocarbons for the production of plastics. Scientists and chemists are constantly finding new sources that can be used as bases. In the field of hydrocarbons, there are two major organic groups to consider: (a) aliphatic or straight-chain molecules, and (b) cyclic or ring-shaped molecules. Aliphatic hydrocarbons may be divided further into three types of hydrocarbon: (a) alkanes or paraffins; (b) alkenes or olefins; and (c) alkynes or acetylenes.

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2.2.4 Polymers

If a large number of molecules bond together in a regular pattern, a polymer is formed. A polymer is made up of many units repeated in a pattern. This repeating unit (mer) should be considered to be bi-functional or di-functional (two reactive bonding sites). The chemical reaction that joins monomers (mers) together is called *polymerisation*. If the polymer consists of similar repeating units, it is known as a *homopolymer* (meaning same). If two different monomers are polymerised, the resulting polymer is called a *co-polymer*. If three different monomers are polymerised, a *terpolymer* is the product. Polymers are the basic building blocks for the manufacture of the vast range of plastics. Plastics are divided broadly into two main categories: thermoplastic (soften on heating and can be re-used) and thermosetting (harden on heating and cannot be re-used).

2.2.5 Polymerisation

Polymerisation processes can be classified into *two-step polymerisation* and *chain polymerisation*. Linear polymerisation and non-linear step-growth polymerisation are processes in which the polymerisation occurs with more than one molecular species. Also, chain-growth polymerisation processes occur with monomers with a reactive end group. Chain-growth polymerisation processes include free-radical polymerisation, cationic polymerisation, ring-opening polymerisation and metallocene-catalysis polymerisation.

The atomic composition of polymers consists primarily of non-metallic elements such as carbon (C), hydrogen (H) and oxygen (O). In addition, recurrent elements are nitrogen (N), chlorine (C), fluorine (F) and sulfur (S). Polymers may also contain other non-metallic elements such as silicon (Si) in silicone or beryllium (B).

There are various ways that monomers can arrange during polymerisation but they can be broken down into two categories: crosslinked and uncrossed-linked. Furthermore, uncrossed-linked polymers can be subdivided into linear and branched polymers. The most common examples of uncrossed-linked polymers that present the various degrees of branching are polyethylene (PE). Another important family of un-crosslinked polymers are copolymers.

Copolymers are polymeric materials with two monomer types in the same chain. A polymer that is formed by three monomer groups is called a *terpolymer*. Depending on how the different monomers are arranged in the polymer chain, the patterns are distinguished as *random, alternating, block* or *graft* copolymers.

Although *thermoplastics* (soften on heating and can be re-used) can crosslink under specific conditions such as gel formation, if PE is exposed to high temperatures for prolonged periods of time, *thermosets* (harden on heating and cannot be re-used)

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and some elastomers are polymeric materials that can crosslink. This crosslinking causes the material to become resistant to heat after it has solidified. Usually, this crosslinking is a result of double bonds that break, allowing the molecules to link with their neighbours. One of the oldest thermosetting polymers is phenol-formaldehyde (also known as phenolic resin). The reaction in which phenol molecules react with formaldehyde molecules to create a three-dimensional (3D) crosslinked network that is stiff and strong (thereby leaving water as the byproduct of this chemical reaction) is called *condensation polymerisation*.

2.2.6 Polymer structures

The properties of plastics are affected by the arrangement of atoms and molecules. The atomic arrangement of the polymers can be classified as *crystalline, amorphous* or *molecular*. *Crystallinity* is the three-dimensional arrangement of atoms, ions and molecules in a regular pattern. Diamonds and table salt are two common materials with crystalline structures that can be seen readily. Because of the considerable length of polymer molecules, there could be less crystallisation. Because the molecular chains are only partly ordered, most crystalline plastics are not transparent in the solid state. Partially crystalline (semi-crystalline) polymers such as the linear polyolefins, polyacetals and polyamides (PA) are, as a rule, translucent-to-opaque.

The crystalline content of some polymers may be >95%, whereas the remainder is amorphous. Crystallinity of low-density polyethylene (LDPE) is ≈65%, whereas high-density polyethylene (HDPE) may be >95%. The crystallisation of bulk polymers is characterised by the formation of large crystalline aggregates called *spherulites*.

The folded-chain alignment of molecules is called a *lamellar* (plate-like) structure. In ordered polymers, chains are folded back on themselves to produce parallel chains perpendicular to the face of the crystal. These crystalline structures within the polymers help to scatter light. They give PE and polypropylene (PP) a milky appearance. Upon normal processing, a crystalline polymer may begin to form spherulites as it cools. Processing may help align or orient the molecular chains. Oriented alignment of molecules on one axis may be desirable because this produces greater crystallinity and higher tensile strength. Controlling the crystallisation process is a basic consideration in determination of the physical properties of a polymer.

Materials that are *amorphous* (without form) have atoms or molecules that are non-crystalline and without long-range order. An analogy of an amorphous polymer could be a mass of cooked spaghetti. Polymers are amorphous in the molten state, and rapid quenching may preserve most of this amorphous state. This method may prevent many of the chains from realigning to form crystals. This method is used sometimes in the production of PE and polyethylene terephthalate to improve transparency. Amorphous polymers are usually less rigid than crystalline ones.

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Polymers are transparent if most crystallinity can be prevented. LDPE will be more transparent if crystallinity is reduced. HDPE is semi-crystalline and has a high melting point.

Many components are needed to form a plastic, but a polymer are is basic material from which a plastic is formed. Fillers, solvents, plasticisers, stabilisers, colourants and additives influence many of the characteristics of plastics. A resin is the polymeric material that helps impart many of the physical characteristics of solid plastics. It is the molecular arrangement of the polymer resin that determines whether a plastic is *thermoplastic* or *thermosetting*. Thermoplastics increase in plasticity with temperature; they become soft with heating and solid if cooled to room temperature. Thermoplastics can be formed readily into any shape because weak bonding forces allow slippage between molecules, whereas the molecules themselves are held by the stronger covalent bonds. Thermoplastics can be re-used, but there is a limit to the number of times recycling can be done because repeated processing causes some the additives to be lost and thus causes degradation.

Thermosetting plastics are polymeric materials with structural frameworks that do not allow deformation or slip to occur between molecular chains. They are composed of strong, primary covalent bonds and may be thought of as one large molecule. In thermosetting materials, heat is commonly used to cause a chemical reaction (polymerisation) resulting in crosslinks between chains. In a low-molecular-mass state, heat and pressure are commonly used to cause the thermosetting material to flow into a mould cavity. Once solidified, these materials cannot be reshaped or formed again by the application of heat. These materials have a permanent ‘set’ once they are polymerised. Thermosetting plastics are stronger than thermoplastics and have a higher product-service temperature. Thermoplastics may have many processing advantages, however, over thermosets. A major advantage is that thermoplastics can be ground and recycled into other useful products.

2.2.7 Morphological structures

Morphology is the order or arrangements of a polymer structure. The possible ‘order’ between a molecule or molecule segment and its neighbours can vary from a very ordered highly crystalline polymer structure to an amorphous structure (a structure in random order). For example, a purely amorphous polymer is formed only by non-crystalline or amorphous chain structures, whereas a semi-crystalline polymer is formed by a combination of all structures. The semi-crystalline arrangement that certain polymer molecules form during cooling is in large part due to intra-molecular forces. As the temperature of a polymer melt is lowered, the free volume between the molecules is reduced, causing an increase in intra-molecular forces. As the free volume is reduced further, intermolecular forces cause the molecules to arrange in a manner that brings them to a lower state of energy.

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An amorphous polymer is defined as having a purely random structure. However, electron microscopic observations have shown evidence of amorphous polymers that are composed of relatively stiff chains; and which show a certain degree of macromolecular structure and order. Even polymers with soft and flexible macromolecules such as polyisoprene (which was the first bundle-like structure to be identified) are relatively weak and short-lived if the material experiences stresses. The shear thinning viscosity effect of polymers is sometimes attributed to the breaking of such macromolecular structures.

Before the existence of macromolecules was recognised, highly crystalline structures had been suspected. Such structures were discovered if undercooling or stretching cellulose and natural rubber. It was found later that a crystalline order also existed in synthetic macromolecular materials such as PA, PE and polyvinyls. Because of the polymolecularity of macromolecular materials, a 100% degree of crystallisation cannot be achieved. Hence, these polymers are referred to as 'semi-crystalline'. It is usual to assume that a semi-crystalline polymer is formed by small regions of alignment or crystallites connected by random or amorphous polymer molecules. The speed at which crystalline structures grow is dependent upon the type of polymer and temperature conditions. This phenomenon is mainly because at the beginning nucleation occurs at a finite rate.

2.2.8 Polymer blends

Polymer blends are polymeric materials made by mixing or blending two or more polymers to enhance the physical properties of each individual component. Common polymer blends include PP-polycarbonate, polyvinyl chloride (PVC)-acrylonitrile-butadiene-styrene (ABS) and PE-polytetrafluoroethylene. Polymer blending is accomplished by distributing and dispersing a minor or secondary polymer within a major polymer that serves as a matrix. The major component can be thought of as the continuous phase and the minor components as the distributed phase or dispersed phase in the form of droplets or filaments. When creating a polymer blend, one must remember that the blend will probably be re-melted in subsequent processing or shaping processes. For example, a rapidly cooled system, frozen as a homogenous mixture, can separate into phases because of coalescence when re-heated. For all practical purposes, such a blend cannot be processed. To avoid this problem, compatibilisers (which are macromolecules) are used to ensure compatibility in the boundary layers between the two phases.

Blending can also be considered to be mixing, which is subdivided into 'distributive' and 'dispersive' mixing. Studies of the development of the morphology of polymer blends have shown three competing mechanisms: distributive mixing, dispersive mixing, and coalescence. The process begins if a thin tape of polymer is melted away from a pellet. As the tape is stretched, surface tension causes it to rip and to form into

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threads. These threads stretch and reduce in radius until surface tension becomes sufficiently significant to lead to disturbances. These disturbances grow and cause the threads to break down into small droplets.

2.2.9 Filled polymers

Fillers are, in general, accepted as being materials that are intentionally placed in polymers to make them stronger, lighter, electrically conductive or cheaper. Any filler will affect the mechanical behaviour of a polymeric material. For example, long fibres will make it stiffer but usually denser, whereas foaming will make it more compliant and much lighter. Conversely, a filler such as calcium carbonate will decrease the toughness of the polymer while making it considerably cheaper. Some fillers such as glass fibres or glass spherules, will increase the strength of a polymer, whereas others will decrease it. ‘Reinforced plastics’ refer to polymers (matrix) whose properties have been enhanced by introducing reinforcement (fibres) of high stiffness and strength. Such a material is called a ‘fibre-reinforced polymer’ or a ‘fibre-reinforced composite’.

2.2.10 Modified polymers

The properties of thermoplastics can be modified by adding additives such as a plasticising agent. If a plasticising agent is added, the glass transition temperature (T_g) shifts to lower temperatures and, consequently, the shear modulus starts to drop at a much lower temperature. In essence, the plasticiser replaces a temperature rise by ‘wedging’ these typically low-molecular-weight materials between the polymer’s molecular structures, generating free volume between the chains. This additional free volume is equal to a temperature rise, which consequent lowers the T_g, making a normally brittle and hard thermoplastic softer and compliant.

Some amorphous thermoplastics can be made high impact-resistant (less brittle) through copolymerisation. The most common example is ABS. Butadiene chains vitrify at temperatures below −50 °C, so ABS is very tough at room temperature in contrast to polystyrene (PS) and acrylics by themselves. Due to the T_g of the materials that form the blend, ABS shows two general transition regions, one around −50 °C and the other at 110 °C, which are visible in logarithmic decrement and the shear modulus.

2.2.11 Polymer groups

The main group of polymers relevant to this section on *polymeric composites with rice hulls* (PCRH) are *PE, PP, PS and PVC,* which are linear homo-polymers polymerised from unsaturated monomers or from the transformation of analog

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polymers. This group is the major commodity group of thermoplastics. Another group of polymers that exhibit double bonds and belong to the family of elastomers are *polyacetals; polyethers; polyaryleters*; and *polyaryletherketones*.

The existence of a double bond allows these polymers to undergo vulcanising or crosslinking. Polycyclo-olefins are also an important group as high-resistant thermoplastics. Polyacetals and polyethers are polymers that have a heteroatom (oxygen) present in the backbone of the molecule. The heat resistance of these polymers is increased significantly by the introduction of bulky aromatic building blocks into the molecules, thereby significantly reducing intra-molecular mobility. The oldest thermoplastics that are still in use today are cellulose polymers. The rigid cellulose molecules make them difficult to process, requiring the use of plasticisers or other polymers. The high polarity of cellulose molecules makes them highly hydrophilic and sometimes soluble in water.

Among the most important group of polymers are PA and linear poly-condensates, which are used in engineering applications, as well as in fibres and films. Due to hydrogen bonds and aromatic components, some of these materials are resistant to high temperatures. However, they are hydrophilic polymers known for their high absorption of water. Linear polyesters are also poly-condensates, which have gained notoriety only in the form of polyarylesters. Special co-polyesters have such stiff molecular segments that they exhibit anisotropic behaviour even in the melt state. Polymers exhibiting such behaviour are called ‘liquid crystalline polymers’. Polyimides are the stiffest molecules. They are conductive and semi-conductive polymers that are high temperature-resistant with a very high heat-deflection temperature. An important group of technical thermoplastics are the polyarylethersulfones and polyarylsulfides. Their unique molecular structure, composed of aromatic and sulfur-based building blocks, makes them high-strength plastic materials for engineering designs.

2.3 Properties of plastics

The properties of plastics can be categorised as:

- Compatibility of material properties
- Mechanical properties
- Friction and wear
- Environmental properties
- Water absorption
- Weathering effects
- Rheological properties
- Permeability properties
- Electrical properties
- Optical properties
- Acoustic properties

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All of these properties are important in the general processing of plastics, but I will present information only on the properties that are relevant to the subject under the presentation *polymeric composites*.

2.3.1 Compatibility of material properties

In the design and production of composites, material compatibility is the most important aspect for a successful end product, and is dependent largely on the compatibility of the materials being used. Testing of materials is a specialised area, and the average producer of composites cannot engage in this area of activity because it takes good knowledge, experience and equipment to do so. However, a producer of composites can make use of the many databanks available and base the design of the intended composite on this information. For a producer already in business, these databanks will be of immense value to sustain good-quality production and to improve the products already being made.

For the beginner, a basic knowledge of composites would help greatly, and these databanks will be a base upon which a producer can experiment and finalise the composite formula. Some of the important basic properties required for compatibility are: specific gravity; density; water absorption; melt flow; tensile strength; flexural properties; softening temperature; and coefficient of thermal expansion.

2.3.2 Mechanical properties

Polymeric materials are used in various designs of composites because of their low cost, easy processing ability and desirable material properties. Mechanical considerations for designing include: fatigue; tensile strength, flexural strength, impact, compressive strength, hardness, damping, cold flow, thermal expansion, and dimensional stability. Composites that need dimensional stability necessitate careful selection of materials (though fillers will improve the dimensional stability of most plastics). A factor often used for the evaluation and selection of materials is the strength:mass ratio (i.e., the ratio of tensile strength to the density of the material). End applications may require a minimum safety factor (also called a ‘design factor’).

2.3.3 Friction and wear

Friction can be defined as the resistance that two surfaces generate as they slide (or try to slide) over each other. Friction can be between dry surfaces or lubricated surfaces. If dealing with polymers, the process of two surfaces sliding past each other is complicated by the enormous of heat that can be generated and stored near the

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surfaces due to the low thermal conductivity of the materials. The analysis of friction between polymer surfaces is complicated further by environmental effects such as relative humidity and the likelihood of a polymer surface to deform if stressed.

Temperature influences the coefficient of friction significantly. For example, in the case of PE, the friction first decreases with temperature. At 100 °C, the friction increases because the polymer surface becomes tacky. The friction coefficient starts to drop as the melt temperature is approached. Another example of a similar pattern would be seen in PA. Wear is also affected by temperature conditions. Wear rates will increase rapidly as the surface temperature of the polymer increases, causing it to become softer and tacky.

2.3.4 Environmental effects

The environment in contact with a loaded or unloaded component of a composite plays a significant part in its properties, durability and mode of failure. The environment can be a natural one such as rain, hail, ultraviolet (UV) radiation, detergents, and high-temperature environments. Any damage in a polymeric composite due to the influence of the natural environmental is usually referred to as *weathering*. These conditions can be simulated in laboratory tests, so some designers of composites carry out these tests in advance and make the necessary adjustments to ensure a better end product, depending on the importance of its end applications.

2.3.5 Water absorption

All polymers absorb water to some degree, but some are sufficiently hydrophilic that they absorb large quantities of water to significantly affect their performance. Water will cause a polymer to swell, serving as a plasticiser, consequently lowering its performance in terms of electrical and mechanical behaviours. Increases in temperature will also result in an increase of free volume between the molecules, allowing the polymer to absorb more water.

2.3.6 Weathering effects

Weathering effects are of special interest to this book because a major product of PCRH comprises the manufacture of extruded board for outdoor applications. Common problems encountered with polymeric composites if exposed to the elements are cracks, warping and brittleness due to the action of UV rays, moisture and extreme temperatures. Fading of colour is another aspect. These features are significantly absent if these polymeric composites are used for indoor applications. PCRH

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have definite advantages because a high content of silica in the composite will nullify these effects. Addition of additives will also help to a very great extent and also provide enhanced mechanical properties. The location and climate of a region can affect the mechanical properties of polymeric composites significantly. The effects of weathering can very often be countered with the use of pigments such as titanium dioxide or carbon black, which absorb UV radiation, making it more difficult to penetrate the surfaces of polymeric composites. Again, the presence of silica in a polymer composite will form a barrier against radiation and moisture absorption.

2.4 Moulding process for plastics

The range of plastic raw materials is immense and they are available to processors as resins, powders, granules, and pellets. The main focus of this book is the processing of composites, but some of the main processing methods are mentioned below for the benefit of the reader. The manufacture of composites is discussed in detail in later chapters. Some of the main moulding processes are presented below:

- *Extrusion* is a process in which plastic materials are moulded into profiled lengths using an extrusion system comprising a hopper, a barrel with 3–4 heating zones and a head with a nozzle that determines the profile shape. This will be connected to a haul-off system with cooling arrangements and a final length-cutting station or winding system. Products made from this process are: pipes, profiles, cables, tubes and boards. This is one of the processes in which PCRH will be made into profiled extruded lengths, and will be discussed in detail in later chapters.
- *Injection moulding* is a process in which a heated mass of plastic material is injected into a closed mould through an opening of one-half of the mould. These moulds can have a single or multiple cavities with a cooling system, and the movement of one-half of the mould is operated by electric or hydraulic means. The products made by this process are, in general, solid, and can be bottle caps, handles, trays, toys, or engineering items. This will be the second process under discussion with regard to the processing of PCRH.
- *Compression moulding* is one of the oldest forms of processing plastic resins.

In general, thermosetting materials are used but thermoforming resins can also be moulded. The plastic material is introduced into a mould cavity placed horizontally, and the top-half of the mould is moved vertically using hydraulic or electrical power and clamped-down tight. Compression moulding is similar to making waffles. Heat and pressure forces the material to flow and occupy all areas of the mould and, after a pre-determined cooling cycle, the part is removed. Sometimes, excess material will flow out through the vents and the part will have to be buffed to remove the flash. To remove moisture from materials used in powder form, they are pre-heated using infrared, induction or other heating methods, before

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introduction into the mould. This will also help reduce the production cycle. To increase output, some systems may use a screw extruder, which will produce preformed ‘slugs’ that can be loaded directly into the mould cavity and also giving more control of waste material.

Common plastic materials used in compression moulding are: thermosetting bulk moulding compounds, phenolics, urea-formaldehyde and melamine. This method of processing is selected if large parts with thick walls are to be made. Some items produced in this way include: melamine plates, cups, saucers, plug tops, and decorative items. This is the third process where the use of PCRH resins in pellet form can be used and will be discussed in detail later.

The processes shown below are also important for the conversion of resins to products. They are highlighted for the benefit of the reader, but are not discussed because they are not relevant to this book:

- Compounding
- Laminating
- Casting
- Thermoforming
- Expansion
- Foaming
- Coating
- Blow moulding

Of the processes listed above, injection moulding forms ≈70% of processing activity. However, extrusion will take precedent with the production of PCRH resins in pellet form and the conversion of these pellets into end products, which will be presented in detail. The use of composite resins in injection moulding and compression moulding is becoming widespread because plastics processors are taking advantage of the additional factors of cheaper resins and shorter moulding cycles.

2.5 Recycling of plastics

Recycled plastics also play a major part in the product manufacturing phase of PCRH, so this subject is discussed here briefly and in detail later for the benefit of the reader.

Recycling of plastics can be divided broadly into two major categories: industrial and post-consumer recycling of plastic scrap. Industrial scrap is easy to recycle. Many manufacturers recycle them on the factory floor and re-introduce into the production line within the same company as a ‘regrind’ or sold to third parties as a homogenous, reliable and uncontaminated source of resin. Post-consumer recycling of plastic scrap requires the material to go through a complicated and time-consuming operation before the material can be reclaimed. Bulk of the post-consumer plastic

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waste comes from commercial, agricultural and municipal wastes. Municipal plastic wastes consist primarily of packaging waste but also from appliances and electronic equipment.

Post-consumer plastic wastes require collecting, handling, cleaning and size reduction through shredding and grinding before they can be processed into a re-usable form. The initial stage of the source and collection methods forms the most critical aspects of a recycling operation. The demand for recycled plastics, generally in pellet form, is increasing with rising costs of pure plastic resins. One may consider that the demand for recycled materials from bottles (which probably forms the bulk of plastic wastes in pure form) has the greatest demand from various manufacturing sectors. Sometimes, the plastic wastes for collection at source may have different grades separately but mostly they will be found in a mixed form, and they will need extra effort to sort out before recycling can start. Some countries have identification codes on the packages but even these may not help being lost in the mix. Separating thermoplastic wastes from thermosets is important if one is to achieve quality recycled material for re-processing. If it is difficult to identify a plastic waste then certain tests (e.g., water floating test and burning test) can be employed. The problem of mixed colours also arises, and it is best to recycle them separately as far as possible. Also, the use of additives will help to enable one homogenous colour and, in some cases, the manufacturers may ask for multi-coloured recycled material to produce somewhat ‘psychedelic’ finishes. In the production of PCRH, recycled plastic wastes can also be used as the matrix.

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3 Composite technology

3.1 Principles of composites

The general principle of a composite is the combination of ≥2 different components with a common base, which acts as the matrix. The new material will have the base properties of both components but better properties such as light weight, higher strength, aesthetic finishes, and wider end-applications depending on the design of the composite. In general, composites may cost more but polymeric composites with rice hulls (PCRH) will yield composites that are less expensive than standard ones (especially as a biomass waste); in this case, rice hulls are used as the constituent component. Composites with rice hulls will be considered in two segments: PCRH as pellets and PCRH as extruded profiles.

Composites are usually made up of fibres and a matrix. Most commonly used fibres have been glass-fibres, Kevlar, carbon-fibres, and steel whereas, more recently, other reinforcement materials (e.g., biomasses) are being used. The fibre is embedded in the matrix to make the matrix stronger. Fibre-reinforced composites (FRC) have two special properties in that they are lighter and stronger, with some special composites being even stronger than steel but weighing much less. One of the main advantages of these types of composites is their ability to make automobiles and other vehicles lighter and thus fuel-efficient as well as lessening environmental concerns.

Matrices provide a common base for holding together whichever reinforcements are used. Although some fibres are strong, they can be brittle. A matrix can absorb energy by deforming under stress (i.e., a matrix adds strength and toughness to a composite). Fibres may have good tensile strength (i.e., they are strong if pulled) but they usually have weak compression strength, and this is countered by the matrix. When making composites, the designers use different matrices for different end applications. If a cost-effective composite is desired, some cheap matrices can be used that will yield decent properties. The unsaturated polyester/styrene system is a good example. Cheap matrices are fine for everyday applications but have drawbacks. They shrink if cured, absorb water easily, have low impact strength, and are not very resistant to chemicals. However, with the advent of new technologies, as discussed in this book, whereby common polymers such as polyethylene (PE); polypropylene (PP); vinyls; and high-density polyethylene (HDPE) coupled with rice hulls (which contain high contents of silica) have opened up a vast array of possibilities.

Fibre-reinforced plastics involve polymers (matrices) whose properties have been enhanced by introducing a reinforcement (fibres) of higher stiffness and strength. Such a resulting material is called a ‘fibre-reinforced polymer’ (FRP) or a FRC. One of the main purposes of introducing a fibre into a matrix is to transfer the load from the weaker material to the stronger one. This load transfer occurs over the length of the fibre. If the fibre lengths are short, the composites are referred to

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as ‘short-fibre composites’. If the fibre lengths are long, the composites are referred to as ‘long-fibre composites’. The lengths of the fibres and their orientation in the matrices play a key part in the final quality of a composite. In the case of PCRH fibres, the two main important factors are water content (the less the better) and the particle size of the ground rice hulls (the smaller the better).

Although the term *reinforced plastics* is not very descriptive of polymeric composites, it implies that another agent(s) has been added to the plastic material to improve or strengthen the matrix, which will result in a superior product. In this context, terms such as *advanced, high strength, engineered* or *structural* composites came into being. PCRH, irrespective of whether they are in the form of resin pellets or processed products, will have the added advantage of being cost-effective as compared with standard products.

3.1.1 Principles of polymeric composite resins

Traditionally, the production of polymer resins have been based on crude oil as a starting source with the by-product (liquefied ethylene gas) used as the base for most polymers. However, due to rising costs, polymer engineers and scientists have been suggesting alternative sources such as minerals, vegetable oils and biomasses. Nevertheless, the average prices of most polymer resins to product manufacturers have been increasing, and resin manufacturers are always on the lookout for cheaper sources. The concept of composites has been based on ‘finished’ composite materials, but the industry has been shifting to polymer resins with fillers, fibres and other constituent components to produce cheaper resins similar to normal standard ones.

The principle of producing PCRH, as presented here, is the compounding of common and popular polymers such as PE, PP and HDPE with finely ground rice hull powder with the addition of fillers, lubricants, stabilisers and colourants. This mixture is processed by extrusion and finally a process to make it into pellets for easy processing into products. Theoretically, the process looks straightforward but the entire process needs close attention and control because there are variants that must be controlled to achieve acceptable resins by the end producers. These composite resins are now being made and used by manufacturers of extruded, injection-moulded and compression-moulded products. This process is presented in detail in the chapters that follow.

3.1.2 Principles of polymeric composite extruded profiles

In principle, profiled extrusions can be made from the already available composite resins or by starting from scratch. In the latter scenario, the rice hulls are made into a powder form, dried and then compounded with selected polymers with additives, with all operations being carried out in one production line.

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Use of these profiled extrusions was intended originally to elicit a better material with improved properties for decking and outdoor applications. However, due to the versatility of the material, its uses are now expanding into other areas. This process will basically be a complete extrusion line consisting of drying (rice hulls), mixing with polymer, extrusion, cooling of extrudate, haul-off and cutting to desired lengths. A manufacturer will have the option of using one of these complete online operations or starting with the already compounded resins in pellet form, in which case the machinery costs will be much less. In China rapid developments are taking place with these types of extruded profiles. While maintaining the basic principle of composites, and by varying the additives used, many products are being made that have a wide range of applications, such as building construction and furniture.

3.1.3 Principles of polymeric composites in injection moulding

Injection moulders have been using standard polymers and plastic-recycled materials. Moulders have been experiencing frequent increases in the prices of raw materials, which limits profitability. The advent of polymeric composite resins in pellet form is starting to ease this problem. At the beginning, processors were cautious in using these new resins but, with time, they are now beginning to use them with confidence. In principle, use of these composite resins is more or less the same as for using standard resins. The same machines can be used but with slightly different temperatures, injection time and cooling time. Due to lower amount of polymer in the resin, the distinct advantages are: lower melt temperatures, shorter dwell time (cooling), lighter part weights and lower power consumption. These factors lead to lower costs of the injection cycles in addition to lower material costs. However, one disadvantage may be the limitation in wall thicknesses, and very thin walls may not be possible due to the presence of fibres.

3.1.4 Principles of polymeric composites in compression moulding

Polymeric composite resins can be used readily in compression moulding. The principle of compression moulding in plastics is the introduction of a plastic resin into the bottom-half of a horizontal pre-designed mould cavity with the top-half clamped hydraulically and the entire mould heated. Compression moulding used to involve the moulding of large parts using thermoset plastic resins in powder form. Two distinct disadvantages are the need to dry the powder to remove moisture before moulding and also, being a powder, seepage from the clamped mould and thus the requirement to de-flash after part removal. Thermoforming resins can also be used, but they probably will not provide the strength, stiffness and impact

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resistance required in parts moulded in this way. Composite resins will provide strength and stiffness but might need an additional additive to boost impact resistance. If using polymeric composite resins, the exact amount of resin can be put into a mould, which will not result in seepage of the melt, thus eliminating the need for de-flashing afterwards.

3.2 Formation of composites

Composites can be formed in many ways and all methods, whether they are laminated, extruded, compounded or impregnated, can be classified as *composite processing*. Over the years, the importance and need for composites have grown tremendously, especially in the industrial sector and, due to continuing research, the use of biomasses have also come to the forefront as reinforcing fibres. At the beginning, only thermosetting plastics were commercially reinforced in large quantities, but today the demand for reinforced thermoplastics is increasing rapidly. Because thermoplastics materials can be processed readily in many ways, various innovative uses have resulted.

Reinforced moulding compounds may be moulded by injection moulding, matched dies, transfer moulding, extrusion moulding and compression moulding to elicit products with complex shapes and a broad range of physical properties. Of these, extrusion moulding and injection moulding are the two most common and effective methods of processing composite resins. Fibres, short fibres of milled glass, fillers, tiny glass spherules, and metallic fibres are, in general, used for reinforcing moulding compounds. The main composite reinforcing processes are:

- Extrusion
- Matched die
- Hand layup
- Spray-up
- Rigid vacuum forming
- Vacuum bag
- Pressure bag
- Filament winding
- Centrifugal reinforcing
- Pultrusion
- Cold stamp forming

3.2.1 Extrusion

Other than the production of composite resins made by extrusion (discussed previously), composites are also made by extruding layers of laminates. This could take

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the form of sheet extrusions and layering at multiple stations with the thicknesses and widths dependent upon the capacities of the machines being used. Hot surfaces may provide sufficient tackiness for bonding but sometimes adhesives may have to be used. Colouring or desired surface finishes can be obtained by additives, dyes, pigments or masterbatches. For cooling the substrates, air or water can be used. If light weight is desired, foaming agents can also be used.

3.2.2 Matched die

In this method a ‘matched’ male and female mould are used to shape-reinforced resins in the form of compounds. Bulk moulding compounds (BMC) are a ‘putty-like’ mixture of resin, fillers, catalysts and short-fibre reinforcements. BMC are isotropic with fibre lengths usually <0.04 cm. and they are sometimes called ‘premix’ or ‘dough-moulding compounds’ (DMC) and, in general, come in rope-like preforms. They are moulded by compression moulding or transfer moulding. DMC have some advantages over preform processing. This fibrous putty may be extruded and fed automatically into a matched-die so that only an exact calculated amount is put into the mould, thereby preventing seepage and waste due to excess material feed. This operation can be divided further into ‘open’ and ‘closed’ mould processing. Injection, compression, transfer, stamping and matched die are closed-mould operations. Open-mould operations include hand layup, sprayup and filament winding. Sometimes, both operations overlap, whereby open-mould methods are used to reform a part, and a closed-mould operation is used to complete a moulding and curing a composite.

Sheet-moulding compounds (SMC) are leather-like mixtures of resins, catalysts, fillers and reinforcements. They are made in sheet form, so fibre reinforcements can be much longer than in BMC or SMC, thereby enabling greater glass loadings and thus lighter products, with the longer fibres providing improved mechanical properties.

SMC are fed to moulds and go through phases of pressing, curing and demoulding in one continuous cycle. SMC need a processing pressure of ≈500–2,000 psi, with processing temperatures varying with product design and polymer contents.

Composite product designs that require thick walls or sections need thick moulding compounds with strength being provided by the dominant fibre direction. Some are filament-wound on a mandrel with a protective film wrapped over the final layer, and the preform is removed and stored for moulding later. A variation of this process is called *macerated reinforcing processing*. Macerated parts are produced by chopping the reinforcements into small pieces of length ≈2–100 mm to be processed in the matched moulds. Reinforced resin products made from matched die moulds are strong and may have a superb surface finish, both inside and out.

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Major markets for BMC- or SMC-moulded parts are in the transportation and appliance industries. For example, shower and bath mouldings as well as appliance housings are made of BMC. As the name implies, SMC are used for large parts such as automotive body panels, hoods, boat hulls, furniture and appliance components.

3.2.3 Hand layup processing

For hand layup processing, in general, thermosetting (hardens on heating) resins are used. Only atmospheric pressure is used in applying the saturated reinforcing material to the mould, so this can hardly be called a ‘moulding’ process. *Open moulding* may be a more descriptive term. In this method, a mould half is coated lightly with a release agent, a layer of catalysed resin is applied, which is allowed to polymerise and gel to a tacky state. This first coat/layer is a specially formulated gel-coat resin used in industry to: improve flexibility; be blister-resistant; and to provide a surface finish and weatherability. Gel coats based on neopentyl glycol, trimethylpentanediol glycol and propylene glycol provide major advantages as surface treatments for reinforced-polyester products.

The gel coat forms a protective surface layer through which fibrous reinforcements cannot penetrate. A prime cause of deterioration of fibre-reinforced plastics is penetration by water, which can take place if fibres protrude at the surface. Once the gel coat has partially set, reinforcement is applied. Then, more catalysed resin is poured, brushed or sprayed over the reinforcement. This sequence can be repeated until the desired thickness is achieved. In each layer the mixture is worked to the mould shape with hand rollers, and then the reinforced-laminate is allowed to cure and harden. Application of external heat may also be used to accelerate polymerisation and faster curing. Hand layup and spray operations are often used alternatively to obtain a resin-rich superior finish, or a matt finish. Coarser reinforcements are then placed over this layer. Some operations and designs use preforms, cloth, or matt materials for additional strength in selected areas of a part. Among the main advantages of hand layup composites are low-cost tooling, minimal requirement of equipment, and the ability to mould large parts. The disadvantages are that the process is labour-intensive, the production rates are low, and the quality is dependent largely on the skill of the operator. Also, the operator must take safety measures to counter exposure to hazardous chemicals.

3.2.4 Spray-up processing

Spray-up is similar to hand layup but it can be accomplished by hand or machine. A mixture of resin, catalyst and chopped reinforcements are sprayed

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simultaneously into a mould shape. After the gel coat has been applied, spray-up of the resin and chopped fibres begins. Care must be taken not to damage the gel coat. Roll out helps to ‘densify’ (eliminating air pockets and aiding in the wetting action) the composite. Poor roll out can induce structural weakness by leaving air bubbles, dislocating the fibres, or in poor coating of reinforcement. Heat may be applied to accelerate curing of the composite and increasing the production rate. This process allows the creation of very complex shapes, and production rates can be much higher than those seen for layup methods. To ensure uniform mechanical properties throughout the composite, care must be taken to apply uniform layers of materials. In complex composite parts or stressed areas, additional thickness, metallic stiffeners or other reinforcing components can be placed and sprayed over.

3.2.5 Rigid vacuum forming

In a process sometimes called *rigidised shell spray-up*, a thermoplastic (softens on heating) sheet is thermoformed into the desired shape, eliminating the gel coat. Some commonly polymers used in the process are polyvinyl chloride; acrylonitrile-butadiene-styrene; polycarbonate; and high-impact polystyrene (HIPS). These shells are reinforced by hand layup or spray-up for added strength (if necessary) to obtain strong composites. Bath tubs, sinks, small boats, refrigerator shells, exterior signs, car-top carriers or other similar products are made from these composites. Final products with great finishes and in colours can be achieved with these composites.

3.2.6 Vacuum-bag process

In vacuum-bag processing, plastic films such as polyvinyl alcohol, neoprene, PE or polyester is placed over a layup and drawn between the film and the mould using vacuum suction of ≈85 kPa. The plastic film forces the reinforcing material against the mould surface, producing a high-density product free of air bubbles. Mould design and tooling for vacuum-bag processing is costly if large parts are made. Output also can be slow as compared with high-speed injection moulding. This process involves moulds having male and female halves. If a smooth surface is required on the exterior of a boat hull, the female part of the mould would be selected whereas, in the case of a sink, a male half of the mould would be selected. For easy removal of the finished composite and for protection of the mould surface, plastic films, waxes, and silicone resins can be used as release agents.

Popular *wet layup* resins are epoxies and polyesters. Pre-pregs of polysulfone, polymide, phenolics, silicones or other resin systems may also be used. Reinforcements may include honeycomb materials, fabrics, paper, foils or other impregnated

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forms. After the mould has been protected with a release wax or film, a peel ply of finely woven polyester or polyamide (PA) fabric is positioned carefully. The laminate layers are then placed in a specific design pattern on the peel ply. A second peel ply is placed on the laminate layers, followed by a release film or fabric such as Teflon fabric. Because the perforations in the fabric allow air and excess resin to escape, this layer is sometimes called the ‘breather ply’. The vacuum bag can be made of any flexible material that is airtight and will not dissolve in the matrix.

3.2.7 Pressure-bag processing

Pressure-bag processing is costly and slow. However, large, dense composite products with good finishes (inside and outside) are possible. Pressure-bag processing involves use of a rubber bag to force the laminating compound against the contours of a mould. In general, pressure (≈35 kPa) is applied to the bag during the heating and curing cycle. The mould and compounds may be placed in a steam or heated gas autoclave after layup. Autoclave pressures of ≈350–700 kPa achieve greater glass-fibre loading and aid in the removal of air. All pressure designs for the mould and pressure bag must be able to withstand the moulding pressures. This method of processing may suit the production of long hollow pipes; tubes; tanks; or other objects with parallel walls.

3.2.8 Filament winding process

Filament winding processes produce strong parts by winding continuous fibrous reinforcements on a mould. Long continuous filaments can carry bigger loads than random, short filaments. For some applications beryllium; PA; polymides; polysulfones; polyesters; and other polymers are also used. Specially designed winding machines may lay down these strands in a pre-determined pattern to give maximum strength in the desired direction. During *wet winding*, excess resin matrix and entrapped air will be forced out between the strands. Depending on the end product designed, the filament winding tension can be varied.

In *dry winding*, pre-impregnated reinforcements help to insure consistency in design of the resin-to-reinforcement content. These pre-impregnated reinforcements can be machine- or hand-wound on the tooling. Curing can be accelerated by heated mandrels (tooling), ambient ovens, chemical hardeners or other energy sources. Many cylindrical laminated forms are produced by this method. The collapsible mandrel must have the desired shape of the finished product. The advantage of filament winding is that it allows the designer of the composite to place the reinforcement in the areas subject to the greatest stress. Containers made by this process usually have a higher strength:mass ratio than those made by other methods. Filament-wound applications include pressure vessels, underwater buoys,

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nose cones, storage tanks, automotive parts, helicopter blades, fuselage and many aerospace parts.

3.2.9 Centrifugal reinforcing

In centrifugal reinforcement, the resin matrix and reinforcing materials are forced against a pre-designed mould surface by centrifugal forces generated through rotation of the mould. During this rotation process, the resin is distributed uniformly through the reinforcement by centrifugal forces. Heat is then applied to help polymerise the resin. This method is similar to the rotational moulding process. Large tanks and tubing can be made this way.

3.2.10 Pultrusion

Pultrusion is a method in which composites can be made by pulling a resin-soaked matting with fillers and other additives through a long die heated to 121.1–176.6 °C. The product is shaped and the resin is polymerised because it is drawn through the die. Additional heating will also help accelerate production rates. This process is similar to the standard extrusion process, in which a hot-melt resin is *pushed through* a die orifice. In pultrusion, resin-soaked reinforcements are *pulled through* a heated die and the resin is cured. Pultruison dies are, in general, 60–159 cm in length and heated to aid polymerisation. Cure must be uniform by careful control to prevent cracking, delamination, incomplete cure or sticking to the die surface.

Depending on the equipment used, production output will vary but, in general, will be ≈3 m/min. Common resins used for this process are vinyl esters, polyesters and epoxies. Fibrous glass is used widely for this process (though graphite; asbestos; carbon; boron; polyester; and PA fibres may also be used successfully). Extra reinforcements can also be positioned in the pultrusion product, in which extra strength is required. Hot-melt thermoplastic materials and resin reinforcements may also be used. Parallel orientation of reinforcements produces a strong composite to the direction of the fibres. Some operations will allow the use of SMC or wound preforms in combination with other continuous reinforcements to improve properties in more than one direction. Some of the products made this way are: gutters; fishing rods; automotive springs; frames; golf shafts; tennis racquets; vaulting poles; and other profiled shapes.

3.2.11 Cold stamp forming

Fibrous glass-reinforced thermoplastics and HIPS in sheet form can be cold-formed similar to that seen for metal sheet stamping. These products will have long

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reinforcements and special additives to improve the strength:mass ratio. During the forming process, a sheet is pre-heated to ≈198.8 °C and then formed on normal standard steel stamping presses. It is possible to produce parts with complex designs and varying wall thicknesses with this method. Production rates will be dependent upon the equipment used but, in general, on average outputs ≈200 per h can be achieved. Common products made this way are: motor covers, housings, appliance bodies, seat backs, outdoor furniture, automotive interior trims and many others.

3.3 General properties of composites

The designer of composite products must have a good knowledge of the properties and behavioural patterns of the individual constituent materials to be used to achieve the maximum desired properties of the final composite. In the context of polymeric composites, a sound understanding of polymer properties will help greatly. Hence, one may make use of the many information sheets on the properties and specifications of polymers available. In this section, only the relevant properties of polymeric composites that are important for the practical end applications of these composites are discussed:

- Density
- Compressive strength
- Impact strength
- Permeability and sorption
- Weathering
- Warping
- Water absorption
- Friction and wear
- Fatigue
- Aesthetic properties

3.3.1 Density

Density is the mass (weight) per unit volume of a material or product. It is commonly expressed as g/cm^3 in the metric system but the appropriate SI-derived unit of density is kg/m^3. Density is an important property for composites. For example, lightweight composites play a key part in applications in aircraft, aerospace and automobile applications, whereas denser composites are required for outdoor applications such as decking. The relative density of a plastic is the density of a given substance divided by the density of water. In the production of polymeric composites, addition of fillers will increase density but composite designers may also use foaming agents and other additives to decrease density.

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3.3.2 Compressive strength

Compressive strength is the amount of force required to crush or rupture a material. Values are expressed as multiples of the unit Pascal, such as kilopascal (kPa) or larger units. Compressive strength is calculated by dividing the maximum load (force) in the unit Newton by the area of the specimen being tested (in square metres). Values of compressive strength may be useful for distinguishing between different plastics to be used as matrices. Such values may be especially useful for the testing of filled or foamed composite products.

3.3.3 Impact strength

In practice, nearly all polymer composites are subject to impact loads. Impact strength is the resistance of any material to withstand constant pressure under strain is and the point before fracture. Many polymers are tough and ductile, so they are very often well suited for this type of loading. The impact strengths of composites made from copolymers and polymer blends can be quite different. For example, composites using propylene-ethylene as the matrix will give higher impact strength than those made with PP-PE blends. If used as matrices, elastomers are liable to have poor tear strength and are thus prone to ripping. The tear strength of these elastomers can be improved by the addition of certain types of particle fillers, for example, well-dispersed carbon-black filler in the matrix. Larger particles will act as accumulators of microscopic stress and will lower the strength of the polymer composite.

3.3.4 Permeability and sorption

Polymers, in general, due to their low density, are prone to permeability by gases and liquids. In practice, polymeric composites are liable to come into contact with various materials, with some of it diffusing through surfaces. Absorption of these diffusing materials at the interface of the polymeric surfaces is also known as *adsorption*. A good example of adsorption is in outdoor applications such as decking, in which environmental materials are deposited on the surface of composite lumber. Concentration of the permeating substances inside the materials results in the transport of that substance, which is called ‘molecular diffusion’. The cause of molecular diffusion is the thermal motion of molecules that permit foreign molecules to move along the concentration gradient using intermolecular and intramolecular spaces. Diffusion is only one part of permeation. First, the permeating substance must penetrate the surface of the polymeric membrane. Similarly, the permeating substance must be desorbed on the opposite side of the membrane. The

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quantity and surface area of diffusion is dependent upon the quality and uniformity of the composite material. In practice, this can also be minimised by application of a suitable preventive coating on the surface.

3.3.5 Weathering

If exposed directly to the elements, polymeric composites tend to show cracks due to stress at levels significantly less than those not exposed to the environment. The main causes for these cracks are ultraviolet (UV) rays, moisture and heat. Such exposure can result in early decay of the composite material. It is difficult to assess which of these weathering elements (or which combinations) affect the decay of composites the most. The location and climate of a region can play a significant part on the weathering of polymeric composites. Losses of strength, loss of aesthetic values, and surface discolouration can be attributed to the action of UV rays, whereas moisture is responsible for decay and heat for warping. Composite designers can make use of standard weathering tests and make suitable adjustments to achieve maximum results by the selection and incorporation of suitable additives and fillers.

3.3.6 Water absorption

All polymers absorb water to some degree, but some are sufficiently hydrophilic that they absorb large quantities of water to significantly affect their performance. Water causes polymers to swell, lowering their performance, particularly mechanical properties. Increases in temperature results in the increase of free volume between the molecules, making the polymers absorb more water. Absorption of water also causes decay and warping when subject to drying. The environment or the media in contact with the loaded or unloaded composites plays a significant part on the properties of a composite, lifespan and mode of failure. The most common environmental issue is rain, hail, sleet or other types of spills and are most significant in outdoor applications (though indoor applications also sometimes experience this hazard).

3.3.7 Friction and wear

Friction can be defined as the resistance that two surfaces experience as they slide or try to slide past each other. Friction can take place in a dry state (direct to direction surface interaction) or in a ‘wet’ state, in which the surfaces are separated by a thin film of lubricating fluid. Several tables are available that show the coefficient

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of friction of different polymers that composite designers can use. However, if dealing with polymers, two surfaces sliding past each other is complicated by the fact that an enormous amount of frictional heat can be generated and stored near the surfaces due to the low thermal conductivity of polymers. The friction between polymers can be complicated further by environmental effects such as relative humidity and the possibility of a polymer surface deforming under stress. In polymeric composite lumber in outdoor applications, for example, surface deterioration take places due to constant human activity requiring periodic maintenance. In PCRH, hardly any maintenance is required, as discussed in later chapters.

3.3.8 Fatigue

Loading of any composite material that finally leads to failure after a certain number of cycles is called *fatigue*. 'Dynamic fatigue' is of extreme importance because a cycle or fluctuating load will cause a composite product to fail at much lower stresses than under monotonic (continuous) loads. Fatigue in polymeric composites is dependent largely on the environment, temperature, frequency of loading a surface, and stress factors. For example, due to surface irregularities, scratches and cracks on the surface, failure due to fatigue is more likely in extruded composite products than in injection-moulded or compression-moulded products.

3.3.9 Aesthetic properties

With PCRH, it is possible to achieve very pleasing finishes. Some composite end-products will need a glossy finish, whereas others require a matt finish. These end-products can be achieved by suitable additives and, in the case of extruded products, the extrusion die/system will play a key part in this aspect. In injection moulding and compression moulding, the mould surfaces will also have a key role on the type of finish. With regard to colour, virtually any colour is possible but starts with good homogenous mixing processes to ensure (i) blending of the rice hulls with the matrix and base additives, and (ii) uniform absorption of the pigments or dyes (whether they are in the form of powder, liquid or master-batches). Special colour and grain effects can be achieved by special additives and a combination of pigments and dyes of different colours. Some producers of polymeric composites (especially lumber) may opt for a protecting coating or lamination to protect the surface.

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4 Common polymers and additives used for processing

Since the emergence of *polymeric composites*, the practice of using only one or two basic polymers as the matrices for composites has spread to a wider range of polymers. Ongoing research is working out the possibilities of using combinations of polymers, polymer blends and other, newer polymers as matrices. However, this chapter will deal with the most common polymers, which are tried and tested and are yielding the best results as polymeric composites from a practical and commercially viable angle. To achieve optimum results of end products, it is essential for composite designers, formulating chemists and producers to have a reasonable understanding of the properties and behavioural patterns of common polymers used today.

The basic ingredient for polymers is the monomer ethylene. Ethylene is a gaseous hydrocarbon derived, in general, from petroleum sources. It has the formula C_2H_4 and can be identified as a pair of methylene groups connected to each other. Ethylene is usually produced from the refining of crude oil but can also be generated by the dehydration of ethanol. Ethylene is a stable molecule that polymerises only upon contact with catalysts. Because the catalysts are highly reactive, ethylene must be of high purity. The conversion is highly exothermic (i.e., the process gives out a lot of heat). Coordination polymerisation is the most pervasive technology, hence metal chlorides or metal oxides are used. The most common catalyst used is titanium chloride. Ethylene can also be produced through radical polymerisation but this method has only limited utility and requires high-pressure apparatus.

The following polymers have been selected as being the most suitable and capable of producing commercially viable polymeric composites for a wide range of end applications:

- Polyethylene (PE)
- Polypropylene (PP)
- Polyvinyl chloride (PVC)
- High-density polyethylene (HDPE)
- Polystyrene (PS)
- Acrylonitrile-butadiene-styrene (ABS)

4.1 Polyethylene

PE (or polythene) is one of the most common plastic resins. Its primary uses are in packaging; plastic bags; plastic films; geo-membranes (agricultural applications); containers; bottles; and caps. For some time now, PE has been used as a matrix for bio-plastic composites. Many types or grades of PE are available for use in industry.

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The basic chemical formula for PE is $(C_2H_4)nH_2$. Hence, PE is usually a mixture of similar organic compounds that differ in terms of the value n, where n is the number of repeating units.

4.1.1 Physical properties

PE is a thermoplastic polymer consisting of long hydrocarbon chains. Depending on the crystallinity and molecular weight (MW), a melting point and glass transition temperature (T_g) may not be observable. The temperature at which the melting point and T_g occur varies strongly with the type of PE. For standard commercial grades of medium-density polyethylene (MDPE) and HDPE, the melting point is typically in the range 120–129.4 °C, whereas the melting point for average commercial low-density polyethylene (LDPE) is 104.4–115.5 °C.

4.1.2 Chemical properties

Most grades of LDPE, MDPE and HDPE have excellent resistance to chemicals (i.e., they are not attacked by strong acids or strong bases). They are also resistant to gentle oxidants and reducing agents. PE burns slowly with a blue flame, having a yellow tip, and gives off an odour of paraffin. The material continues to burn upon removal from the flame source and produces a drip. Crystalline samples do not dissolve at room temperature. PE (other than crosslinked PE) usually can be dissolved at elevated temperatures in aromatic hydrocarbons such as toluene and xylene, or chlorinated solvents such as trichloromethane or trichlorobenzene.

4.1.3 Classifications

The PE family is very large and consists of eleven basic categories based mainly on its density and branching. Their mechanical properties are dependent largely on variables such as the extent and type of branching, crystal structure and MW. The main categories are:

- Ultra-high-MW PE
- Ultra-low-MW PE (or PE-Wax)
- High-MW PE
- HDPE
- High-density crosslinked PE
- Crosslinked PE
- MDPE
- Linear low-density polyethylene (LLDPE)

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- LDPE
- Very LDPE
- Chlorinated polyethylene

According to technology currently being used for the production of polymeric composites with rice hulls (PCRH), the most common and productive polymers from the list shown above are LDPE, HDPE and LLDPE. However, technology advances, and the designers of these polymeric composites may use some of the other grades as well to achieve better properties for the end products, but will also have to take the polymer costs into account.

4.2 Polypropylene

PP (also known as polypropene) is a thermoplastic polymer made from the monomer propylene. An addition polymer, it is rugged and usually resistant to many chemical solvents, bases and salts. This polymer is used in various applications: packaging, ropes, textiles, plastic parts, labelling, automotive components, and audio appliances.

4.2.1 Chemical and physical properties

Most commercial PP is isotactic (atoms arranged in a similar configuration) and has no intermediate level of crystallinity between that of LDPE and HDPE. Usually, PP is tough and flexible, especially if co-polymerised with ethylene. This allows PP to be used as an engineering plastic material, competing with materials such as ABS. PP is reasonably economical and can be made translucent if uncoloured but is not readily made transparent as PS, acrylics or certain other plastics. PP has good resistance to fatigue, is often opaque, and can be coloured by pigments.

The melting point of PP is ≈171.1 °C. Perfectly isotactic commercial grades of PP have a range of melting points (160–171.1 °C) depending on the grade and crystallinity. Syndiotactic PP with a crystallinity of 30% has a melting point of ≈129.4 °C. The melt flow rate or melt-flow index (MFI) is a measure of the MW of PP. This index helps to determine how easily the molten raw material will flow during processing. PP with a higher MFI if used as a matrix for composite resins will fill a mould more easily and faster and also facilitate easy and faster extrusion of composite profiles. As the melt flow increases, however, some physical properties (e.g., impact strength) decrease.

There are three general types of PP: homo-polymer (single monomer), random copolymer and block copolymer. The co-monomer is typically used with ethylene. Ethylene-propylene rubber added to propylene homopolymer increases its low-temperature impact strength. Randomly polymerised ethylene monomer added to PP

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homopolymer decreases polymer crystallinity and makes the polymer more transparent. PP is liable to chain degradation from exposure to heat and the ultraviolet (UV) radiation present in sunlight. Oxidation usually occurs at the tertiary carbon atom present in each repeat unit. A free radical is formed here and reacts with oxygen, followed by chain scission to yield aldehydes and carbolic acid. In external applications, it shows up as a network of fine cracks and crazes that become deeper with prolonged exposure. To counter this effect in external applications, UV-absorbing additives can be used. Carbon black also provides some protection from UV attacks, but this use may be limited by the type of desired surface finish. The polymer can also undergo oxidisation at high temperatures, a common problem during processing. Antioxidants are usually added to prevent polymer degradation.

4.3 Polyvinyl chloride

PVC is a thermoplastic resin. It is probably the third most widely produced plastic resin. PVC is a white, brittle solid available as a powder or granules. It can be made softer and very flexible by the addition of plasticisers, the most widely used group being the phthalates. It is insoluble in alcohol but slightly soluble in tetrahydrofuran. PVC is used widely in construction work because it is more effective and usable than traditional materials such as copper, iron or wood in pipes or profiled applications. PVC is also used in applications such as electrical cable insulation, upholstery, coating textiles, inflatable products, window frames, and conduits.

4.3.1 Production

PVC is produced by polymerisation (joining of basic units) of the monomer: vinyl chloride. About 80% of production involves suspension polymerisation. Emulsion polymerisation accounts for ≈12% and bulk polymerisation accounts for the remaining 8%. The monomer is introduced into a pressure-tight reactor with a polymerisation initiator, along with other additives. The contents of the reaction vessel are mixed continuously to maintain a suspension to ensure a uniform particle size of the resulting PVC resin. The reaction is exothermic so needs cooling and, because the volume is reduced during the reaction, water is added continuously to maintain the suspension. Polymerisation is started by compounds called ‘initiators’, which are mixed into the droplets. These compounds break down to start the radical chain reaction. Some initiators start the reaction rapidly but slow down, whereas others have the opposite effect. A combination of both is often used to achieve a uniform rate of polymerisation. After the polymer has grown by about tenfold, the short polymer precipitates inside the droplets of the monomer, and polymerisation continues with the precipitated solvent-swollen particles. Once the reaction has

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finished, the resulting PVC slurry is degassed and stripped to remove excess monomers, which can be recycled. The slurry is dried further in a hot air bed and the resulting powder is sieved before storage or pelletisation.

4.3.2 Additives for polymers

The product resulting from polymerisation of vinyl chloride monomers is unmodified-PVC. Before this PVC resin can be processed into finished products, it is necessary to convert it into a usable compound by the incorporation of additives such as heat stabilisers, UV stabilisers, lubricants, plasticisers, impact modifiers, thermal modifiers, fillers, flame retardants, biocides, blowing agents, and pigments. All types of monomers after polymerisation, with the resins in the raw state, will need additives to make them into workable polymers. All these additives are not needed as a whole but only some are needed; this factor is dependent upon the final grade to be produced to suit end applications. Some of the important additives and properties are presented below.

4.3.3 Plasticisers

Most vinyl products contain plasticisers that dramatically improve their rheological performance and mechanical performance. Plasticisers are used as processing aids as softening agents for polymers and also because they have the same effect of raising the temperature of polymers. The most common plasticisers are derivatives of phthalic acid. Plasticisers are selected based on their compatibility with the polymer, low volatility and cost. These materials are, in general, oily colourless liquids that mix well with PVC particles. Phthalates can be divided into two groups (high-MW and low-MW) with the high-MW phthalates. Plasticisers are most commonly added to alter the mechanical properties of a polymer (e.g., stiffness, toughness and strength). For example, adding a plasticiser such as dioctyl phthalate to PVC can reduce its stiffness and enable the mix to be soft and with reduced viscosity, as well as with other additives for easy flow (e.g., coating on fabric in the manufacture of artificial leather).

4.3.4 Important properties

PVC has high hardness and mechanical properties. The mechanical properties improve with increased MW but decrease with increased temperature. The heat stability of PVC is poor and, if the temperature reaches ≈104.4 °C, PVC starts to decompose. Its melting temperature is 121.1 °C. The linear expansion coefficient of PVC is small and

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has flame retardancy, the oxidation index is ≥45. Therefore, incorporation of a heat stabiliser during processing is crucial to ensure the properties of the end product.

The two basic grades of PVC are: unplasticised polyvinyl chloride (uPVC) and soft PVC (flexible PVC). Rigid PVC (uPVC) has a density of 1.3–1.45 g/cm^3, whereas soft PVC has a density of 1.1–1.35 g/cm^3. PVC is a polymer with very good electrical insulation but, because of its highly polar nature, may be inferior to non-polar polymers such as PE and PP.

4.4 Polystyrene

PS is a synthetic polymer made from the liquid petrochemical monomer styrene. PS can be rigid or foamed, as in expandable polystyrene (EPS). General-purpose PS is clear, hard and brittle. It is an inexpensive resin per unit weight and used widely in industry (especially in injection moulding and extrusion). PS is naturally transparent but can be coloured readily. As a thermoplastic polymer, PS is in a solid glassy state at room temperatures but flowed easily if heated above its T_g. Being a thermoplastic, the molten polymer becomes rigid again on cooling and can be re-used. It is very slow to biodegrade unless special biodegradable additives are incorporated in the polymer. Some of the common applications for rigid PS are: packaging, containers, caps, trays, disposable cutlery, tumblers, tubing, and lids; whereas foamed PS are used for end applications such as insulation board, packaging, fish boxes, decorative facades, and floating devices.

4.4.1 Structure of polystyrene

PS is a long-chain hydrocarbon in which alternating carbon centers are attached to phenyl groups (aromatic benzene rings). Basically, PS contains the elements carbon and hydrogen. The properties of the polymer are determined by short-range van der Waals attractions between polymer chains. The molecules are long-hydrocarbon chains comprising thousands of atoms, so the total attractive force between the molecules is large. If heated, the chains can take on a higher degree of conformation and slide past each other. This intermolecular activity confers flexibility and elasticity. The ability of this system to be deformed readily above its T_g allows PS to be softened and processed upon heating.

4.4.2 Polymerisation

PS is the result of basic styrene monomers interconnecting through polymerisation (joining of basic units). During polymerisation, the carbon-carbon pi bond in the

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vinyl group is broken and a new carbon-carbon single (sigma) bond is formed, leading to the attachment of another styrene monomer to the chain. The newly formed sigma bond is much stronger than the pi bond that was broken, thus it is very difficult to depolymerise PS.

The only commercially important form of PS is *atactic* (i.e., phenyl groups are distributed randomly on both sides of the polymer chain). This random positioning prevents the chains from aligning with sufficient regularity to achieve crystallinity. If the phenyl groups are positioned on alternating sides of the polymer chain, the PS produced is *syndiotactic*. This form of PS is highly crystalline and is, in general, not produced because the polymerisation process is slow.

Pure PS is brittle but sufficiently hard that a fairly high-performance product can be made by giving it the properties of a more flexible or stretchable material by combining it with polybutadiene rubber. These two materials cannot be mixed because of the amplified effects of intermolecular forces on polymer insolubility. However, if polybutadiene is added during polymerisation, it can become chemically bonded to PS, forming a graft copolymer. This process helps to incorporate normal polybutadiene into the final mix, resulting in *high-impact polystyrene* and opening up more possibilities for the use of PS.

4.5 High-density polyethylene

HDPE is a thermoplastic polymer made from petroleum sources. This resin is used widely in the plastics industry for applications such as corrosion-resistant pipes, geo-membranes, plastic lumber, bottle caps, food containers, auto fuel tanks, plastic bags, water pipes, electrical/plumbing boxes, hard hats, and industrial safety equipment. Common and popular special applications are the use of HDPE, whereby large sheets are employed for the prevention of pollution from soil and groundwater from solid wastes, and also for the pyrotechnics trade. Milk jugs and other blow-moulded hollow products are also important applications of HDPE.

4.5.1 Properties

HDPE is known for its high strength:density ratio. The mass density of HDPE is 0.93–0.97 g/cm^3. The density of HDPE is only marginally higher than that of LDPE, but HDPE has little or no branching, giving it stronger intermolecular forces and a tensile strength than LDPE. The difference in strength exceeds the difference in density, giving HDPE a higher specific strength. It is also harder and more opaque and can withstand higher temperatures of ≈121.1 °C for short periods and ≈110 °C for long periods of time.

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4.6 Acrylonitrile-butadiene-styrene

ABS polymers are opaque thermoplastic resins formed by the polymerisation of ABS monomers and have many diverse properties. ABS is classified as a *terpolymer* (i.e., composed of three monomers). Their development as commercial polymers resulted from research on synthetic rubber. The proportions of the three monomers can be varied, which accounts for the great number of possible properties. Graft polymerisation methods are, in general, used to make various grades of ABS. They are versatile resins and can be processed easily on all thermoplastic processing machines. Some of the applications for ABS are: appliance housings, light luggage, pipes, tool housing, extruded lumber, automotive parts, tool boxes, and furniture components.

4.6.1 Properties

ABS resins are *hygroscopic* (moisture absorbing) and pre-drying before processing is advised. Some of the main properties of ABS are:

- Ease of processing and fabrication
- Easy to colour
- High impact-resistant
- High degree of toughness and rigidity
- Good electrical properties
- Excellent adhesion to metal coatings
- Fairly good weather resistance
- High gloss finishes
- Good chemical resistance
- Light weight
- Very low moisture absorption (post moulding)

4.7 Polymer additives

For efficient processing of polymers, using additives with basic resins is essential. Additives are available in a very wide range and forms such as liquids, pastes and solids. These are needed (in addition to aid ease of processing) to enhance the properties of a product and achieve the desired finishes. The list below shows the general additives used in the plastic processing industry but, with PCRH, additional special additives are required to achieve the special properties or finishes desired. For example, in the extrusion of lumber using PCRH, special additives can be incorporated in addition to the standard ones to achieve veneers similar to those of natural wood:

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- Anti-blocking agents
- Slip additives
- Plasticisers
- Stabilisers
- Antioxidants
- Flame retardants
- UV stabilisers
- Anti-static agents
- Blowing agents
- Colourants
- Fillers

4.7.1 Anti-blocking agents

Sometimes, sticking between polymers is experienced due to the friction of low-MW molecules. If adding anti-blocking agents to a resin(s), the blocking force between the layers can be reduced significantly. The mechanism of action that lowers the blocking forces is the surface roughness caused by the well-dispersed particles.

Some commonly used anti-blocking agents are:

- *Limestone* is a relatively low-cost material for the production of low-quality products. It is primarily calcium carbonate but may also contain magnesium carbonate.
- *Natural silica*: Rice hulls have a high content of silica.
- *Synthetic silica gel* is an anti-blocking agent with a high surface area and is used for high-quality products.
- *Talc* is readily available in fine powder form and composed of magnesium hydrosilicate.

4.7.2 Slip additives

Some polymers are very tacky, which causes them to cohere to themselves and adhere to other surfaces during processing, which may also be an advantage in the extrusion of polymeric composite lumber. Slip additives should be incompatible with the polymeric material, causing them to migrate to the surface. When designing polymeric composites, one should work out if slip additives are actually required. Some of common slip additives are listed below:

- *Erucamide*, which migrates slowly to the surface of a polymer and, due to its low volatility, remains on the surface longer.
- *Oleamide*, which migrates faster than erucamide and is known as a fast blooming (migrating) slip additive. In general, it is the choice for large-volume processing.

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- *Stearamide* is used in conjunction with erucamide and oleamide and provides an anti-blocking effect.

4.7.3 Plasticisers

Plasticisers are solvents mixed into a polymer to alter its rheological or mechanical properties. Plasticisers also function as processing aids because they have the same effect as raising the temperature of a polymer, resulting in lowering of its viscosity, thus reducing the risk of thermal degradation during processing. Plasticisers are also used to alter the mechanical properties of a polymer, such as stiffness, toughness and strength.

4.7.4 Stabilisers

Polymer degradation can occur due to a combination of heat and oxygen. During processing, heat or energy produces free radicals that react with oxygen to form carbonyl compounds, giving rise to yellow or brown discolourations in the final product.

4.7.5 Antioxidants

Addition of an antioxidant suppresses thermal degradation during polymer processing. Antioxidants also can be classified as stabilisers and, to achieve optimal results, good practice would be to use a blend of stabilisers to create a synergistic stabilising effect. Irrespective of the system used, they will not fully eliminate thermal degradation but will slow it down. Once the stabilisers have been consumed by the reaction with oxygen, the polymer is no longer protected against thermal degradation.

4.7.6 Flame retardants

Most polymers are flammable due to their organic origins, and have always been a serious technical problem. However, some additives that contain halogens (e.g., bromine and chlorine) or phosphorous reduce the possibility of ignition within a polymer component or, once ignited, slowing down the spread of flames and possibly self-extinguishing of the flames. Due to the importance of their safe uses, many flame-retardants are under constant review and some are even banned. Many flame-retardants are used with synergists such as antimony oxide, iron oxide, zinc borate, zinc phosphate and zinc stearate.

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4.7.7 Ultraviolet stabilisers

UV action on plastics causes discolouration and degradation of the polymer material, which is due to the action of light and oxygen. In the post-production of polymeric composite lumber this could pose a problem, especially for light-coloured finishes if they are used for outdoor applications, whereas dark-coloured finishes show very minimal effects or not at all, even if they are used outdoors. Most of the damage occurs because of the action of UV rays in sunlight, which causes deterioration of appearance due to micro-crack formations and, consequently, a reduction in mechanical performance, as well as chemical resistance, among others. To reduce this photo-oxidation, special chemicals called 'light-stabilisers' or 'UV-stabilisers' are available. The protection offered by these UV-stabilisers involves blocking, absorption and dissipation of the harmful radiation so that it does not turn into heat.

Sterically hindered amine light-stabilisers give very good results. Organic nickel compounds are also used often. Carbon black and other pigments are also often used to protect plastics from UV rays.

4.7.8 Antistatic agents

Polymers have such low electrical conductivity that they can easily build-up electric charges. The rate of static charges generated at the surface of a component can be decreased by reducing the amount of surface contact, whereas the rate of decay of charges is increased through surface conductivity. Hence, a good antistatic agent should be an ionisable additive that allows the charge to migrate to the surface, while also creating bridges to the atmosphere through moisture in the surroundings.

In general, antistatic agents are applied externally to the polymer surface by spraying or dip-coating after being dissolved in a suitable solvent carrier. The advantage of externally applied antistatic agents is that only very small amounts of these agents are needed, and that the effects of the additives are immediate. A disadvantage would be that externally applied additives wear off with time due to friction, moisture and other external factors. Internally applied agents can be blended directly into the polymer matrix. These also work as lubricating agents (lowering surface friction and reducing generation of static charges) or as conductors (by creating a water-absorbing layer on the surface of the polymer and creating a conduction path to the atmosphere). Many antistatic agents are available but one may consider using *fatty acid esters*, *ethoxylated alkylamines* or *diethanolamides*, which are non-ionic antistatic agents. For more polar polymers such as PVC and styrenics, anionic antistatic agents such as *alkylsulpfonates* or *alkylphosphates* can be used.

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4.7.9 Antimicrobial agents

Bacterial growth is a very high priority concern, especially for polymeric composites used for outdoor applications, due to wet and damp conditions. This growth leads to many hazards for composite products and must be dealt with effectively. For polymeric composite materials used for indoor applications, this may not be a real problem but, if used in highly air-conditioned atmospheres, microbial growth is possible. Antimicrobial agents (also known as 'fungicides') are used to slow down or prevent the growth and propagation of bacteria.

Plasticised PVC, LDPE and polyesters are particularly susceptible to microbial attack. PVC and polyurethanes (PU) are by far the main plastics that require fungicides to be incorporated. PVC itself is resistant to microbial attack, but the plasticisers used serve as nutrients for fungal growth. Antimicrobial agents are also known as 'bio-stabilisers' and, because of their prices and efficacy, over half of antimicrobial agents are arsenic-based agents. However, due to ecological and toxicity concerns, other non-arsenic-based agents are being used widely.

4.7.10 Blowing agents

In the processing of plastic resins, the task of a blowing or foaming agent is to produce cellular polymers (also called 'expanded plastics'). The cells can be closed completely (e.g., rigid foams) or open cells (e.g., flexible PU foams). These agents can be incorporated during polymerisation, as in EPS, or added to the polymer mix during processing. In the present context, polymeric composites in which the reinforcement content in the polymer matrix with biomasses is high result in heavy end products (e.g., extruded lumber) and this property is good for outdoor applications, where they have to bear loads and withstand the environment. This property gives the composite products a longer life and lessens maintenance that may be required. However, for polymeric composites for indoor uses, lighter products will be preferred for easy handling, fabrication and lighter load-bearing. This is where blowing agents or foaming agents will be useful.

Polymer foams can be produced by mechanically 'whipping' gases into the polymer or by chemical agents or physical means. The basic stages of a foaming process are: (i) cell nucleation; (ii) cell expansion; and (iii) stabilisation of the cell structures. Too much cell expansion or foaming of the polymer will be harmful to the end product due to lessening of the properties. Cell nucleation occurs if, at a given temperature and pressure, the solubility of a gas is reduced, leading to saturation and expulsion of excess gas to form bubbles. In EPS, for example, the polymer resin is in the form of tiny spheres, each one with a very small amount of an inert gas. If heated, this gas is activated to expand and form cells within the polymer. This is a chemical foaming process that will produce closed cells. In the production of flexible PU,

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water acts as the main blowing agent and sometimes methylene chloride is added to achieve very light densities.

Many popular blowing agents are available. If a complete online process is used for a polymeric composite extrusion line, a chemical blowing agent can be added to the polymer matrix, rice hull powder and other additive mixes during compounding. Some of the commonly used chemical blowing agents are: azodicarbonamides (a pale-yellow to orange powder), hydrazinc derivatives (a slightly yellow crystalline powder), semicarbicides (a white crystalline powder), and carbonates (white powders).

4.7.11 Colourants

Colourants can be divided into two categories: pigments and dyes. Pigments are organic or inorganic materials that are practically incompatible with polymeric materials, and must be dispersed into a polymer melt using a relatively intense mixing method. Pigments come in several forms such as powders, granules, liquid/solid concentrates and masterbatches tailored by compounders. For easy dispersion, a composite producer can select a masterbatch where the pigment is already incorporated into the same polymer and available in liquid or solid forms. Dyes are compatible with polymer melts. Because dyes dissolve in the resin, there are no visible particles and they will not affect the transparency of the material mix. When selecting colourants, some of the important aspects are:

- *The colour index* is a classification for pigments and dyes.
- *Heat resistance*: Check the highest processing temperature and exposure time.
- *Light fastness*: Rating between 1 (low performance) and 8 (high performance).
- *Weather fastness*: Most suppliers will provide information.
- *Migration*: Most pigments or dyes can migrate to the surface. Also called *blooming* or *bleeding*.
- *Abrasion*: Many inorganic pigments are very abrasive, thereby causing long-term damage to processing equipment.
- *Chalking*: If too much pigment is used, the surface of a part degrades during weathering.

4.7.12 Fillers

Fillers play an important part in the processing of plastics. They can be classified as those that: reinforce a polymer matrix and improve its mechanical performance; take up space and thus reduce the amount of polymer to make a product (sometimes called an ‘extender’); are used to lower costs as well as to increase the density of the product. Polymers that contain fillers that improve their mechanical properties are referred to as ‘reinforced plastics’ or ‘composites’. Composites can be dived

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broadly into composites with high-performance reinforcements and composites with low-performance reinforcements. High-performance composites are those in which the reinforcement is placed inside the polymer so that optimal mechanical behaviour is achieved, such as in the case of glass fibres in an epoxy resin (fibreglass products). Low-performance composites are those in which the reinforcement is sufficiently small that it can be dispersed well into the matrix. These materials can be processed in the same way as their unreinforced counterparts.

Probably the most common filler used to reinforce polymeric materials is glass fibre. However, modern technology is using wood fibre and other biomass fibres with exciting prospects for rice hulls, which are now being used to produce polymeric composite resins and extruded profiles with improved properties. These biomasses, which are being used as reinforcements and extenders, also increase the stiffness and mechanical properties of some thermoplastics. To improve the bonding between the polymer matrix and reinforcement, coupling agents such as silanes and titanates can be added. Extenders used to reduce the cost of composite products are most often particulate fillers. The most common are calcium carbonate, silica flour, clay, and wood flour.

The additives discussed so far are the general ones required for converting raw resins into polymers for processing. For PCRH, as with wood flour polymer composites, additional special additives must be incorporated into the polymer matrix and the rice hulls mix to get whichever finishes are desired for the end application (e.g., outdoor, indoor, furniture applications). These additives will be discussed in later chapters with regard to the processing of PCRH.

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5 Rice hulls for composites

5.1 Introduction

Rice is the staple diet of many people all over the world. More than 100 million metric tonnes of rice are produced annually, especially in Asia and the Far East. Rice hulls are the protective coatings of the rice seeds or grains. These hulls are formed by a hard material and are unique products of nature. They contain ≈20% opaline silica in combination with a large amount of structural polymer called *lignin*. These hard coatings protect the rice seeds during the growing season until harvest.

Previously, separation of rice grains from hard coverings was a laborious process. However, modern processing employs many advanced machines that make it much easier, faster and more efficient. During milling, hulls are removed from raw grains to reveal whole brown rice grains, which may then be milled further to remove the brown (bran) layers, resulting in white rice. This abundant natural agricultural waste has posed problems with regard to disposal. The few traditional uses for these leftover hulls have not fully eliminated this problem. However, once the true nature and properties of these hulls (especially the high content of silica) had been discovered, more sustained efforts were made through research and development to find end uses for these versatile hulls. Two of the lucrative uses of these rice hulls are the production of polymeric composite resins with rice hulls for the processing of plastic products (cheaper resins) and the production of excellent lumber as an ideal substitute for natural timber. One may even say that these products have better properties than the naturally occurring ones. Also, they can be considered to be ‘green’ products with tremendous potential to ease global environmental concerns by reducing the felling of trees.

5.2 Properties of rice hulls

Rice hulls are unique within nature. This abundant agricultural waste has all the properties one could expect of some of the best insulating materials and, due to diligent research, its true potential is emerging. Tests carried out have shown that rice hulls: do not flame or smoulder very easily; are highly resistant to moisture penetration and fungal decomposition; do not transfer heat very well; are not odorous; do not emit gases; are not corrosive with respect to metals such as aluminium, copper or steel.

In their raw and unprocessed state, rice hulls constitute class-A insulation material. Therefore, they can be used very economically to insulate walls, floors and roof cavities in building construction. If used in panels or as reinforcement in composites, they function as cost-effective insulating materials for most applications. With the new emerging technology of polymeric composites with rice hulls,

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products made by injection moulding and compression moulding have wide ranges of applications, but the most versatile range is for products such as lumber made by extrusion. Until recently, this humble gift of nature has not been exploited by scientists and researchers, and only now are they beginning to understand the full potential of rice hulls.

Rice hulls are very tough and abrasive, consisting of two interlocking halves. These halves encapsulate the tiny space vacated by the milled grain and, in proximity to a myriad of other hulls, they form a thermal barrier that compares well with that of other excellent insulating materials. Using rice hulls in their natural, loose form is not practical, so ideally they should be made into products suitable for practical applications. Do rice hulls burn? Yes, they do but with difficulty. In fact, if a mass of loose rice hulls is set on fire (when used as a fuel for steam boilers), the ideal would be to sprinkle a little highly inflammable liquid such as kerosene oil and, once the mass is lit, it burns well with high heat content. Air cannot flow freely through a pile of rice hulls to provide oxygen to sustain rapid combustion so they do not combust easily. The bulk density of loose rice hulls is similar to that of baled straw and anyone who has tried to burn a bale of straw understands the problem associated with the availability of oxygen. Lack of oxygen may be one of the problems but is not the main problem.

The high percentage of opaline silica within rice hulls is most unusual in comparison with other plant materials. Some scientific evaluations have concluded that, during the combustion of rice hulls, the silica ash may form a ‘cocoon’ that prevents oxygen from reaching the carbon inside. Another school of thought among scientists is that, because silica and carbon may be partially bonded at the molecular level, silicone carbide is formed during high-temperature combustion and that the presence of this heat-resisting compound impedes the easy combustion of rice hulls. Other scholars say that, at certain temperatures, the molecular bond between the silica and carbon in the hull is strengthened, thereby preventing the thorough and uniform burning of the hull. The general conception is that, even if a pile of loose rice hulls can be ignited, it will tend to smoulder rather than flame. However, practical experience by the author (operation of steam boiler with rice hulls as fuel) can certify to the fact that, once a pile of loose rice hulls is truly lit and a good flame stage has been reached, it maintains this status with the constant feed of loose hulls and burns with a good flame and high heat content. The value of the resulting ash, which hitherto has not been exploited, is also emerging as material with many possibilities (see later).

Rice hulls (also called ‘rice husks’) are flame-retarding and self-extinguishing. A lighted match thrown onto a pile of rice hulls will, in general, cause it to burn and smoulder without producing a high flame. Production of a flame will require a flammable starter to ignite the pile. Depending on the length of burning, the resulting ash will be grey or black; both have many useful applications. Conventional cellulose insulation requires the addition of large quantities of flame- and smoulder-retardants.

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The concentration of flame- or smoulder-retardant chemicals such as boric acid, sodium borate ammonium sulfate, and aluminium sulfate in conventional cellulose may be ≤40% by weight. These chemicals are expensive and incorporating them into the cellulose fibre is not easy. Importantly, rice hulls do not require flame- or smoulder-retardants and, if used in insulation applications, additional chemicals are not required.

In general, all organic materials absorb or release moisture until they come into equilibrium with the relative humidity of the surrounding air. The high presence of silica on the outer surface of rice hulls impedes the atmospheric transfer of moisture into the hull. Also the presence of a small percentage of a bio-polyester in the rice hull in combination with a wax produced by the rice plant forms a highly impermeable barrier to moisture and heat. The high concentration of opaline silica on the outer surface of the rice hull also strengthens and makes the outer shell hard. However, due to lignin within the rice hull, this hardness is tempered with flexibility and elasticity. The rice hull is hard and yet elastic, so it resists settling and compression far better than some materials.

Rice hulls are available at minimal cost and in some cases may be even available free. In applications where they are used as loose filling in their natural form for insulation, costs would be very much less as compared with other commercially available insulating materials, especially because rice hulls do not require shredding, hammer-milling, fluffing, fiberising or binding for this application. Perhaps the most significant cost associated with the utilisation of rice hulls is their transport. Having a bulk density of ≈5.6 kg/m^3 may cost extra unless they are compressed and packed in such a way as to reduce transport costs. In general, it is accepted that loose rice hulls can be compressed to a bulk density of ≈16 kg/m^3 without destroying their properties. Depending on the type of transport and costs, it may not be necessary to reach this maximum compression, and a lesser compression may be acceptable. Although rice hulls have many versatile and practical applications, this chapter details the use of rice hulls as a reinforcing component in polymeric composites.

5.3 Chemistry of rice hulls

Rice hulls are a unique gift of nature and their full potential is being exploited only now. Rice hulls do not need to be mined or manufactured in processes that generate air pollution, water pollution or erosion. Rice hulls do not deplete our reserves of fossil fuels as do the processes for manufacturing polymeric compounds from petroleum sources. As an insulation material and utility reinforcement for composites, rice hulls now rank among the best. Their ready availability and cheap costs are important factors to consider.

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To protect the rice seed during growth, the hull is formed from hard materials, including opaline silica and the polymer lignin. It is generally accepted that these hulls contain 20% opaline silica but, if they are burnt into ash, test results have shown silica content of ≤70% of volume. The production of ash goes through two stages: the first is a ‘grey’ state when the silica content is at its maximum and then a ‘black’ state. Rice hulls can be used to produce mesoporous molecular sieves, which are applied as catalysts for various chemical reactions as a support system. The ash is also a very fine thermal insulation material and can have finer particle size, even better than cement, and thus could have many applications in the building industry. Here, I would like to offer the theory that using the fine ash of rice hulls as the reinforcing component instead of rice hull flour would be more beneficial in the production of polymeric composites. Higher contents of silica, volume to volume, between fine ash and rice hull flour for added properties such as additional strength and weathering may justify this theory. Also, combined use of rice hull ash and rice hull flour in the production of polymeric composites should be tested to yield better products than those being made currently.

5.4 Uses for rice hulls

Most countries grow rice, more so in Asian and Eastern countries, where it is their staple diet. Rice hulls resulting from the growing, harvesting and processing of rice is a gift of nature as a recyclable resource having many current and potential uses. Up to recently, this lowly byproduct of growing rice has been regulated to being used only as animal feedstock and for the poultry industry, with most of it being discarded as waste. However, due to increasing global environmental concerns, researchers and scientists have realised the important potential of rice hulls in a wide range of applications, especially as an ideal substitute for natural wood in the form of lumber. Thus, the use of rice hulls in the production of polymeric composites gaining ground fast *via* the production of: (i) polymeric composite resins for moulding, and (ii) lumber through extrusion. Some of the important uses of rice hulls are presented below.

5.4.1 Extrusion, injection moulding and compression moulding

Polymer resin moulders are always on the lookout for cheaper resins to be able to be competitive in the market because they also have to battle with rising labour costs and other manufacturing costs. Since the arrival of composite resins with rice hulls, moulders, though very interested, have been showing caution in using these resins (as with any new material). As the research and development of these composite resins continues, moulders who have already started using these resins can

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do so with more confidence. Here, I would like to recommend that the use of rice hull ash (grey state) or a combination of ash and rice hull flour would result in better-quality composite resins. Currently, these composite resins are being used only for extrusion, injection moulding and compression moulding, but it is expected that they will be used for other areas of plastic mouldings as well.

5.4.2 Animal feed industry

Rice hulls as a recyclable resource have many useful applications in the poultry and animal farming industries. In the former, they are used primarily as bedding for poultry and also as feed mix. In the animal feed industry, they are used as a fibre source, premix and pellet binders. Rice hulls are offered by specialty producers as different grades and grinds. The three main grades are 20/80 and 30/80 (rough) and 80. Typically, rough grind is used as a fibre source in animal feed, 20/80 and 30/80 are used as a premix animal feed, supplements and 80 grade as a pellet binder, and unground hulls are used as bedding for animals and poultry.

5.4.3 Lumber from composites

Rice hull flour (finely ground hulls) is an ideal composite material for polymeric composites. Processing involves the mixing and compounding of plastic resins with rice hull flour with additives such as fillers, lubricants, binders, and colours depending on the end result desired, and then using an extrusion process to produce profiled lumber. Depending on the type and size of the extrusion system, there will be limits to the size of the profile section and width that can be produced, but lengths carry few limitations. These products are ideal substitutes for natural wood, and reports after testing and usage reveal many excellent and beneficial properties.

5.4.4 Building materials

Rice hulls are class-A thermal insulating materials because they are difficult to burn and resist penetration by moisture (which stops the propagation of mould or fungi). Tests have shown that if they are burned, rice hulls will produce a significant amount of silica. Rice hulls are also a potential source of amorphous reactive silica. If burned completely, the ash can have a Blaine number (particle size) of ≤3,600 as compared with a Blaine number of 2,800–3,000 for concrete (i.e., it is finer than cement). Silica is the basic component of sand, which is used with cement for plastering and concreting. This fine silica from rice hulls provides very compact concrete. This ash is also a very good thermal insulating material. The

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fineness of the ash also makes it a very good material for sealing fine cracks in civil structures, in which it can penetrate deeper than conventional cement-and-sand mixtures.

5.4.5 Production of glass

The fact that rice hulls contain 20% opaline silica is significant in the manufacture of glass because glass is composed primarily of silica. Heating rice hulls to high temperatures will turn it into glass spheres. This opaline silica may be combined with silicone dioxide (sand) to form a glass composite. This composite material can then be used to produce all types of glass products. Some home-insulation products are glass that has been blown into strands, and rice hulls would make excellent materials for insulation. These glass spheres can also be used as filler in the manufacture of plastic foams (e.g., flexible polyurethane foams).

5.4.6 Rice hulls ash in road building

Recycling of increasing volumes of plastic wastes, whether it is from domestic or industrial activity, is a challenge with regard to environmental pollution. Although there are many recycling programmes, one might say it is a ‘losing battle’ because of the volumes produced. However, recently, a little-known town in India, faced with this problem, came up with a unique way to deal with this. With little or no knowledge of science or chemistry, they experimented using a combination of plastic wastes and bitumen to discover a novel way to recycle plastic wastes so as to minimise pollution. They have perfected a way of using this combination in road building.

The plastic waste is shredded into small pieces using a granulator or shredder and then added into heated bitumen (≤60% by volume) and mixed thoroughly. The high temperature melts the plastic easily. If this mixture is used on a road surface, it gives a very smooth and flexible coating. According to reports, a road surface made in this way does not crack, can bear high loads, and water seepage is minimal. I suggest that addition of a small proportion of rice hull ash, which is rich in silica, will greatly improve these properties. I recommend a basic combination of 40% bitumen; 50% plastic waste; and 10% silica ash. The silica will blend easily and give additional strength and form a surface coating to prevent rainwater absorption and seepage.

5.4.7 Fuel for steam boilers

Most rice-producing farmers use rice hulls as fuel for their rice-mill steam boilers. These boilers are low-pressure/low-volume and, because only small volumes of

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steam are required, the rice hulls can be fed directly into the furnace through an additional opening close to the ‘peep hole’. A more important application is that rice hulls can be used for industrial steam boilers too. I present the following case study from actual design and practice.

5.4.7.1 Case study

Products: Expanded polystyrene (Styrofoam) fish boxes, insulation board, fishing floats and hot/cold containers.

Output: 2 metric tonnes per month.

The basic equipment was a block mould, separate moulds for all items, and a hotwire cutting machine. All moulds were connected through steam lines to a steam boiler with specifications of 100 psi and steam volume of 500 lbs steam/hour. Use of diesel oil as fuel proved to be expensive and an alternate fuel had to be found. After some research and experimentation, a method was found on how to use rice hulls in the natural state. The rice hull feed design contained a pipe (diameter, 3 inches; and length, 5 feet) with a flange at one end attached to a blower motor turning at 3,000 rpm. Halfway along the pipe was an opening in which a hopper with a control valve was mounted. The other end of the pipe opening had an elbow bend containing an adjustable nozzle that was connected through a flange to the base of the boiler furnace. Rice hulls were introduced into the hopper and the blower motor started. Rice hulls were blown along the pipe, with the stream controlled by the valve, and a cascade effect was created inside the furnace. To promote initial ignition, a small amount of kerosene oil was sprayed onto the cascading rice hulls and the whole mass ignited. By good control of stream using the control valve in the hopper, a sustained and continuous fire was achieved. An immediate reward was a reduction in the cost of the boiler fuel by 90%.

5.4.8 Rice hulls in fertilisers

Rice hulls are a renewable resource of fertiliser. Rice hulls in fertiliser can recycle nutrients and eliminate wastes. Using rice hulls and rice hull/manure composts and vermicomposts improve the fertility, organic matter, physical properties and structure of soil over long periods. Rice hull composts are especially useful for boosting the humus content of the organic matter of soil, thereby providing a long-term source of nutrients.

Nature also helps by way of worms in the soil, which can play a key part in rice-hull decomposition because rice hulls can be difficult to compost due to their high content of cellulose and lignin. Their waxy surface cover also impedes microbial attack due to their low capacity to absorb water. Using composts made by mixing rice hulls with manure greatly contributes to micronutrient content and improves the soil

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structure because of greater retention of water and air. This is a good example of utilisation of crop residue and its transformation into a resource. Rice hulls with their high contents of lignin and cellulose are a source of the precursor of humus (the organic-matter component with the greatest stability and nutrient availability). Researchers have developed composting practices of rice hulls to obtain fertilisers that are suitable for use in other applications (e.g., public and domestic gardens). These ready-to-use organic fertilisers are also sold in bags made from recycled paper or plastics.

5.4.9 Rice hulls in cement bricks

Traditionally, most rice hulls have been disposed of as waste. However, for some time, the practical possibilities of such agricultural waste have been emerging in applications, particularly in building construction. Two significant factors to promote the search for alternate materials are (i) environmental concerns, and (ii) the shortage and increasing costs of traditional materials used for particular applications. Examples include cement bricks or clay bricks for building construction.

Many manufacturers of cement and clay bricks are now mixing in a high proportion of rice hulls in the form of ash or in its natural state to produce excellent bricks. According to reports from researchers and actual users of these bricks, they perform well against the elements, vermin and mould, and could easily replace the part of natural sand (silica) because rice hulls (especially in the form of ash) are high in silica. Reduced material costs are also a significant factor.

5.4.10 Rice hull briquettes

Briquettes have been in place for a long time as a cheap source of fuel for many applications. Growing environmental concerns have prompted people to look for alternate solutions for heating and ambiance fires that result in minimal environmental pollution. The economic aspects of alternate fuels to replace traditional fuels are also significant. Traditionally, petroleum-based fuels had taken precedence and this trend will probably continue for some time, especially where large industrial applications are concerned.

However, briquettes may be better suited for low-end applications. At present some briquettes are made from different materials, mostly wastes. In Asian and Far Eastern countries, briquettes made from rice hulls are very popular. China and Thailand are offering to produce briquettes having dimensions of 20–40 cm (length) and 5–7 cm (diameter) and these densified briquettes will have a heat content of

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3,000–4,000 kcal/kg. Rice hulls in the densified state are difficult to ignite, so manufacturers may incorporate an igniting promoter in the mix. There will be a market for the ash that results from such procedures.

5.4.11 Rice hull ash

The ash produced after hulls have been burnt is high in silica. The list below shows some of the possibilities in which this material can be applied but a word of caution is called for. Irrespective of the process that results in the production of ash or the method employed directly to produce rice hull ash, a very fine 'dust' will be emitted into the air in addition to the deposits of ash at the bottom of a device. In general, this dust will emerge through a chimney and, if not grounded through a curved chimney, will cause air pollution and create problems for any buildings close by:

- Aggregate and filler for the production of concrete and board
- Economical substitute for micro-silica/silica fumes
- Absorbents for oil and chemical spills
- Soil ameliorants
- Source of silicone
- An insulation powder in steel mills
- Repellents in the form of 'vinegar-tar'
- Release agent in the ceramics industry
- Insulation material for homes and refrigerants

5.4.12 Case in point

I present a case in point for the benefit of readers of this book for the possibility of using rice hulls in the natural state as fuel for steam boilers on an industrial scale.

On a contract received by a group of businessmen in the Philippines, I set up a complete manufacturing plant for three sizes of Styrofoam fish boxes to include project design, factory building, machinery, technology, and training. To save initial project costs and not delay the start of production, the supply of steam was taken from the neighbouring factory, which was manufacturing silk threads from silk worms. Interestingly, their steam boiler was fuelled by rice hulls in the natural state. This system was quite advanced and more or less automatic, with effective collection of ash to the ground.

During the second year of operation, the producer of Styrofoam fish boxes, on my recommendation, installed his own steam boiler system fired with rice hulls with automatic operation. Rice hulls were freely available locally, which enabled this producer to minimise fuel costs.

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5.4.13 Rice hulls in building construction

I present some polymeric composite products with rice hulls other than the number-one product: composite lumber in building construction. Over the years, people have used natural wood in all types of construction work: domestic, industrial or other. Natural wood has a very wide range of applications but, due to rising costs and particularly serious environmental concerns with deforestation on a global scale, it was merely a matter of time before people would find alternatives.

One such product is roof tiles. Mixtures of polymers (pure wastes or recycled), mixed with rice hull flour, a small percentage of cement, additives and colours, has led to production of roofing tiles with excellent properties and a wide range of finishes and shapes. The practice of using polyethylene or polyvinyl chloride as the polymer matrix will no doubt extend to other polymers. Another product is floor tiles based more or less on the same formulation mix. One big advantage is that wastes can be used, with probably the ideal being recycled wastes in pellet form for easy compounding. Using this same concept, strong roofing sheets in any colour or shape can also be produced and, according to reports, are already in use.

The possibilities of rice hulls and their ash have many exciting and challenging possibilities of applications, and even the producers of polymeric composites are coming up with interesting products. In fact, the actual producer is probably the most knowledgeable source with first-hand information to initiate practical new products.

5.4.14 Miscellaneous uses

Rice hulls are also used in other applications:

- Fibre used in pet food
- To increase the lautering ability of a mash when brewing beer
- As fillers for fireworks
- For improving the extraction efficiency of fruit-juice pressing
- Stuffing pillows
- Insulation boards

This list shows the versatility of rice hulls and there is no doubt that as research and development takes place, newer applications will emerge. For most end processes, the inherent moisture content may be a concern and may have to be controlled by pre-drying before use.

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6 Polymeric composites with different constituents

6.1 What are wood plastics composites?

Wood plastic composites (WPC) are presented because they are an important branch of polymeric composites and used widely in many countries. The main difference between wood plastic composites (WPC) and polymeric composites with rice hulls (PCRH) is that, while the polymer matrices remain virtually identical, the reinforcing constituents are different in that one uses wood flour whereas the other uses rice hull flour. Using comparatively new technology, the emergence of PCRH is gaining popularity and its superior properties and wider range of end applications will no doubt pave the way as the number-one product as an ideal substitute for natural wood or lumber.

WPC are composite materials made of wood flour/fibre and thermoplastic polymers such as low-density polyethylene (LDPE); high-density polyethylene (HDPE); polypropylene (PP); polyvinyl chloride (PVC); acrylonitrile-butadiene-styrene; and polystyrene (PS). Polyethylene (PE)-based WPC are by far the most common, and virgin resins or recycled resins (or a combination of both) can be used. Depending on the end application targeted, these composites can be made into grooved, hollow or solid profiles. In addition to wood flour and plastic resins, WPC can also contain other lingo-cellulosic and/or inorganic filler materials. Many cellulose-based fibres, such as pulp fibres, peanut hulls, bamboo, and straw as fillers or reinforcement can also be used.

WPC came on the market in the 1990s but are considered new materials relative to the long history of natural lumber as a building material. Manufacturers of this composite lumber claim that it is more environmentally friendly and requires less maintenance than the alternative: treated solid natural wood. This composite lumber can be made in any colour and with/without simulated wood grain effects and aesthetically pleasing finishes.

6.1.1 General properties of wood plastic composites

WPC with ≤90% wood fibre or wood flour are possible but optimum properties are achieved with ratios of 40–60% for a given WPC formulation. The proportions of filler and reinforcement plus the types of additives used decide the nature of the properties of the final product. WPC are designed and formulated to meet end-application requirements. The general theory is that for high-end applications it is best to keep the wood flour content 70% whereas, for low-end applications, this content could be much higher.

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WPC are more rigid than natural lumber and have a lower thermal expansion coefficient than polymers. They are available in very attractive finishes, much like high-end wood. Unlike wood, WPC do not splinter easily and can be produced in many shapes and sizes. These composites can be produced by standard extrusion, injection moulding or compression moulding to almost any shape in solid or hollow designs, and large three-dimensional profiles are also possible. WPC producers are constantly on the lookout for improving: retention of physical properties, colour retention, as well as resistance to mould, mildew and water penetration, particularly related to outdoor applications. Constant development is taking place on improving the resistance to weather conditions because most productions of WPC are for outdoor applications such as decking, fencing, and benches.

To achieve good-quality WPC, additives are essential and indispensable, even though they are used in small quantities in a formulation. These additives provide homogenous mixing which results in sufficient stiffness, rigidity and good stability against light and heat. WPC are much stronger than natural lumber and are less prone to warping. Critical contributors to the quality of these composite products are flame retardants because without them their applications will be limited due to building-trade regulations. Flames may spread slowly in WPC but they can become highly combustible due to wood content. However, safety standards for construction and transportation can be met easily with the use of correct fire-retardant additives. Most flame-retardants do not have major adverse effects on mechanical properties while providing ecological and environmental benefits. Non-halogenated flame-retardant additives do no release corrosive gases in the case of a fire and will emit only very low levels of smoke.

6.1.2 Technology of wood plastic composites – the basics

Wood is not the only natural fibre used in polymer composites but is the most common. However, it is expected that the use of rice hulls with emerging technology will take precedence in the future because rice hulls have much better physical and chemical properties.

WPC were first produced and marketed as superior weather-resistant material as compared with natural wood. WPC have rapidly expanded into many other end uses. With the advent and availability of high-end additives and constant development, WPC producers have been able to offer improved products, especially for the construction industry.

The basic benefits of using wood fibre or wood flour with plastics are increases in the modulus of elasticity and lowering of the coefficient of thermal expansion, which result in automatic cost reductions. The standard process for producing WPC lumber is by extrusion, which is technically demanding and requires efficient equipment, with the design of the screw being the most important. Other important

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factors are the moisture content and the particle size of wood flour. For general-purpose applications, after the particle-reduction stage a final pass through a 120-mesh screen may suffice but, if smooth finishes are desired, a pass through a 80/100 mesh is required. Moisture content may vary but should ideally be ≈1% and ≤2%. The choice of additives and fillers is dependent upon the properties of the end applications, whereas colours can be obtained by pigments or masterbatches. If recycled polymers are used and they comprise different colours, then achievement of the final desired colours may be more difficult.

Ground wood fibre may contain moisture content as high as 8–12% by weight depending on humidity. Excess residual water in the extrudate leaving the extrusion die will cause swelling of the WPC profile. Hence, it is essential to remove any excess moisture content well before the compounded mass enters the extrusion barrel. Extruders have de-volatisation capacity using atmospheric and vacuum venting but the amount of water that can be removed from a WPC extrudate is limited. For counter-rotating extruders, the highest production that can be achieved is if the moisture content of the wood flour is dried to ≤1% before it is fed into the extruder. Co-rotating extruders can achieve much better finishes than counter-rotating extruders, and can also tolerate higher contents of moisture in the feed, with a range of 2–4% by weight. For co-rotating operations, reduction of the moisture content to <2% may be counter-productive with lesser throughput because evolution of steam from the extrudate has a beneficial cooling effect.

Counter-rotating and co-rotating extruders can process wood fibre extrudates at moisture levels of 1 and 4%, respectively, but at the expense of throughput. Reducing the throughput increases the time the mass stays in the extruder, which increases the water percentage that has to be removed from the extrudate. If the amount of water in the wood that is fed into the extruder is double the recommended amount (e.g., 2% in counter-rotating extruders and 8% in co-rotating extruders) then, as a general rule, the maximum throughput will be reduced by ≈50%. Extrudates with excess moisture at the die develop localised bubbles under the ‘skin’ of the profile. If the moisture level is sufficiently high, the skin separates itself entirely from the underlying profile as water expands and vaporises.

Wood is a very complex material comprising primarily cellulose and lignin. This is an important fact in WPC production because cellulose and lignin degrade >190 °C. There are two significant mass-loss events in the thermogravimetric analysis of water, with a 5% loss at lower temperature ranges and a possible 70% loss at high temperature ranges due to the decomposition of cellulose and lignin. These values are important in the pre-drying of wood flour before mixing with the polymer matrix. The difficulty of non-satisfactory drying of the wood flour poses problems for WPC producers when considering the temperature ranges for standard extruder operations. Hence, a producer of WPC will be making a profile in which the constituent with the highest weight percentage in a formula is likely to be undergoing thermally induced decomposition as it enters the extrusion die. Preventing this

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decomposition (or at least controlling it adequately) poses a great challenge in WPC extrusion. Common quality-quality problems for WPC arising from thermal degradation of wood are distortion of the extruded profile (known as 'dog boning' or 'swelling').

6.1.3 Market potential for wood plastic composites

WPC have been around for well over 25 years and have been made with various agricultural wastes (though most are made with wood flour). Thus far, WPC are used widely in decking, fencing, and outdoor applications. WPC developers and end users are beginning to realise the great potential that WPC have for wider ranges of applications and thinking 'outside the box' is greatly helping this cause. One application area for WPC that is receiving increasing attention is its use within 'road furniture': guard rails, sound barriers, traffic cones, mileage posts, sign posts, road-lane markers, snow fences and crash barriers. Research has been initiated to work out the possibilities of replacing currently used materials in many of these highway applications, particularly with WPC utilising woody biomass. The relatively low-tech products related to highway infrastructure could provide better opportunities for utilisation of significant volumes of biomasses because they are harvested, processed and used locally.

A range of street-furniture products based on WPC utilising recycled wood and recycled plastics are being marketed by companies in Australia and China and include: bollards, street signs, park and street benches, tree stakes, bin enclosures, parking aids, wheel stops, handrails and posts. Other, perhaps more exotic potential applications being developed include electric-vehicle charging points made from 70% cellulosic wood fibre and 30% PP being developed in Germany to protect cables, power outlets and switchgear as replacements for steel. According to reports, the European Commission in its latest industrial policy has announced six priority areas which include bio-based products, as well as sustainable construction and raw materials. A greater potential exists for bio-plastics and bio-based products, particularly if the plastic content in a WPC were to be biodegradable.

Many organisations have tried to use recycled materials to make WPC but often the only major problem is reassurance about continued supplies over long periods of recycled materials of adequate and consistent quality. Using recycled materials need not necessarily reduce the quality of a final product. In China (where most of the wastes from Western countries are welcomed, especially plastic scraps), a prominent manufacturing company has announced the use of waste wood, waste newspaper and magazines together with two types of plastic bottle scraps. According to their reports, they employ an 'air-laying' (term used in the paper industry) and melt-blending processing methods. *Air-laid composites* made from demolition wood wastes and milk bottles made from PE or beverage bottles made

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from PE terephthalate have properties that did not differ much from composites made from virgin ingredients.

With the *melt-blending* process, composites were made from waste paper, milk bottles made from PE and battery cases or plastic ketchup bottle regrinds made from PP. The quality of the waste-paper products were superior to the ones made with magazines and compared well with products made from wood flour. WPC made from recycled newspaper could itself be recycled further several times, meaning that it could be re-extruded repeatedly with very little degradation. However, the availability of used newspaper is not what WPC producers would like. A steady supply of used newspaper in large quantities is very unlikely because well-established markets in wrapping and packaging are established.

The European Union (EU)-funded *SustainComp* project was commissioned to develop demonstrator products made from bio-plastics reinforced with wood fibres. Some of the products developed were: a cushioning system for electronic devices; an extruded component for bus seats; toy building blocks; an advertising display panel; a compostable cutlery set for catering applications. For all of these items (except the cutlery set), the composites developed were from starch-based bio-plastics filled with wood fibres. Residues from heating and cooking, for example, have been suggested to be possible raw materials for WPC products bonded with appropriate polymers. The polymer resin component is the more expensive one, but WPC can absorb more wood than resins and thus the cost reduction will be significant. Other important considerations are the process ability of the raw materials and their effect on the properties and characteristics of the finished articles.

Use of WPC for decking is by far the largest application area but the potential for using them in other exterior and interior applications are strong. Most of the predicted growth is expected to be in construction applications, most of which will be extruded. Important end uses within the construction sector (besides decking) include siding; cladding; fencing; and window applications. Injection-moulded products have been used in diverse end uses, including paper-manufacturing applications and musical instruments, as well as vehicle and shoe parts, whereas various other processing technologies have been adopted in the automotive sector. Furniture components offer considerable potential for WPC and several products have been marketed. Various studies have forecasted that the dilution of expensive polymers with wood flour to form polymeric composites will become of increasing economic benefit. Furthermore, the end products are environmentally friendly, largely free from rot and do not require painting because aesthetically pleasing finishes can be easily achieved. They are also machinable like natural wood and have practical advantages over traditional products.

Another interesting end application is the production of ‘green’ computer parts, especially computer keyboards. A German moulding company, Amper Plastik R. Dittrich, is using a biodegradable grade of cellulose ester compound to produce the base of the world’s first ecological computer keyboard. This product also

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contains *Arboform*, a colourable and biodegradable material based on lignin from waste wood. The lignin is combined with other natural fibres such as flax or hemp and some polymer resin, and this compound can be injection moulded. Arboform has a ‘PS-like’ feel and properties and compares well with traditionally produced ones.

PCRH will have distinct advantages over WPC with wood flour due to the high content of silica in the rice hulls flour. Thus, one could expect additional and a wider range of end applications due to superior physical and mechanical properties. PCRH technology and products are virtually new but, given time, the demand for them would expand.

6.2 Role of polymers

Common understanding may be that plastic is plastic and that wood is wood. There are a wealth of differences between each type and grade, and a designer of a WPC composite and the producer must have a good understanding of both for successful production. If a combination of polymers is used, the designer must ensure complete compatibility between the polymeric matrices and a good knowledge of their properties that will be needed.

PVC, PE and PP are the most commonly used polymers in WPC extrusion. PVC is suited for counter-rotating extrusion with low screw speeds because it degrades the material if subjected to high shear or temperatures higher than normal standard temperatures. PE and PP are suited for co-rotating extruders because these polymers can withstand high shear and temperatures better than PVC. These features allow co-rotating extruders to achieve throughputs >3,000 lb/h with a screw diameter of ≈100 mm. Because WPC is a ‘temperature-limited’ extrusion process, the rule of thumb for scale-up is the square of the screw diameter of the extruder. For example, given a throughput of 1,600 lb/h on a 73-mm extruder, the expected throughput of a 103-mm extruder is (103/73) 2 × 1,600, which is = ≈3185 lb/h.

PE is probably the most commonly used plastic polymer for WPC. HDPE is used in WPC applications because of its better physical properties than LDPE or linear-LDPE. HDPE with a melt flow index (MFI) of 0.3–1.0 g/10 min (known as ‘fractional melt grades’) are better suited for WPC applications such as decking and other outdoor uses but with limitations. HDPE with very low melt flows, such as 0.2 g/10 min, require higher specific energy to process in the extruder, which means higher melt temperatures. Because the wood content in a WPC mix will degrade at >190 °C, to maximise throughput a WPC producer will have to choose a plastic resin with a high MFI that will give a consistent physical properties as required by the targeted end product.

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6.2.1 Variations in polymer matrices

Plastics are chemically simple but complex with respect to chain lengths, chain configuration, molecular-weight distribution and crystallinity. These properties are seldom measured at WPC extrusion plants but can have a dramatic impact on WPC production. The producers generally depend on the manufacturers of polymer resins for accurate information.

Most of the plastics used in WPC (or in part) may consist of recycled material or part virgin material. WPC producers may also use off-spec virgin material quite successfully. Because the properties of these streams are not tightly controlled, there can be significant variation in the parameters of the extrusion process over time. These variations can affect the maximum throughput volume and scrap rates. Variations in process throughput of ≈15% over a few days are not uncommon. These variations can occur as the same frequency as plastic delivery to the WPC production plant. Measuring the melt index of the incoming plastic polymers gives an incomplete (but still useful) indication of the processing characteristics of a particular plastic resin to be used. However, even this relatively simple measurement is often lacking in WPC producing facilities.

WPC production makes significant use of lubricants as a process aid. Lubricants in WPC have two broad functions. The first is minimising the heat of the exrudate due to shear forces and to limit the melt temperature. The second function is to overcome the no-slip boundary condition on the surface of the profile die so that the profile has a smooth ‘skin’. General lubricant levels in PE-based WPC formulae are ≈3–5% by weight. PP-based WPC formulae generally contain 1–3% lubricant.

In the largest single market for WPC, which probably is outdoor applications such as decking, mechanical properties are important to the installer and the end user of the product. The resistance to bending under a load or the modulus of elasticity of the product determine how much structure is needed to support a deck surface and the ‘feel’ of the deck under the feet of the end user. The product’s resistance to breaking under load or the modulus of rupture is a matter of end-user safety with any deck installation. The importance of cost must also be considered.

Compared with 100% wood, WPC have lower moduli of elasticity and rupture. Coupling agents have been developed to improve the mechanical properties of WPC. The most common coupling agents are maleic anhydrides. These work by improving adhesion of the plastic matrix to the surface of the wood fibre. The benefit of coupling agents must be weighed against increased formula cost, higher specific energy in the extruder, and reduced effectiveness of external lubrication in the profile die. Use of a capstock layer on WPC raises the performance of the product in several ways. WPC are relatively soft and have poor resistance to scratching. The wood fibre in the WPC is prone to attack by mould, colourants, antioxidants and anti-ultraviolet (UV) agents. These factors make the production expensive if distributed throughout the whole profile mass if only the surface has to be protected.

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Thus, a capstock layer of a harder plastic with all these required protective additives will greatly help the final performance of a WPC.

6.3 Production of wood plastic composites

WPC may be one of the most dynamic sectors of the plastic industry. Although the technology is not new, there is growing interest in the new concepts being exploited by WPC producers, which opens the door to a wider range of the end-application possibilities these composites offer. The production of WPC typically uses fine wood wastes such as hardwood, softwood, plywood, peanut hulls, and bamboo mixed with various plastic resins. The mix is compounded to a dough-like consistency and extruded to any desired profile through a die.

Additives such as colourants, lubricants, coupling agents, anti-UV agents, foaming agents, and reinforcing agents are incorporated as formulated to achieve the properties desired for particular end applications. With possibilities of ≤70% wood content, these composites virtually behave like natural wood and can be worked with standard woodworking tools. Selection of the correct compounding and extrusion equipment is very important in the production of WPC composites.

Production of these WPC takes place in two stages. The first is when the polymer matrix and the constituent (e.g., wood flour) are mixed thoroughly and compounded with additives and then made into resin pellets using an extrusion-pelletising system. The second is the conversion of these composite resin pellets to lumber using a suitable extrusion system. The size and capability of the extrusion system will determine the parameters of the profiles: width, thickness, and production rate. Some producers may opt to use sophisticated extrusion systems that can eliminate the pelletising stage and extrude profiles direct from the compounding stage in one fluent and continuous process. Composite resins in the form of pellets are used by injection moulders and compression moulders, and these practices are gaining popularity and momentum, especially because these resins are cheaper.

The technology of producing polymeric composites shows the importance of the planning and designing of suitable matrices, reinforcement and additives to produce practical and cost-effective products to suit pre-determined end applications. The first important factor is that the compatibility of the polymer matrix and the reinforcement materials. The matrix may contain virgin material or a combination of virgin and recycled material, but the moisture content of the reinforcing fibre must be as low as possible (preferably ≈1%) and the smaller the particle size, the better the chance of achieving a homogenous mix. For compounding, additives must be selected carefully.

Coupling agents are essential for achieving polarity. Typically, polyolefins grafted with maleic anhydride act as coupling agents to significantly improve mechanical properties. The polar functional groups of a coupling agent reacts among

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others, with the hydroxyl (OH) groups of the wood to form a genuine chemical bond, whereas the non-polar areas of the coupling agent have strong affinity to the non-polar polyolefin chains. Coupling agents improve adhesion between polymer resins and fibres, which reduces the rate of moisture absorption and increases strength properties such as impact, tensile and flexural strength. Coupling agents also help in the dispersion of fibres, which may allow increased wood content. Most WPC tend to be heavy so, depending on the end application, producers may opt to include a foaming agent in the formula to lighten the end product. In this case, coupling agents aid in foaming with better dispersion and improve melt strength at the extruder die exit.

Lubricants are used widely in the production of WPC to improve extrusion rates. Developers are coming out with excellent lubricants that have better compatibility with other additives and great processing improvements. The demand is for more colour variety, especially dark wood colours, so a wider range of pigment colours is being made available by the producers. Most WPC are used for outdoor applications, so light stabilisers are required to maintain the original colour. Light stabilisers are also essential to aid weather resistance, counter UV rays, and to arrest brittleness due to weathering. Biocides are needed to be added to control mould and mildew, which result in surface staining or discolouration and affect long-term durability. The addition of antimicrobials will protect the wood in WPC against decay and fungi, as well as preventing surface mould growth and slowing down the effects of UV degradation. Foaming of WPC is becoming increasingly important because it offers benefits such as weight reduction, cost reduction and increases stiffness. Foaming makes the WPC more like wood for cutting and fastening as well as for maintaining cost competiveness. Although foaming increases the complexity of the process and may reduce the output rate, savings in raw material will outweigh these issues. High-performance additives transform WPC to a high-end product and continue to drive the demand for these products for challenging applications.

6.4 General applications for wood plastic composites

Since their appearance ≈25 years ago, WPC materials have gained popularity and momentum in outdoor applications and now in building construction (an important application as replacement for lumber). Their aesthetic and low-maintenance properties are continuing to drive growth as an alternative for wood applications. In Asian and the Far Eastern countries, use of WPC is widespread and customers are finding them more durable than natural lumber. Another big advantage the WPC have over natural wood is that they can be easily produced in many profiles to suit end applications, whereas, labour-intensive work is required to turn natural wood into desired shapes and profiles.

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Some of the general applications of WPC are:

- Outdoor decking
- Fencing
- Park benches
- Outdoor chairs
- Window frames
- Door frames
- Partitioning
- Railings

6.5 Long fibre-reinforced thermoplastics

Long fibre-reinforced thermoplastics (LFRT) are discussed here for the benefit of the reader because LFRT are fast growing in importance for applications in the automobile industry. The automobile industry is looking constantly for lighter materials that are also cost-effective: polymeric LFRT are providing them with great possibilities.

LFRT are a recent development in which PP or other thermoplastic polymers are compounded directly with long glass fibres and the moulded. These new polymeric composites are the ‘buzz’ of the automobile industries (particularly in the USA and Europe) and considered to be one of the most important trends in the plastics industry. Glass fibres of length ≈12≤50 mm give much higher stiffness, strength and toughness than the 3-mm fibres used up to now.

LFRT have excellent mechanical properties and stiffness:weight ratios, which is of great interest to the automobile industry. In-line compounding processes for long-fibre materials offer users more flexibility because they can compound and process such materials in accordance with their own formulations and also use ready-made compounds. For this process, gravimetric feeders are used to feed the main polymer as well as the additives. Key features of a feeder to achieve high accuracy over short intervals are resolution of its weighing device and the response of its process controller. Lengthy performance timescales permit a given blending accuracy to be attained with a poor-performing weighing system. However, to achieve the same accuracy in a short interval (a characteristic of continuous mixing operations) a much higher weighing performance is required.

Three processing technologies are used for production: E-LFT, D-LFT and S-LFT. E-LFT is direct in-line compounding and extrusion of LFRT as profiles or sheets. D-LFT is direct in-line compounding and compression moulding of long-fibre thermoplastics. S-LFT is direct in-line compounding and injection moulding of LFRT. All three processes use gravimetric continuous feeders for accurate continuous feeding into the compounding extruder. Long fibre-thermoplastic composite technology uses special screw configurations for single and twin extruders.

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The base polymer is, in general, fed with a single screw extruder or vibratory loss-in-weight feeder. The integrated vacuum receiver is responsible for the steady refill of the feeder. Additives such as colourants and stabilisers as powders or pellets are added *via* smaller loss-in-weight feeders (single or twin screw, vibratory feeders or bulk solid pump feeders). Edge trimmings or recycled materials can be shredded and fed back into the process at a predetermined ratio using vibratory loss-in-weight feeders. Glass-fibre filaments are pulled into the extruder from continuous glass rovings on bobbins by rotation of the screw shaft. The throughput of the fibreglass is volumetric and should be quite steady. Each fibre strand is monitored by a sensor. The gravimetric throughput can also be checked by the bobbins mounted on scales and by measuring weight loss over time.

Most long-fibre thermoplastic end products are produced for the automobile industry. Some of the moulded parts include body panels, sound shields, front-end assemblies, structural body parts, truck panels and housings, as well as doors, tailgates and fender sections. Development is also taking place in other sectors, such as in electrical and building industries.

6.6 Polymeric composites with other fibres

Although wood is one of the many bio-fibres being considered for the replacement of mineral fillers and glass fibres in thermoplastic composites, the American company *RheTech* has recently introduced two other fibres, agave and coconut, into its wide range of products. Coconut fibres can be obtained by grinding coconut shells. Coconut fibres have a high strain-to-failure of ≈30% and major automotive companies such as Ford are investigating the possibilities of using them for automotive plastics. Applications envisaged are various types of trim, storage bins and centre console substrates.

Agave fibres come in many varieties (including sisal) and have been used for a wide range of applications not necessarily connected with plastics. The wood content in WPC must demonstrate cost-effectiveness in competition with several other natural fibres and fillers. Wood has a distinct advantage in allowing a composite to retain many of its characteristics, such as appearance and the traditionally liked ‘woody feel’ in resonance with nature. Dimensional stability in wet conditions can often be a weakness of plant-based fibres. The mechanical properties and flammability of the composite also have to be considered.

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7 Important stages of the production process

A producer of polymeric composites, whether using rice hulls or wood fibres, must have a thorough knowledge of polymers to be used as matrices and also the production process. The design and formulation of the composite mix and the additives, in keeping with the requirements of the end application, is very important in producing good composites. The basic stages of the process are: particle-size reduction, drying to reduce moisture levels of the fibres; mixing and compounding; pelletising; extrusion. Many options are available for the set-up of a processing line, such as individual machinery for each stage or a complete online operation from feeding of the raw fibres to final extrusion of the composite. Here, extrusion is mentioned because probably 75% of polymeric composites with rice hulls (PCRH) are extruded, whereas pelletised composites are injection moulded and this subject is dealt in another chapter. Companies supply rice hull fibres and rice hull flour to customer's specifications, such as moisture levels, particle size, and density, which may have advantages but the cost must be evaluated.

7.1 Reduction of particle size

The chemical, pharmaceutical, food, mining and plastic industries rely on size reduction. This process uses methods such as shredding, grinding of polymers for recycling, extraction of a valuable constituent from ores to facilitate separation of grain components and production of particles of an appropriate size for a given use. There are many methods for particle-size reduction and different equipment which are often developed empirically to handle specific materials.

Knowing the properties of the material to be processed is essential. Probably the most important characteristic governing size reduction is hardness because almost all size-reduction methods involve creating new surface areas, and this requires adding energy proportional to the bonds holding the feed particles together. In industrial terms, hardness can be gauged on a scale from 1 (soft) to 10 (hard). Whether a material is tough or brittle (with brittle materials being easier to fracture) is also important. Other characteristics include particle-size distribution, bulk density, abrasiveness and temperature-sensitivity. Flow properties can also be a major factor because many size-reduction processes are continuous but often have 'choke points', at which bridging and flow interruption can occur. For example, some size-reduction equipment is fed by chutes, which might constrict flow. In general, the feed flows adequately but the crushed particles tend to compact and flow with difficulty. Intermediate storage bins or containers may aggravate flow issues by causing compaction and bridging. Theoretically, softer materials produce finer particles than harder materials. Nearly all size-reduction methods result in some

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degree of fine particles. Hence, unless production of very fine particles is the objective, it usually is more efficient to undertake size reduction in stages, with removal of the desired product after each operation.

7.1.1 Equipment used for reduction of particle size

Size-reducing equipment relies on compression or impaction. Compression is applied *via* moving jaws, rolls or a gyratory cone. The maximum discharge size is set by the clearance, which is adjustable. Impact-based equipment commonly uses hammers. Continued size reduction increases the number of particles and the amount of surface area per unit of volume. Size reduction also modifies the physical characteristics of ingredients, resulting in improved mixing, pelletising and, in some instances, handling and transport. In the case of production of polymeric composites, particle-size reduction of rice hulls enhances blending of the mixture of rice hulls and polymer matrix.

Rolls, in particular, can produce very fine particles. Rolls are used in flour milling, in which crushing yields different-sized particles, allowing separation of purified flours. Here, moisture content is important so that, for example, the bran is soft and remains in large pieces, whereas the endosperm is brittle and fractures into small granules. Corn can be separated from starch and other fibre by roller milling because it selectively absorbs water and is made into flakes, whereas the starch fractures. Roller mills accomplish size reduction through a combination of forces and design features. If the rolls rotate at identical speed, compression is the primary force used. If the rolls rotate at different speeds, shearing and compression are the primary forces used. If the rolls are grooved, a tearing or grinding component is introduced. Coarse grooves provide less size reduction than fine grooves do. There will be little or no noise or duct pollution associated with approriately designed and maintained roller mills. Their slower operating speeds do not generate heat and there is very little loss of moisture. Particles produced tend to be uniform in size, meaning very little fine material is generated. The shape of the particles tends to be irregular; more cubic or rectangular than spherical. The irregular shape of the particles means they do not pack as well. For similar-sized particles, the bulk density of material ground on a roller mill will be ≈5–15% less than material ground by a hammer mill.

Impact mills use revolving hammers to strike incoming particles and to break or fling them against the machine case. The hammers might be fixed, or more commonly, pivoted. Typically, the hammers can be reversed to provide added life before they need to be replaced. In jet mills, particles strike each other as they are transported in a stream of air or steam. For the initial reduction of the large materials, a rotating drum propels the feed into the air, where the pieces strike each other and fracture.

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Hammer mills reduce the particle size of materials by impacting a slow moving target, such as a rice fibre, with a rapidly moving hammer. The target has little or no momentum (low kinetic energy), whereas the hammer tip is travelling at ≥4,880 m/min and perhaps >7,000 m/min (high kinetic energy). The transfer of energy that results from this collision fractures the fibres into many pieces. Sizing is a function of hammer-tip speed, design and placement of the hammer, screen design, hole size, and whether or not air assistance is used.

Because impact is the primary force used in a Hammer mill to reduce the size of particles, anything that increases the chance of a collision between a hammer and a target increases the magnitude of the collision or improves material output, and is also advantageous for particle-size reduction. The magnitude of the collisions can be escalated by increasing the speed of the hammers. If the drive speed and screen size is kept constant, the increased hammer-tip speed obtained by increased rotor diameter produces particles of smaller mean geometric size. Particles produced using a hammer mill will, in general, be spherical, with a surface that appears polished. The distribution of particle sizes will vary widely around the geometric mean, such that there will be some large-sized and small-sized particles.

Ball, pebble and *rod mills* are rotating cylinders that are partially filled with metal or ceramic balls, flint pebbles or rods. The units can produce very fine powders, such as pigments for inks and paints. The crushing mechanism is a combination of impact with the grinding media and shearing between the media and the cylinder walls. A variation is a *jar mill*, in which relatively small ceramic containers holding some grinding media are rotated on a machine. It is ideal for small batches of materials for testing and for laboratory purposes.

For size reduction of polymer resin wastes, standard machines such as *shredders, granulators, pulverisers* and other types can be used. If virgin polymer resins are used, they can be used directly.

7.2 Drying of rice hulls

Paddy farming or rice farming is generally done on a large scale. Because of the sheer volume of the harvests, a farmer after the process of milling (in which the grain is separated from the hulls) is very likely to heap the hulls outdoors, out in the open exposed to the elements, or may store it in large sheds. Thus, hulls will absorb some moisture and become dry if sunlight is available and this cycle is repeated. The net result is that if a producer decides to avail himself of the hulls in this condition for whatever reason (e.g., close proximity to his/her plant, easy transport, economic reasons), drying of the material in bulk will have to be carried out before the final extraction of moisture to achieve the desired moisture levels before compounding with the polymer matrix or additives. For these two operations, different drying systems must be used.

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7.2.1 Bulk drying systems

There are many drying systems and, for the benefit of the reader, a wide spectrum of drying systems is presented here in general terms. There are three basic methods of removing moisture from materials such as: air dryers, infrared (IR) dryers and spray dryers. Air drying brings the material to be dried into direct contact with hot or cold air. It is the most widespread method and is used by *flash dryers, freeze dryers, fluid bed dryers* and *rotary dryers* for applications for food processing, paper production, pharmaceutical, pollution control and agricultural industries. IR dryers use energy from IR wavelengths to remove moisture from the inside out, without overheating the material. In spray dryers, after any solid material is separated it is directed into a spray of hot steam that quickly causes moisture to evaporate. Drying can be done in batches or in a constant stream in continuous dryers, which are frequently also conveyor dryers. Conveyor dryers use a conveyor belt to move the material through a dryer. Both are commonly used in air-drying systems.

Most drying units used in small operations (e.g., at home) are simple air dryers. Air warmed by gas or electric heating elements is dispensed into a machine and interacts with the material or any items inside. The moisture evaporates and the resulting vapour leaves through an exhaust vent. Rotary dryers (sometimes referred to as ‘drum dryers’) use hot air to heat a rotating drum. Wet materials are placed inside and may pass through multiple chambers before completing the process. Air may come in direct contact with each compartment or may be held in a separate chamber whose radiating heat will be adequate to dry the material. Many powders are dried this way, including industrial chemicals. Flash dryers can be classified as air dryers so long as air is the heat source used for drying. A short burst of high heat can be used to dry the material quickly as it passes through the drying duct.

Fluid bed dryers use a permeable surface to support the materials. Air or gas is heated and released into the dryer until all particles begin to vibrate slightly. The vibration indicates that the velocity of the air slightly exceeds the velocity of gravity. This type of drying is often used for materials that are mostly uniform in size. Technically, freeze dryers are air dryers except that, in their case, the air reaches such a low temperature that sublimation occurs and materials become so cold that all moisture freezes. The solid moisture (ice) is then given just enough heat that it becomes a vapour, bypassing the liquid stage altogether and leaving the material dry.

IR dryers do not use air to dry materials. Instead they harness heat energy from certain wavelengths of electromagnetic radiation. IR radiation is absorbed by solid matter and so dries from the inside out. By matching the absorption characteristics of the material, the drying process is efficient in terms of time and resources.

Demand for the latest and most cost-effective dryers in all aspects of their functions have led to innovations and new technologies. Improvements in material

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management, manufacturing techniques, and new technologies have impacted the constant demand for more efficient and cost-saving machines.

7.2.2 Summary

- *Air dryers* are the most common type of industrial dryers. The material to be dried comes into direct contact with heated air dispensed by the machine.
- *Continuous dryers* remove moisture from a constant flow of material that enter the dryer, are dried and then exit, all without stopping.
- *Conveyor dryers* use a belt to move materials through a dryer at a continuous feed rate. Agricultural materials are often dried on a belt or similar conveyor dryer system.
- *Compressed air dryers* remove water and other contaminants from compressed air and the lines that carry it. This is done *via* refrigerant or desiccant processes.
- *Desiccant dryers* remove water and moisture from a material by absorption of grainy materials such as silica gel or activated alumina.
- *Flash dryers* are industrial dryers that dry a material during exposure to a short burst of intense heat. Water sludge is often dried this way at water-treatment plants for easy removal of contaminants.
- *Fluid bed dryers* force heated gas through a permeable surface, where it comes into direct contact with a bed of solid materials, causing the moisture inside them to evaporate.
- *Food dryers* remove moisture from fruits, vegetables, meats and other edible products. Dried foods preserve nutrients, colour and flavour while reducing weight and volume, making them easy to pack and transport.
- *Freeze dryers* are used to dry heat-sensitive material such as chemicals in small batches.
- *Gas dryers* use gas to heat and dry a material as desired. These dryers are quite common.
- *Industrial dryers* are used for removing moisture from materials in a business or manufacturing process.
- *IR dryers* are used most often for the curing of water-based inks and coatings.
- *Rotary or drum dryers* can be gas, liquid or solid fuel fired and pass material through a heated rotating drum. Sometimes these drums will have multiple chambers that allow longer passes to get through the drum.
- *Spray dryers* take a material such as wet powder and spin it centrifugally, then direct a line of spray of the material into a drying chamber, which rapidly dries the material. This type of dryer is also called a *dispersion dryer*.
- *Vacuum rotary dryers* are used for applications in which low-temperature drying of a material is desired, as in the chemical and pharmaceutical industries.

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7.3 Mixing and compounding

Mixing and compounding is a very important stage in the production of composites with rice hulls. Formulation must be carried out carefully with the end application in mind. Selection of the polymer matrix, the minimum specifications for the rice hull flour or rice hull fibre, the additives and colour requirements become very important for a successful composite. Once the formulation has been finalised, the next step is mixing and compounding to obtain a homogenous mass that can be fed into an extruding system for further processing as pellets or profiled extrusions. Depending on the volume of production, there are many types of mixers and compounding systems, which may comprise a single-screw extruder, twin-screw extruder or multiple-screw compounding.

7.3.1 Industrial mixers

Blenders and dispensers are used throughout the composite manufacturing industry. Basic applications include simple blending of dry powders to the sophisticated dispersion of solids into high-viscosity fluids. Some in the range of mixers include double planetary mixers, planetary dispensers, high-shear mixers, horizontal ribbon, tumble and vertical blenders. The success of composite chemistry can go so far as the ability of equipment used to the cost-effectiveness of the composite. For this purpose, the process engineers and composite producers are aware of the latest mixing technologies available.

7.4 Single-screw compounders

Twin-screw compounding extruders are the preferred choices for large industrial compounding processes. However, a ‘quiet revolution’ has been taking place over recent years with sustained research and development, and many single-screw compounding extruders are now coming on the market. For the first time in decades, several genuinely efficient single-screw compounders are available, some of which are the result of advances in flow simulation and computer-aided design, whereas some are improvements in metal cutting. Some of these machines can be used in-line with extrusion and injection moulding.

Until recently, screw designers have tried to improve single-screw mixing with variations on decades-old designs such as fluted cylinders, densely flighted screws, and the ‘pin’ or ‘pineapple’ mixer, among others. Compounders who want more dispersive action could also add separate devices onto the end of an extruder such as a cavity-transfer mixer, which has pockets in the rotor and barrel that push and

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pull the melt for extensional mixing or a planetary gear mixer, in which a short screw is ringed by six smaller ‘orbiting’ screws.

Among the newest single-screw mixers are devices with floating rings. These mixers have a smooth cylinder that ‘floats’ around the screw and has rows of holes around the circumference. The ring rotates more slowly than the screw. The rotor inside the cylinder has hemispherical ‘dimples’ or depressions, corresponding to the holes in the ring. The combination of holes and depressions combine to force the melt to move forward and backward. More rotor-stator systems, plus barrier designs and other types of mixing sections also number among recent developments. The new mixing designs do not claim to match the efficiency of twin-screw mixing but they do a better mixing job than previous single screws, thereby boosting the properties of finished parts, allowing higher colour concentrations and also permitting quicker colour changes. They are supposed to also improve the homogenisation of ingredients and give better output by ≈25%.

7.5 Twin-screw compounders

In addition to the already established suppliers of twin-screw extruders, the advent of new companies makes choices for the buyers more complicated. For example, several new manufacturers of twin-screw compounding extruders have entered the North American market during the past few years and this fact, combined with the expanding product lines from well- known companies, has widened the field of choice enormously.

The two main types of twin-screw extruders for compounding are co-rotating intermeshing and counter-rotating non-intermeshing extruders. A third, a twin-screw counter-rotating intermeshing extruder, operates at low screw speeds and is used primarily in polyvinyl chloride (PVC) processing. The second major group of extruders considered are twin-rotor continuous mixers, which use ‘wing-type’ rotors, similar to those in Banbury batch mixers, rather than screws to accomplish mixing and do not generate high pressures. These machines are based on the concept of continuous mixing but, for compounding mixtures for composites with rice hulls, it is recommended that twin-screw compounding extruders be used.

7.5.1 Basic characteristics

Twin-screw compounding extruders use varying degrees of distributive and dispersive mixing to combine two or more materials into a homogenous mass. Distributive mixing blends the components uniformly in the mixture. In dispersive mixing, materials undergo changes in physical characteristics such as reduction in agglomerate size. Both types of mixing require mechanical shear energy to be transmitted

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into the polymer matrix, created by the screws rotating against the walls of the extruder barrel. Where these machines differ the most is in what happens to the material in the shear field at the apex, where the two screws meet.

Screws of the co-rotating intermeshing types convey materials forward in a ‘figure-eight’ pattern. In general, materials alternate between moderate shear against the walls of the extruder barrel and high shear in the apex region. Shear-inducing kneading blocks can be added to increase dispersive mixing and specialised screw elements can be added for distributive mixing. Non-intermeshing screws impart only minimal shear at the apex. Materials processed with non-intermeshing screws experience moderate shear against the barrel walls, then relax in the apex region. In these machines, the rotation of material in the screw channel and interchange of material between the screws is said to provide constant distributive mixing. Compounder sections can be added to provide higher shear for dispersive mixing.

Also using the counter-rotating non-intermeshing principle is a number of twin-rotor continuous mixers. One feature of these machines is that they separate mixing and pumping functions. Freed of the restrictions of combining pumping and mixing in the same barrel, these types of machines reportedly have the flexibility to optimise mixing for a wide range of materials. Forces on bearings and components are radial and not axial because in twin-screw extruders shearing takes place mainly between the tip of the rotor to the barrel wall. Because there is little thrust, more energy can be directed into mixing.

7.5.2 Co-rotating intermeshing extruders

The largest group of new suppliers of machines in recent years has been for co-rotating intermeshing twin-screw extruders. One important overall trend in twin-screw compounding is the ability to process increasingly greater volumes for a given size machine. Several manufacturers of co-rotating intermeshing twin-screw machines claim to offer machines that maximise free volume or the free space in the barrel that determines volumetric processing capacity. Free volume may be defined by the centreline distance between the screw shafts and the outer diameter (OD)/inner diameter (ID) ratio of each screw.

Three distinct benefits if higher free-volume processing are:

- Fluidisation can be minimised when feeding powdery materials, which permits higher throughput rates.
- Residence time can be maximised, allowing higher throughput rates on some chemical reactions and formulations of highly divergent viscosities.
- Vacuum entrainment can be minimised, allowing higher volatile levels to be drawn from the process. In addition, its clamshell barrel design can be an effective screw design tool.

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According to specifications, some screws have two channel depths at the same screw diameter whereas in some, the screw flights are deeper and the root of the screw is reduced. According to the manufacturers, the larger free volume, coupled with high-torque capability, results in higher throughput.

Another important aspect of the free-volume issue is the ability to transmit power through the shaft to the material. The relationship between free volumes and power varies with different machines and suppliers. Technical reports claim that a 1.55 OD/ID ratio for the latest super compounders optimises the balance between free volume and power for a wide range of materials, and also provide high torque, which aids faster processing. An added benefit is that the power per unit of free volume is constant, making scale-up easier because of consistent shear rate from one size to the other, assuming the same degree of channel fill.

Another related trend in co-rotating intermeshing twin screws is their ability to run at increasingly higher speeds. Some extruders can reach very high speeds, especially on the larger ones. At the higher speed ranges, the limiting factors are process-related (i.e., whether it is possible to maintain product quality at those high rates). Other limiting factors may be wear-related, as with abrasive fillers. Composite processing with rice hulls poses this problem because the mixture will contain silica from the rice hull flour and will also generate extra heat. However, extruder manufacturers have overcome this problem with specially designed screws. For non-abrasive mixtures, higher speeds can be achieved easily. Shear stress can often be minimised by screw design so that even some temperature-sensitive materials, such as polycarbonate (PC), can benefit from higher outputs.

7.5.3 Counter-rotating non-intermeshing extruders

Suppliers of counter-rotating non-intermeshing twin screw machines bring several advantages to feeding, mixing and venting, with some machines that can be converted into all major operating modes. One advantage of this type of machine is maximum free volume, which is the result of two related design factors inherent in non-intermeshing screws: (i) greater centreline distance can be achieved between screw shafts; and (ii) flight occlusion (in which the wiping function of screw flights against the root of the opposite screw takes up some volume). A third point relates to flexibility. Because the screws do not intermesh, it is possible to vary the root diameter to provide much-needed shear energy for the application. Some process engineers think that counter-rotating non-intermeshing machines may provide higher output rates of ≤30% than co-rotating intermeshing machines of the same screw diameter. The non-intermeshing screw configuration also has implications for power. This extra available horsepower for the same screw diameter enables its machines to handle greater speed, volume and length-to-diameter ratio (L/D).

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Counter-rotating non-intermeshing machines are well suited to distributive mixing and provide a high degree of flexibility and control of the shear energy imparted. One advantage of the low-shear field in the apex is that it reportedly permits relatively high screw speeds in compounding shear-sensitive materials. If more shear is needed, compounder sections may be added. Staggered screw flights provide cross-channel and radial back mixing. Interestingly, non-intermeshing extruders decouple mixing efficiency from screw speed so that mixing remains relatively efficient at low speed. These machines also have advantages in terms of feeding and venting. In feeding, the downward motion of the counter-rotating screws is said to allow wider openings across both screws and to promote better feed acceptance. The same principle applies in venting, in which wider openings are provided directly above the apex.

7.5.4 Continuous mixers

Twin-rotor continuous mixers are distinguished from twin-screw extruders in that they do not generate pressure. These counter-rotating non-intermeshing machines segregate mixing and pumping functions, the latter of which may be undertaken by a single-screw extruder or gear pump after the mixing section. They have a conventional screw configuration only in the initial feeding and melting section. Intensive shearing in the mixing section is created between the rotors and chamber walls, coupled with kneading between the rotors and a rolling action of the material itself. A wide range of materials can be run on the same configuration by adjusting certain process parameters, such as the temperature of water circulating through the barrel jacket, rotor speed or volume control. Ample clearance between the rotors as well as between rotors and the chamber barrel is said to be an advantage for mixing abrasive materials.

7.6 Pelletising of polymeric composites

When thinking about pelletising, probably the first thing that springs to mind is the traditional compounding, extrusion and pelletising of the polymer melt into standard-size pellets for easy processing. There are different methods of pelletising, for example, standard extruded strands, cooling of strands and cutting to desired sizes, and pelletising under water. If standard polymers are compounded and then pelletised, it is more or less a simple processing method for which many lines are available and which may differ in procedures for different polymers to be fine-tuned for optimum quality and output (although the basics are the same). However, in the case of pelletising polymer composite melts, different parameters have to be met.

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Although it is easier to process and produce polymeric composite profiles starting from composite pellets, it is equally practical to produce polymeric composite profiles from basic raw materials in a complete in-line processing unit. The advantage of pelletised composite resins is in terms of injection moulding and compression moulding. In general, it is accepted that the biggest volume of plastic processing is in injection moulding, so the importance of pelletised composite resins will increase. Production of polymeric composite profiles by extrusion is by far the greatest volume in polymer composite processing.

Worldwide, the so-called polymer composite wood plastic composite (WPC) has gained in importance. However, with the introduction of PCRH, this will take precedent over other materials, especially because they will have better properties and a wider range of applications. Agri-fibres are considerably cheaper than using 100% pure polymer resins but there is the exciting possibility of replacing natural wood in the long run.

Manufacturers of conventional strand pelletising systems have been supplying the plastic industry with newer models for many but the advent of bio-plastic composites brings the need for new processing technology. Manufacturers of underwater pelletising systems (who have production been in this business for a long time) claim that using underwater pelletising systems allow higher bio-filled composites from 40% (conventional) to 65% (underwater systems). Due to the development of pelletising systems, many newer models are appearing on the market and a producer of polymer composites will have the option of using these systems or even opt for a custom-made system to suit a particular polymer composite formulation. Also, a significant feature of the newer models is that one system can produce different sizes of pellets on the same run.

PCRH are rapidly becoming more important in the plastic injection moulding industry because these moulders are getting more comfortable with using them while realising the importance of reduced resin cost. A separate chapter on this subject is presented later.

7.7 Processing of polymeric composites by extrusion

The largest volume of polymeric composite products, whether they be WPC or PCRH, are produced by extrusion. Other emerging processing methods are injection moulding and compression moulding, in which the composites must be resin pellets for easy moulding, unlike in extrusion, where the material components can be mixed, compounded and processed in a single in-line processing operating system. More than 75% of polymer composite products are made by extrusion, so this chapter will deal with the basics of extrusion technology.

Extrusion is a process by which a thoroughly softened plastic mass is forced through an orifice or die of pre-determined shape and size, which is called the

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extrudate. To extrude a thermoplastic mass, first it must be softened by heat so that it can flow freely and be shaped through the die. This softening by heat is called *plasticisation* or *thermal softening*. The machine that carries out this process is called an *extruder* and may consist of one-, two- or multiple screws that rotate inside the extruder barrel to mix the plastic mass thoroughly and then push the molten melt through the orifice or profiled die to produce extrudates that are usually cooled by water. Extrusion is a continuous process and after the cooling station a haul-off system with cutting equipment decides the length of an extrudate.

A shape or profile is obtained by a die, but the size of the extrudate is dependent upon the size of the extruder, which is generally defined by the screw diameter (e.g., 25, 60 and 120 mm). The important aspect of a screw is its L/D and its configuration. Different types of screws are used for different grades of plastic resins (e.g., polyethylene (PE), polypropylene and PVC) to obtain the maximum output and quality of product. There are also universal screws that may be used for the processing of many plastic resins without having to change from one polymer to another. For PCRH, specially designed screws are required due to the generation of heat and abrasiveness because of silica in the rice hulls and polymer mix. Strictly speaking, instead of an extruder, the correct term should be an 'extrusion system' because an extruder cannot carry out any processing by itself. An extrusion system will consist of several units, and terms such as *post-extrusion line* or *downstream equipment* are associated with an extrusion process. A typical extrusion line with automatic or semi-automatic operation for processing polymeric composites with rice hulls would consist of the following basic equipment:

- Material drying station.
- Particle size-reduction station.
- Mixing and compounding.
- Extruder, screw(s), feed hopper, zonal heaters, motor and drive, cooling fans, control cabinet, extruder head, profiled die, extrudate sizing station, extrudate cooling station, haul-off or take-up station and cutting station.

7.8 Extrusion guidelines

Whichever type of extruder is used for polymer processing, there are certain basic rules a producer should follow to maximise production and make quality products. In the case of processing pure polymers, one may say it is straightforward, with the material being introduced directly into the hopper, heated in the barrel and pushed *via* a screw through a die to make a pre-determined profile. It is more complicated in processing polymer composites and more so if other constituents such as wood fibre or rice hulls are involved. Here, three additional conditions must be met before extrusion of the mass:

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- Adequate drying to remove moisture from the reinforcing constituents.
- Particle-size reduction of these constituents for easy mixing and compatibility.
- Specially designed screws are required to counter the abravesiness and extra heat build-up.

7.8.1 Extrusion screws

In general processing of plastics, different screws are used for different polymers or a universal screw to achieve maximum homogenous mixing and good flow properties. A screw comprises three main areas: feed zone, compression zone and metering zone. All three areas combine to force a smooth, well-mixed hot melt through a profiled die. The heat in each zone must be rigidly controlled with set temperatures to ensure smooth mixing and flow as well as to avoid degradation due to excessive heat or excessive dwell time in the extruder barrel. Most commercial plastics are poor conductors of heat, have poor thermal stability but have high specific heat. This means that materials degrade if overheated or if are not conveyed at the right speed along the barrel of the extruder, and so the melt temperature of a particular polymer becomes important.

7.8.2 Melt temperature

The melt temperature of a material or a mixture is, in general, measured in the die or extruded into the air, in which case great care should be taken to prevent accidents from the very hot melt. A hot melt is sufficiently hot to cause severe burns and also to adhere on skin. Protective wear is needed, especially if starting an extruder or purging at the end of a run.

7.8.3 Temperature settings

The melt temperature is important in extrusion. A supplier of plastic resins will give guide temperatures. In general, the first heat zone (zone 1) is set at the lowest temperature and increased gradually along the barrel up to the die, where the temperature may be set lower than the last zone. Temperature affects the final finish and the output, so constant control of the temperature gradient should be monitored and maintained throughout extrusion. Technological advances make this possible without problems. The temperature settings for polymeric composite mixtures with rice hulls differ from standard polymer extrusions, and a producer of composites will have a choice between trial-and-error or a laboratory test, which will stop a lot of material being wasted.

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7.8.4 Extruder warm-up

The heat supply to an empty extruder should be done with care so that the heating is done within a reasonable time and does not overshoot. Before the material is introduced into an extruder barrel, it should be allowed to equibrate and settle down by running a small batch of the material through the die and checking the melt temperature with a melt probe before starting the production run.

In the event of a stoppage, for example, due to a power failure or a stoppage overnight (which in the case of low-density polyethylene (LDPE) can be left in the barrel), care should be taken to ensure that decomposition or degradation of the material in the barrel does not occur. If this happens, pressurised gases will blow or shoot out hot plastic melt through the die, which can cause serious accidents to operators. The correct procedure is to heat up the barrel below the actual melt temperature of the mixture and equilibrate and slowly increase the temperature of the die to above the melt temperature. The temperatures of the front zone and back zone must be increased to above the melt temperature and then one must work towards the middle zone. Finally, the desired temperatures can be set for all and the extruder allowed to equilibrate before extrusion starts. The time factor is important to avoid material degradation in the barrel.

7.8.5 Heat supply

The actual heat needed to plasticise the composite mixture comes from the barrel heaters and the screw speed. Sometimes the heat generated by the rotating screw is so great that the heat is excessive. In this case a balance must be maintained between the heaters and cooling of the barrel to maintain the required temperatures.

7.8.6 Die heaters

In polymeric composite extrusions, most dies could be profiles of various cross-sections. If a die is divided into more than one zone, better temperature controls can be achieved. In general, electrical heating elements are used with thermocouples as sensors and electronic controllers. There are different types of heaters, such as cartridge heaters, band heaters, and plate heaters. Selection and use of the correct power rating for a heater is important to ensure that dies heat up to the desired temperature in a reasonable time. The three main factors involved in the calculation are: the weight of metal in each zone of the die; the target time desired to reach the required temperature; and the specific heat of the metal used. To compensate for heat losses from the surface of the die, the calculated power rating in kilowatts should be increased by 30–40%.

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Dies are made from metals and are mounted on extruder heads. A basic design comprises three sections: the adaptor (which links with the extruder), the distributor section (which speeds the hot melt into the correct shape or profile) and the land (which maintains a constant cross-section to the flow channel before reaching the die exit lips). If designing dies, some of the important areas to consider are:

- Extrudate shape
- Degradation of melt
- Die design
- Required surface finish
- Blocking due to contamination
- Back pressure from die resistance
- Die maintenance

PCRH are extruded in various profiles such as solid sections, hollow sections and various other profiles. Thus, the design and size of dies becomes important.

- ***Extrusion speeds***
  Some of the heat needed to plasticise the melt is provided by rotation of the screw. The faster the speed of the screw, the higher is the temperature. This phenomenon is due to the increase in the speed of the screw surface, resulting in an increasing amount of shear. To counter localised overheating in the barrel, as a general rule, larger machines are worked at lower speeds, whereas smaller machines should work at faster speeds, which will keep down the shear rate.

- ***Zonal heating***
  An extruder barrel, in general, consists of three regions or zones: feed, compression and metering. Each of these zones has its own heating and cooling systems. In general, small machines will have three zones, whereas the large machines can have up to 12 zones. Each zone can be controlled and monitored independently using microprocessors and other equipment. The required parameters can be set to adjust automatically but these are the barrel temperatures. The more important parameter is the melt temperature of the plastic composite mix, which is also dependent on the rotational speed of the screw and the back pressure.

- ***Extruder venting***
  Some materials develop gases if heated, and an extruder barrel must be provided with approriate venting to allow them to escape. In most cases, it could be air but it could also be vapour, especially if a monomer resin is used. If venting is not available, the gases would be carried along the barrel to the die, thereby causing bubbles in the emerging extrudate. A vent, a hole or a port in the barrel allows gases to escape, preventing excessive pressure build-up inside a barrel, and these openings could be plugged if not required.

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- ***Extruder screen packs***
  Extruder screen packs are an important feature, especially for the extrusion of polymer composites. To achieve a good-quality melt requires a good homogenous mixture, use of even heating, and employment of the correct type of screw(s). This operation must also provide sufficient back pressure, which will enhance additional uniform mixing. Screen packs supported by breaker plates at the front are used to build-up pressure and for this purpose valves and choker plates are also used. Valves can be adjusted to maintain the required pressure, whereas a choker plate consisting of fine steel mesh is placed next to the breaker plate followed by another set of mesh. An extruder may have several choker plates with the last one having the finest mesh. This assembly is placed inside a recess in the breaker plate, where it is held *in situ* by a screwed-in plate. The breaker plate will have large holes which allow the hot melt to pass through and reach the screen pack. The fine mesh screen will hold back foreign particles or contaminants from going through the die. The screen packs can be changed while the machine is running (manually or automatically).

- ***Cooling of the extruder barrel***
  In general, cooling systems are air or water. Each system is switched on by the same controls as the heaters. The simplest are air blowers or fans, which come on if the set temperatures are exceeded and the heaters go off. If water is used, direct and indirect systems are employed. In a direct system, water travels through a coil or channels on the extruder barrel. Indirect systems use water to cool a vapour inside tubes, which condenses and falls back along the tubes into a coil which surrounds the extruder barrel. This cycle is repeated and continued. Different cooling systems may be used but the main purpose is to have uniform cooling of the barrel.

- ***Cooling of the extruder screw***
  If necessary, cooling of the extruder screw can be done by circulating water through a bore or drilling from the rear of the screw. In general, this is done to: (i) overcome a material-feeding problem; (ii) improve mixing; and (iii) counter excessive generation of heat. If it is the first reason, then only cooling of the feed section of the screw is enough and, if it is for the second and third reasons, then cooling should be along the screw. For the extrusion of PCRH, extra heat will be generated due to silica in the rice hulls.

- ***Purging of the extruder barrel***
  Some polymers degrade relatively easily. For example, PVC cannot be left in the barrel at shutdown because it cannot withstand heating on the next start-up. Degradation or burning of material will take place with decomposition, creating gases inside the barrel that can cause serious problems. To prevent this happening, purging materials such as LDPE or polystyrene (PS), which are

more heat-stable, is done to keep the barrel dry at shutdown. At purge time it is advisable to remove or open the extruder head assembly to allow for easy flow and to avoid mixing with the resins.

- ***Cooling of the hopper block***
  Some extrusion systems use cool water to pass around the hopper throat. This ensures that the material enters the feed section of the screw freely. Variation in the temperature of the water source should be avoided and it is best to use a closed loop water recirculating system to ensure that the melt temperature is not affected.

- ***Guidelines for extruder start-up***
  When we talk of an extruder in terms of an extrusion set-up, the whole system is involved. Before starting the extruder(s), all the connected equipment should be started and checked for smooth working and shut down temporarily and restarted before the extruders commence processing. The start-up time of an extruder is the most dangerous time of an extrusion process. If material is left in the barrel from a previous operation, it may decompose and spit out from the die and accessories. Special care should be taken by an operator as he/she has to come into direct contact with the machine to fit the die and accessories. The operator should follow the following basic rules:
  - Review all data and machine settings
  - Ensure all tools required are at hand
  - Wear protective gear
  - Turn power on and set temperature specifics
  - Allow the melt to flow freely until the correct melt temperature is reached
  - Start the extrusion process

  Extrudates coming out of the die must be cooled and many systems are provided by machinery suppliers. In general, water, air or other means are used for cooling, which should be sufficient to prevent warp. Profiled extrudates sometimes take the form or complex or unsymmetrical cross-sections. In such cases, the dies must be designed carefully to achieve uniformity. Extrusion systems have electronically controlled methods that are fully computerised to control wall thickness with an image of the cross-section on a computer for easy monitoring and adjustment (if necessary).

- ***Guidelines for extruder shutdown***
  Different extrusion systems may have different shutdown procedures. However, it is important to work out a sensible and trouble-free shutdown procedure for your system to save time and money. Shutdowns can be due to various reasons, such as power failures, machinery breakdowns, temporary repair, or a shortage of material. For example, during a stoppage due to a temporary repair, one can

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periodically pump the extruder by passing material at a minimum screw speed without allowing molten resin mix to build up inside the barrel. Also, the temperatures can be lowered so that the material inside will not heat up and degrade.

If the shutdown is at the end of a run and the machine has to be emptied due to an unstable material (e.g., PVC), the following steps are recommended:

- Lower temperatures on cylinder heaters.
- Keep die heaters on.
- Put barrel cooling on maximum.
- Purge barrel of material at low speed.
- Watch the pressure gauge (a rise will indicate cooling of the material).
- When the material is relatively cool, close the hopper.
- Using a purging material such as PE or PS to purge the screw dry.
- If no material is coming out of the die, slow then screw speed and then slow it to zero.
- Turn all heaters off and keep barrel cooling on maximum.
- Open the extrusion head, remove and clean the die and the head. A light coating of silicone grease can be applied.
- When the machine is cool, turn off the water supply and main power.

If the extruder is to be left full at the time of shutdown, e.g., using LDPE:

- Lower temperature settings on the barrel.
- Leave the die heaters on.
- Put the barrel cooling on maximum.
- Pump material through the machine while it is cooling.
- When the material coming out is relatively cool, close the hopper gate.
- Keep reducing the screw speed slowly to zero.
- Put barrel cooling onto the automatic setting and ensure that the water cooling is on.
- Turn off the water cooling.
- To restart, follow the warm-up procedures as set out above.

These recommendations are, in general, based on the standard processing of polymer resins but will be more or less the same for processing PCRH. However, a producer will have to work out parameters and procedures which are best for his/her operation. The suppliers of machinery will provide vital information on the technicalities of each machine and in most cases work with the buyers with regard to installation and the initial production trials. An advantage in the processing of polymer composites is that a producer will buy customised machinery to suit the operation.

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8 Colouring of polymers and composites

8.1 Introduction

Although synthetic materials are man-made, it is not unreasonable to think that they are in harmony with nature. Rice hulls, wood and other cellulose-based constituents in a well-balanced blend with synthetic plastics resins are known as polymeric composites with rice hulls (PCRH) and wood plastic composites (WPC), respectively. WPC have been around for some time, particularly in applications such as decking and fencing, but perhaps the importance of coloured products may not have been significant. Now, with the advent of PCRH in a wider range of applications (e.g., outdoor; indoor; building construction; furniture; automobile parts; and sportswear), coloured products are of immense importance. Therefore, designers, developers and producers of polymeric composites must have at least a basic knowledge of colour. This is a speciality area and there are many manufacturers and suppliers from whom ready-made colourants can be purchased. The trend with WPC producers has been in-house experimentation with various combinations for composites, and this will be even more so for PCRH with a wider range of applications. Thus, a basic knowledge of colouring, blending and methodology will be of tremendous value to improve products but cost-effectiveness will also be a key factor.

Colourants can be ranked according to their tone; pigment class; colour index; opacity; light-fastness; tinting strength; and physiological/chemical properties. Unlike pigments, colourants are soluble in plastics. Manufacturers of colourants try to maintain equilibria between natural and synthetic materials and, other than the many standard ones available, most manufacturers offer custom-made services to meet any type of colour and properties required. With advances in the technology of masterbatch colouring, additive masterbatches (i.e., the required additives, for example, anti-ultraviolet (UV) agents) and flame retardants are incorporated into masterbatches.

8.1.1 Theory of colours

Using colours, one can set a mood, attract attention or make a statement. One can use a colour(s) to energise or to cool down. By choosing the right colour scheme, one can create an ambiance of elegance, warmth or tranquility. Colour can be the most powerful design element in a final product if one knows how to it effectively.

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The origin of colour is sunlight, which has thousands of colours but, to our eyes, only a few are visible. Most of us are familiar with the range of colours as shown in a spectrum: violet, indigo, blue, green, yellow, orange and red. These are the colours we can perceive. Colours affect us in numerous ways, both mentally and physically. For example, a strong red colour may raise one's blood pressure, whereas a blue colour will have a calming effect. Being able to offer aesthetically pleasing polymer composites with colour consciousness in harmony to end users, especially in the building construction, automobile and furniture industries, can help achieve spectacular results.

8.1.2 Colour wheel

The *colour wheel* or *colour circle* is a basic tool for combining colours. According to reports, the first colour diagram was designed by Sir Isaac Newton in 1666. The colour wheel is designed so that virtually any colour you pick from it will look good together with another colour. Over the years, many variations of this basic design have been made, but the most common version is the original wheel of 12 colours based on red, yellow and blue (RYB). In general, several colour combinations are considered especially pleasing. These are called *colour harmonies* or *colour chords* and they consist of two or more colours with a fixed relationship in the colour wheel. *Colour impact* is designed to dynamically create a colour wheel to match your base colour. Colours are categorised broadly into *primary, secondary* and *tertiary*.

8.1.3 Primary colours

In the RYB colour model, the primary colours are red, yellow and blue. I would like to state that white and black should also be included so that the primary base is five colours instead of three. Primary colours mean that these colours cannot be achieved by the mixing of any other colours. With this base, it is possible to obtain any colour by mixing among them.

8.1.4 Secondary colours

The three *secondary colours*, green, orange and purple are obtained by mixing two of the primary colours, for example:

- Green: yellow + blue
- Orange: red + yellow
- Purple: red + blue

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8.1.5 Tertiary colours

An additional six *tertiary colours* are created by mixing primary and secondary colours.

8.1.6 Warm and cool colours

The colour circle can be divided into warm and cool colours. These colour aspects become important if composite materials are used indoors in applications such as interior décor, facades, panelling, ceilings and in automobile interiors. *Warm colours* are vivid and energetic and tend to expand in space, whereas *cool colours* exude an impression of calm and create a soothing effect. White, black and gray are considered to be neutral.

8.1.7 Tints, shades and tones

Tints, shades and tones are often used incorrectly, although they are simple colour concepts. If a colour is made lighter by adding white, the result is called a *tint*. If black is added, the darker version is called a *shade*. If grey is added, the result is a different *tone*.

8.1.8 Colour harmonies

I will describe some basic techniques for creating colour harmonies. Complementary colour schemes are colours that are opposite to each other on the colour wheel (e.g., red and green). The high contrast of complementary colours creates a vibrant look, especially if used at full saturation. The colour scheme must be managed well so that it is not jarring. Complementary colour schemes are difficult to use in large amounts but work well if you want something to stand out.

Analogous colour schemes are often found in nature and are harmonious and pleasing to the eye. One must ensure that there is sufficient contrast if choosing an analogous colour scheme. Choose one colour to dominate, a second to support, and a third along with black, white or grey as an accent.

Triadic colour schemes use colours that are evenly spaced around the colour wheel. These colour schemes tend to be quite vibrant, even if you use pale or unsaturated versions of colour hues. To use a triadic harmony successfully, the colours should be carefully balanced. For example, use one colour to dominate and two others for accent.

Split-complimentary colour schemes are variations of the complimentary colour schemes. In addition to the base colour, two other colours adjacent to its

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complement are used. This colour scheme has the same strong visual contrast as the complementary colour scheme but has less tension.

8.2 Masterbatches

Masterbatches are colourants and/or additive concentrates for plastics or synthetic materials that incorporate a level of colourant, (in)organic pigment, pigments to cause special effects, or additives that are higher than those found in the final product. A masterbatch is used to proportion these additives into a larger batch during compounding. Most thermoplastic polymers are used in a particulate structure because this permits considerably less pollution during the process. It also allows for easier and faster assimilation. Manufacturers choose to supply masterbatches in the form of granules for colour uniformity and final colour requirements in keeping with international colour codes and standards.

Some additive masterbatches may contain mineral filler compounds, for example, mineral fillers for modifications of resins such as polyethylene (PE) or polypropylene (PP), with significant ones being calcium carbonate ($CaCO_3$) and barium sulfate ($BaSO_4$).Previously, most fillers were valued for their economic factor but appreciation for mineral fillers has increased as their influence on the functionality and physical properties of plastic products has become more apparent. Using fillers, the density, weight, anti-block and dampening properties of a polymer can be changed easily.

8.3 Liquid and solid colourants for polymer composites

Different systems are being used and this is related to the use of a liquid colourant system comprising at least one pigment and one dye for colouring cellulose polymer composites.

Cellulose polymer composites, in particular lignocellulose polymer composites (e.g., with rice hulls and wood fibres) have the properties of wood and plastic. They are more advantageous because they can be produced even from recycled raw materials. They are gaining in interest due to their potential applications, especially in high-end industrial uses such as building construction, automobile and aviation. The cellulose particles used in polymer composites may have different morphologies and accordingly different largest particle diameters ranging from ≈1–10 mm (shavings), to 0.1–1 mm (fibres) to 0.01–0.1 mm (flour). In theory, the finer the cellulose particle, the greater is the holding capacity of the polymer matrix for these particle, but the tensile strength of the composite decreases.

Although wood has been the preferred cellulose material for composites, not only softwoods like pinewood and cedar wood but also hardwoods such as oak and maple can be used. Examples of agricultural materials that are similarly useful are: rice hulls

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as well as fibres of sisal; flax; hemp; jute; cotton; bamboo; reed; coir; banana fibres; and peanut shells. Preferred polymer matrices come from thermoplastics but other polymer resins may be equally useful depending on their compatibility. In general, additives are used to increase the compatibility between the cellulose component and polymer component of a composite or the interphase adhesion; or to enhance the processability of the composite mix during extrusion, injection moulding or compression moulding.

It is also customary to employ additives to modify the technical properties of a composite. Some common areas are tensile strength, flexibility, density, impact strength, and thermal stability for their mechanical and chemical properties, and to enhance their aesthetic values. Such agents may be foaming agents to expand the polymer matrix and lighten the composite; flow additives; thermal stabilisers; biocides; insecticides; antioxidants; UV absorbers; antistatic agents; flame retardants; fillers and colourants.

Some of the various colouring methods for polymer composites are:

- Granular colour concentrates comprising = 20% by weight of a pigment or dye and 80% by weight of a PE-wax. Concentrates are mixed into a mixture of polymer rice hulls and mixed thoroughly before extrusion.
- An impression of a wood-grain effect on the surface of an extruded profile can be obtained by adding a combination of pigment-olefin masterbatch and a liquid colourant at the time of extrusion.
- Polymer composites based on polyvinyl chloride (PVC) and rice hulls can be coloured with an aqueous dispersion of a pigment. These can include metal oxide pigments such as iron oxide, depending on the final colour desired.
- For packaging materials based on transparent composites with low concentrations of wood flour or rice hull flour, the transparent polymer can be coloured with dye solutions or the constituents can also be coated with coloured material.

The advantageous properties of specially made colourant preparations also come to the fore in the colouration of cellulose particles in cellulose polymer composites. The cellulose particles are readily through-coloured regardless of their size, including even comparatively large wood shavings or rice hulls shells, and acquire strong, bright and lightfast colours. A more efficient colouration of cellulose polymer composites is possible in this way because in cellulose particles the main constituent of a composite is coloured and not just the quantitatively subordinate polymer matrix. The liquid-colourant preparation can comprise 0.5–10% by weight of dye based on the pigment. This pigment may consist of an organic or inorganic pigment plus at least one dye, a dispersant and water, or a mixture of water and a water-retaining agent.

Preferably, the pigments should be in finely divided form, with typical average particle sizes of 0.1–0.5 µm. Depending on the effect desired, the pigments may be used in transparent or other forms. Organic pigments are typically organic chromatic and black pigments. Inorganic pigments can be colour pigment-chromatic,

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black and white pigments, and also lustre pigments. Typical colourants are carbon black (black colour), titanium dioxide (white colour) and iron oxide (red colour).

8.4 Methods of colouring polymers

Colour selections and processing methods are decisions made by the producers of polymer composites supported by the manufacturers or suppliers of the required colours or systems, who provide guidance on how to obtain the best results. Several methods are available but probably the general standard ones used in processing plastics are masterbatches, cube blends and pre-colours.

8.4.1 Masterbatch concentrates

The most common method used by plastic processors are masterbatches consisting of concentrated pigments dispersed into a polymer carrier resin. During processing, the masterbatch is mixed with natural resin and can be compounded with other ingredients in a composite mixture. The percentage use of the colourant will depend on the final colour desired but, in general, small amounts as a percentage of the mixture are sufficient. Masterbatches are the most economical method to colour plastics and can be available in small volumes. Depending on the carrier selected, the same masterbatch may be used to colour several resins or chosen for maximum compatibility and processing ease. If a special colour(s) is needed, a supplier could oblige in a few days because most of them are geared with modern technology and equipment.

8.4.2 Cube blends

Cube blends are colour systems that feature a masterbatch dry-blended with natural polymers that are ready to use. This method can be used by processors who lack metering equipment at the plant. Mixing is controlled carefully by the supplier to eliminate the risks associated with self-blending that can cause variations in colour.

8.4.3 Pre-coloured polymer resins

Processors without experience handling custom colour matches may opt for pre-coloured resins due to their ease of use. Engineering resins that require high masterbatch ratios also benefit from pre-colouring because pigments are polymerised completely into a resin package and are used by processors as supplied. Suppliers

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of these colourants have the technical expertise and resources available to guarantee colour-match accuracy and lot-to-lot consistency with pre-coloured resins. Advances in technology have helped suppliers of pre-coloured resins to meet custom orders with a lead time of just 10 days.

8.5 Universal masterbatches

Universal masterbatches are offered by RTP Company (USA) under the brand name *UniColor* as an innovative answer to colouring multiple polymers, including engineered polymer resins. These products are universal masterbatches with extremely low let-down ratios, typically 1–2%, depending on the resin, and do not require drying before processing. These products are a great solution for processors that want one colour product for applications made from different polymers. Some composites are made with recycled, multiple polymer matrices, so these colouring systems can be used. They are also ideal for small-volume (10 kg) productions runs.

Some of the main colours offered are: white, magnolia, beige, terracotta, brown, yellow, amber, nectarine, red, flame-red, raspberry, fluorescent-green, green, blue, powder-blue, royal-blue, and light-grey. Variations of these colours are also available. Such colours are compatible with polymer resins such as PE; polystyrene; PP; PVC; acrylonitrile-butadiene-styrene; and polycarbonate.

8.6 Custom colours for polymers

If processing straight polymer resins, whether it is a single or multiple blend mix, one may say that it is easy to colour and process. However, processing of polymer composites, especially with wood flour or rice hull flour, is more complicated, especially in terms of colouring and obtaining a uniformity and stability of colour. Many factors can affect colour, including: resins, additives, texture shapes, lighting conditions, usage environment, processing conditions/ methods and, most importantly, human perception of what is required.

In addition, colour fastness, regulatory compliance and industry guidelines can impact the selection of pigments and dyes used to achieve an accurate colour match. Addressing of all these issues is not easy, and processors probably find it cost-effective to work with colour experts or be satisfied with what is on offer. If a custom colour is requested from a supplier, some of the information that may be requested includes:

- *Type of application the colour is intended for and how it is used* will help determine which pigments are best for matching and whether they remain consistent during environmental exposure.

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- *Base polymer resin system and specific grades*: Some pigments are not compatible with all polymers and certain grades need processing parameters, especially temperature ranges, which can degrade many pigments.
- *Processing method*: For example, are the polymer composites to be extruded, injection moulded or compression moulded? This knowledge helps to determine if appropriate dispersion will occur.
- *Level of colour target*: An indication will help the suppler to achieve the best colour and quality match possible.
- *Match type*: Whether an exact match or a several trials are expected can impact on which pigments or dyes are used to control colouring costs.
- *Opacity*: If the composite material needs to maintain transparency, translucency or become opaque is an important factor in meeting match criteria with many polymer resin systems.
- *Final product parameters* (e.g., thickness, width and length weight) will help in recommendations for the use of sufficient concentrations of colour to achieve uniform colour throughout.
- *Supply method*: How a processor wants his/her colour requirements delivered, i.e., masterbatches, cube blends, or pre-coloured form.
- *Composite composition basics*: If the colour will be used in conjunction with which type of reinforcements, fillers, UV agents, and blowing agents. For best results, dyes and pigments used should be compatible with most key ingredients.
- *Visual standards*: If colour requirements are for aesthetic, cosmetic reasons or just for colour codes for identifying different products. This important from a cost perspective.
- *Evaluation of light source*: The quality of colour matches can appear different if viewed under different lighting conditions. Some common sources are daylight, fluorescent and tungsten (incandescent).
- *Instrumental evaluation*: If a colour is going to be checked using instrumentation, a numerical tolerance may be required as the acceptable margin of error.
- *Composite product texture*: The surface type require can influence colour matching. Some common textures that must be identified include glossy, matt, textured, grains, and psychedelic.

Colour matching and the range of ready-made products are highly advanced, and most processors of polymeric composites will have no problem in purchasing most requirements. Processors who have in-house laboratories will have the advantage of trying out colours in ‘mini’ runs, which can also be coupled with experimentations on different composite formulations based on quality improvements and cost reductions. With on-going research and development in many countries, processors of polymer composites will be able to use these data to improve their products.

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9 Manufacturing of polymeric composite resins

9.1 Concept

Over the past decade, plastics have been replacing traditional materials and have spread quickly to cover domestic, industrial, and engineering sectors. They are even used in high-tech applications such as air travel and space travel. Hence, the need for newer and stronger plastics has prompted research and development to produce high-grade polymer resins to meet these demanding challenges.

Due to increasing global environmental concerns and rising costs of polymer resins, the plastics industry has been searching for alternatives for polymer resins, most of which are based on petroleum. For some time now, wood plastic composites made from polymers as the matrices and wood chips and wood flour as the reinforcing constituents have been used first in extruded form and then to injection-moulded and compression-moulded forms. Although the products from these composites have proved to be practical and to compare favourably with traditionally produced products made from pure or recycled materials, issues such as warping, exposure to weather, and durability need to be solved. The advent of polymeric composites with rice hulls (PCRH) has elicited superior products while overcoming these problems.

9.2 Manufacturing process in brief

Technology for manufacturing PCRH is fairly new and the initial product results are very encouraging. The possibilities with these versatile composite resins are vast and are proving PCRH to be suitable for even high-tech applications. Basically, a polymer resin such as polyethylene (PE), polypropylene (PP) or polyvinyl chloride (PVC) is used as the matrix and mixed with rice hull fibre or, preferably, in the form of flour (finely ground powder) and a combination of additives depending on the end application targeted. The polymer matrix can be virgin resin, recycled material or a combination of both, whereas the rice hulls must be moisture-free and the particle size reduced from its original state. Additives can take the form of: ultraviolet (UV) stabilisers; coupling agents; heat stabilisers; or lubricants. Colourants and other surface agents are added if it is necessary to obtain coloured or aesthetically pleasing finishes. Rice hulls are sieved, dried thoroughly to remove moisture, reduced to a fine powder form (preferably) and then compounded with a heated polymer matrix. This polymer mass may consist of virgin material or recycled material or a combination of both. Carefully selected additives are then added to this mix and the whole mass compounded well. This mass then goes through an extruder, in which further mixing takes place, and is extruded through a multi-cavity die placed in the extruder

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head. A set of fine mesh placed just before the die prevents foreign matter going through the die. This is important for the uniformity and purity of the extruded strands. The multiple strands emerging from the die go through a cooling process and then through a pelletising machine and are cut into predetermined sized pellets. The resulting pellets are opaque to slightly yellowish in colour or can be fully coloured.

9.3 Raw materials

As mentioned above, the basic raw materials for manufacturing PCRH are a polymer matrix, rice hull powder, additives and colourant (optional). Each formula will differ in that it will be designed to meet a particular end application. Surface additive agents can produce matt or high-gloss finishes as desired. In general, polymeric composites with reinforcements are on the hard and heavy side and, if lighter products are desired, a blowing agent can be incorporated. For example, hard and heavy products will be ideal for flooring and building construction industries, whereas lighter and aesthetically pleasing products will be ideal for automotive and indoor applications.

9.3.1 Polymers

In general, thermoplastic polymers such as PE; PP; PVC; acrylonitrile-butadiene-styrene; and polystyrene are the easiest to work with. They could be in pellet or powder form, free of atmospheric moisture. Some formulations may use virgin material or recycled material. In the latter, if multiple coloured materials are recycled together, achieving a final single colouring is affected and the formulation has to be adjusted accordingly. If mixtures of polymers are used, it is important to use compatible polymers starting with the melt-flow properties. Polymers are usually available in bags of 25 kg or in bulk (‘Gaylords’) containing ≈ 400 kg. The proportions of the polymer matrix to the reinforcing agents will vary with each formula, but a practical base guide would be 40:60. Higher rice hull contents are possible.

9.3.2 Rice hulls

Rice hulls are available in abundance in many countries. Until recently, the full potential of these humble gifts of nature has not been exploited fully. The possibility of PCRH as suitable substitutes for natural wood is exciting and challenging.

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Rice hulls are different to wood fibres in that the fibre length of rice hulls is only ≈ 0.3 mm as compared with 6–7 mm for wood fibres. Moreover, a substantial part of the silica content is concentrated on the outer surfaces of the hull. If rice hulls are used for the manufacture of composite resins, their special characteristics must be taken into account. Research has found that the surface of rice hulls contain materials that are only loosely bound to the fibre structure underneath. For the sake of easy processability and strength of the final product, it is necessary to have these loosely bound material removed before use. Such 'cleaning' may be accomplished by physical means such as tumbling. Mixtures of raw rice hulls and a fine hard material can be fluidised in a fluid stream such as air to achieve this end. In other words, it is acceptable to subject rice hulls to the abrasive action of a hard material that is sufficiently fine to reach all surfaces of the hulls. The exact method employed for this 'cleaning' is not important and it is generally accepted that this can also be achieved by a grinding action, probably when the particle size is reduced.

To maximise the strength of the product, tests have shown that it is not enough to just 'clean' the hulls but it is also necessary to remove the dust or any other foreign material from the cleaned hulls. This can be achieved by any of the commonly used methods of size separation, such as sieving, air cyclone or air floatation, As they emerge from the rice mill, rice hulls may also comprise pods containing the two husk leaves joined together. Tests have shown that grinding the rice hulls in a hammer mill followed by sieving serves the dual purpose of 'cleaning' and separating the pods into individual leaves with the hulls that can be broken into pieces so as to shorten their length and width. The ideal situation would be to have the rice hulls in a fine powder form for easy blending and mixing with the polymer matrix.

Rice hulls have an inherent moisture-content problem. They are an agricultural waste and the volumes are large, so rice mills after processing may store part of rice hulls to protect them from the elements. However, due to the sheer volume of a rice-producing and rice-milling operation, it may not be possible to protect them from the weather. Hence, supplies from a rice mill will contain a high content of water unless a buyer has a special arrangement with the rice mill. Producers may opt for purchasing their rice hulls from a professional source, where the rice hulls can be supplied in neat bags or in bulk processed according to a producer's specifications. However, this will be at a nominal additional cost. Depending on the end products targeted, a producer of composite resins with rice hulls can specify a particular sieve size and moisture content. To facilitate a good homogenous mixture as well as a smooth and easy-to-process composite compound, the ideal moisture content should be ≤1% and certainly ≤2%. Higher moisture contents will pose processing problems and also swelling of the extrudate at the die.

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9.3.3 Additives

Additives are an essential part of making polymeric composites, some to enhance properties, some to achieve aesthetically pleasing finishes, and some are needed as processing aids. In the manufacture of PCRH, one must remember that, due to silica in rice hulls, the composite mixture is abrasive and generates extra heat in the extruder barrel. Certain special additives may have to be incorporated into the mix to counter these effects. Numerous additives as well as suppliers and producers of composites will have no problems in getting what they want. In fact, a close working relationship with them would greatly help a producer to work out the best additives (or combinations of additives) to use to get the best results. Additives can be in the form of solids, powders or liquids, and some may even be coupled with a particular resin, which will greatly help in compounding. Some of the important areas in which additives are needed to improve or enhance polymeric composites are: compatibility; heat stabilisation; moisture control; anti-UV action; mechanical, chemical or physical properties; light weight; durability; and easy processing.

Basic additives that are used commonly are:

- Lubricants
- Stabilisers
- Anti-UV agents
- Flame retardants
- Coupling agents
- Anti-fungal and microbial agents
- Blowing agents
- Surface finish agents
- Colourants

9.4 Processing machinery and equipment

The complete process can be categorised into five main operations: drying and removal of moisture from the rice hulls; particle-size reduction; compounding; extrusion in the form of strands; cooling and pelletising. The first three phases can be done separately with individual equipment but a producer may opt for an in-line complete processing extrusion/pelletising system. From the previous chapters, the reader will have a good knowledge of the equipment for drying, particle-size reduction, and extrusion. However, for the benefit of the reader, I present below a complete system made with technology by an American company, *Harden Industries Ltd.*, based in China and used in the production of PCRH. There are many systems available and also others emerging in this exciting market of polymer composites. This detailed system will give the reader a thorough knowledge of the production of composite resins.

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The following complete system is presented with permission and courtesy of *Harden Industries Ltd.*, China.

9.4.1 Co-rotating twin-screw extrusion/pelletising line

This line can be used for compounding and pelletising PP with rice hulls/wood flour and low-density PE or high-density PE with rice hulls or wood flour (Figure 9.1). Other combinations are also possible but may need a change of screws depending on the polymer matrix used.

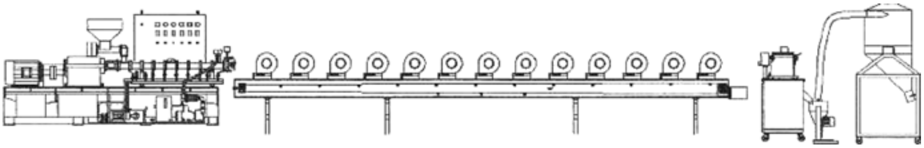

Figure 9.1: SZS-50 (40D) Co-rotating twin-screw extrusion pelletizing line (schematic). Reproduced with permission from Harden Industries Ltd., China. ©Harden Industries Ltd., China.

9.4.2 Specifications

- Machine: SZS-50 (40D) Co-rotating twin-screw extrusion/pelletizing line
- Output: 100–150 kg/h
- Machine list:
  - Co-rotating twin-screw extrusion system
  - Metering feeder
  - SZS-50 (40D) Co-rotating twin-screw extruder
  - Electrical control system
  - Conveying/cooling system
  - Strand pelletiser SUF-100
- Machine details:
  - Metering feeder: volumetric metered
  - Feeder motor: Power, 0.75 kW; two-speed controls; variable frequency speeds
  - Feeding gear box: gearbox reduction ratio, 1:1.5
  - Feeding screw: single screw
  - Material: 38CMoala, nitride
  - Feeding barrel: feed port opening connected to a hopper with a horizontal stainless-steel agitator
  - Hopper: volume, 25 kg; made of stainless-steel (thickness, 1.2 mm)
  - Co-rotating extruder
- SZS-50 (40D) high-torque co-rotating twin-screw extruder

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Figure 9.2 is a photograph of the twin-screw extruder.

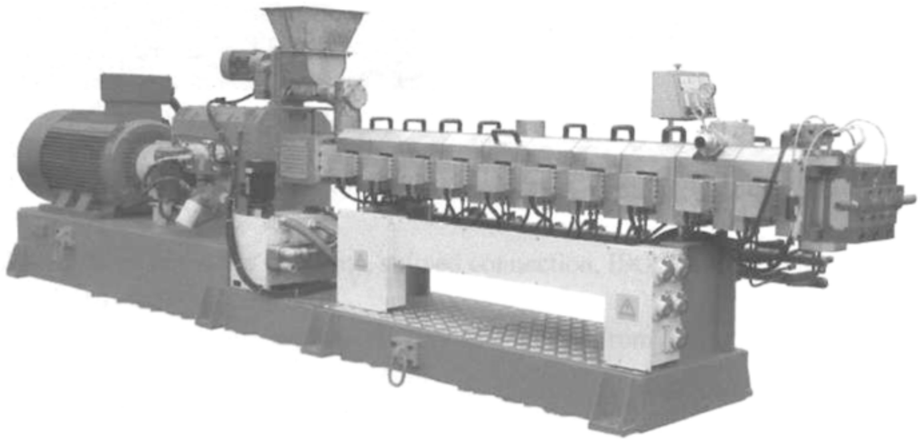

Figure 9.2: High-torque twin-screw co-rotating extruder. Reproduced with permission from Harden Industries Ltd., China.

- Main power: 1.75 kW Siemens AC motor; 2.75 kW AB vector inverter:
  - Gear box: multiple axis distribution transmission
  - Transmission speed ratio: 1:2.4
  - Main motor power: 75 kW
  - Gear box output torque: 1193 mm
  - Manufactured to standards: JB/T8853 2001 and GB10095-88.6
  - Point-to-point oil pressure lubrication
  - Gear box plate cool-heat exchanger
- Screw details:
  - Screw diameter: 50 mm
  - Length/diameter ratio: 40:1
  - Modular screw elements, splined connection International Organization for Standardization (ISO) standard
  - Splined shaft: material, high torque steel; involute splines ISO; processed by CNC machine
- Extruder barrel:
  - Structure: inner waterway; length, 4D
  - Material: integrated alloy coat, HV950-1050
  - Sections: 10 nos × 200 mm = 2,000 mm
  - The first section of the barrel is the feeding section. The fifth section of the barrel is for a natural degassing port; the ninth section of the barrel is for a vacuum degassing port with a force-feeding device

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- Vacuum system:
  - The fifth section of the barrel is for natural degassing and the ninth section is for vacuum degassing
  - Power: 2.2 kW, 380 V/50 Hz
  - Vacuum filter and cylinder
- Barrel water-cooling system:
  - 9 cooling zones: zone 1 is always open
  - High-temperature water pump: 0.37 kW
  - Cylinder water tank: 35 l
  - Plate heating exchanger
  - High-precision solenoid valve
  - Copper in/out water pipes, stainless-steel pipe joint, stainless-steel distribution pipes
- Barrel heating system:
  - 9 heating zones; 10 barrels (the first section is the feeding barrel, unheated)
  - Heating power: 400 W × 8 groups × 10 zones = 32 kW
  - The heating tube has a built-in heater, full explosion-proof design, with energy-saving insulation
- Loose-leaf screen changer
- Electronic control system:
  - Main motor power: Siemens 75 kW, 380 V, 50 Hz, variable frequency speed controller
- Using AB 75 kW inverter:
  - Feeder motor power: 0.75 kW, 380 V, 50 Hz, variable frequency speed controller, using a Danfoss inverter
  - Temperature-control system: Japanese RKC auto temperature controller
  - Buttons and signal lights: all are Siemen’s products
  - Air switch: using Mitsubishi products
  - Industrial-grade dust-free panel
- 250 kg silo and blower:
  - Air pipe: stainless steel (diameter, 4 inches)
  - Silo: 250-kg capacity in stainless-steel
  - Blower: 1.5 kW, 380 V, 50 Hz
- Conveying cooling system:
  - Stainless-steel chain conveyor
  - Motor: 0.75 kW
  - Cooling fans
- Strand pelletiser SUF-100
- Before cooling and pelletising:
  - Working width: 100 mm
  - Power: 7.5 kW with hard gear reducer, motor with AC frequency control
  - Speed: 30–70 M

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- Pellet length: 3.0 mm (adjustable)
- Pellet diameter: 3–4 mm
- Rotating blade material: high-speed tool steel from Sweden
- Fixed blade with alloy coat
- Output: 1,300 kg/h

According to reports, this versatile system is being used in PCRH manufacture. This system is presented in good faith and one may opt to use it as a guide for choosing a suitable extrusion/pelletising system to produce polymer composite resins depending on the investment and volume of production required. It is much easier for a producer of PCRH to create finished products starting with already compounded and pelletised composite resins in natural colour or coloured resins. This procedure will have limitations in that using already compounded resins yields only one type of product with the pre-desired properties, whereas a complete in-line operation gives the producer the flexibility to create different products with different formulations.

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10 Polymeric composites with rice hulls for extrusion

10.1 Concept

Manufacture of polymer composite resins by combining less polymer content and reinforcing with natural fibre such as rice hulls, suitable for processing by extrusion.

Extrusions with polymer resins have been popular in the manufacture of many products for the domestic, industrial and automotive markets. Until recently, most extrusions were done with pure virgin materials, recycled material or a combination of both. The prices of these petrochemical-based polymers have increasing steadily and will keep on increasing and are not likely to come down at any stage. Manufacturers have been on the lookout for possible alternatives and, some time ago, the arrival of polymeric composite resins with wood fibre has had a definite impact on the industry. The concept of fibre-reinforced polymers with mixtures of less polymer and more fibres combined with suitable additives has had a tremendous impact on the extrusion industry. The added advantages of these composite resins, such as light weight, higher strength, better properties and fewer costs have made the extrusion industry flourish using these composite resins in *lieu* of the traditional ones.

With research and development, manufacturers of composite resins can now take them to new heights. These new technologies have resulted in polymeric composites with rice hulls (PCRH) that are easy to process and also give better results than wood plastic composites (WPC). These virtually new composite resins have opened a whole new range of possibilities to include not only outdoor applications such as decking and fencing, but excellent products for domestic, indoor, building construction, automotive, industrial, aviation and furniture applications. This is a rapidly expanding market estimated at >£2 billion and growing at 20% annually according to some reports, especially because these products are considered to ideal substitutes for natural wood.

10.2 Production of additives for polymeric composites with rice hulls

To achieve good final products, the polymer composite mixture for extrusion or the pelletised resins require a combination of suitable and compatible additives. These composite mixtures can be compounded and extruded directly or some producers may opt for extruding the ready-made pelletised resins. The advantage of the former is that a producer can vary the end properties desired using different

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formulations whereas, in the case of the latter, a producer will have to go with the already set properties of pelletised resins. Some of the important basic additives such as coupling agents, lubricants, colourants, chemical foaming agents (CFA) and biocides that are essential are presented below.

10.2.1 Coupling agents

Coupling agents bond rice hull fibres to the resin matrix. They boost the flexural strength and stiffness (usually referred to as the modulus of rupture and modulus of elasticity, respectively) which are terms used in the lumber industry. Coupling agents also improve dimensional stability, impact resistance and fibre dispersion, while reducing creep. Added strength is important in structural applications, especially in the building construction industry. In outdoor applications such as decking, coupling agents are used mainly to reduce water absorption, which tends to swell the surface and could lead to stresses that cause cracking.

Coupling agents are especially valuable in polyethylene (PE)-based composites they overcome the possible incompatibility between the polar chemistry of wood and non-polar resin matrix. Chemically modified grafted polyolefins are available. However, newer developments include chemically modified polyolefins that are not made by grafting, long-chain chlorinated paraffin, and reactive agents suitable for polyvinyl chloride (PVC) composites. Some useful and effective coupling agents are: Polybond3029MP [high-density polyethylene (HDPE)], Fusabond MB-226D (PE), MD-353D [polypropylene (PP)] and Epolene G-2608 (PE).

10.2.2 Lubricants

Lubricants facilitate easier mixing at the time of compounding, increase throughput and improve the extruded surface finish. PCRH composites can use standard lubricants for PE and PVC, such as ethylene bistearamide (EBS), zinc stearate, paraffin waxes and oxidised PE. EBS with zinc stearate is commonly used in HDPE composites. However, there are new alternatives because metal stearates are known to decouple maleic anhydride groups of a maleated coupling agent, thus cancelling the effectiveness of the lubricant and coupling agent.

Polymer composites use nearly as twice as much lubricant as standard plastics. For a HDPE composite with a typical 50–60% fibre content, the lubricant level can be 4–5%, whereas a similar fibre-PP composite uses ≈1–2%. Some of the common lubricants in use are: TPW 104 (PE), TPW 113 (PE), EBS (AcrawaxC), and Glycolube WP-2200 (HDPE).

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10.2.3 Colourants

Colourants are used to achieve aesthetically pleasing surface finishes. They also provide a wood-like appearance and ultraviolet (UV) resistance. Suppliers of colour masterbatches are using colourfast, highly reflective and weather-resistant pigments to meet an increasingly demanding market. One of the biggest challenges of colourants is colour-fading. Tests have shown that pigment levels must be ≥1–3% to overcome colour staining from wood. Colour concentrates tailored for polymer composites typically include a lubricant and are often customised multi-functional packages that may include other agents: coupling agents, antimicrobials and UV stabilisers. There are suppliers of specialised products with customised colour and additive masterbatches for fibre-PE, fibre-PVC, fibre-PP and other combinations. One of the latest to be introduced into the market are colours for fibre-polyolefin for colour finishes such as teak-brown, cedar, weathered-grey and redwood, as well as many custom colour matches in concentrates, liquids and non-dusting granules.

Clariant Masterbatches has a range of colours for tan, dark-red, grey and oak finishes as standard masterbatches, as well as custom colours for PE; PP; PVC; and polystyrene (PS) composites. These colourants are based on fibre contents of 30–70%. *Techmer PM* has introduced colour finishes such as redwood, cedar, brown, white and black as masterbatches, particularly for polyolefin and PVC fibre composites. While these product ranges should cover more or less the needs of composite producers, they have a choice of making requests other specialty colours, if required.

10.2.4 Chemical foaming

Most composites, including PCRH, tend to be heavy and there is a keen interest in the chemical foaming of extruded composites to reduce weight and materials. This will naturally reduce costs in addition to improving surface appearance, increasing processing speeds as well as ease the sawing, nailing, screwing and painting of finished products, if necessary. It is estimated that ≈30% of all fibre composites produced are foamed.

Endothermic (heat-absorbing) and exothermic (heat-giving) CFA can be used. Foaming is more difficult for crystalline polymers such as PE and PP than for amorphous polymers such as PVC and PS because the latter generally have better melt strength. As a rule, the higher the fibre content in a composite, the more difficult it is for foaming on the basis of lesser polymer content being available for foaming. *Clariant Additive Masterbatches* offers a range of CFA, which include endothermic, exothermic and endo-exothermic blends for most polymer fibre blends, which are ideal for composites with fibre content <50%. Foamasol CFA as marketed by *Bergen International* are particularly for decorative mouldings such

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as siding trim boards, railings, spa panels and interior facades, where loss of physical properties from foaming are not an issue. Typical weight reductions for foamed composites are ≈30–35%.

10.2.5 Countering mould and mildew

Mould, mildew and stains on some outdoor composites (e.g., decking) needs the attention of the manufacturers to consider using antifungal biocides that protect the polymer content and maintain its surface appearance, or which preserve the fibre component from decay and also reduce moisture absorption. Many additives will carry out both functions. Unlike in normal WPC, PCRH provide a natural surface barrier to counter these effects due to silica. However, producers may opt to use additional additives to combat these problems.

Weathering and UV radiation have been known to degrade the surface of WPC within a few weeks of exposure. Constant weathering and water absorption affect the surface and colour fading is also probable. Also, moisture can lead to a loss in mechanical properties and provide a more favourable localised environment for fungal growth. *Ciba Specialty Chemicals* offers Irgaguard F3000, said to be a broadly effective fungicide for fibre composites. Another product, Developmental EB 43-25, combines with Irgaguard F3000 to provide a broad-spectrum fungicide that can eliminate or reduce stains due to interactions of iron, tannin and moisture. *US Borax* offers Borogard ZB zinc borate as a preservative for composites. It has broad-spectrum activity against wood-destroying organisms, plus heat, UV stability, as well as resistance to leaching and weathering. New developments for treating natural wood also have great potential for treating wood flour or rice hull flour in composites to prevent colour changes.

10.2.6 Fillers

Fillers are a normal part of most plastic compounding. For polymer composites, fillers such as calcium carbonate (fine powder) or talc can be used. The degree of filling will depend greatly on the end application. In general, a 15–20% use of a filler in a composite mix could be considered feasible. If talc is used (acting as a lubricant), it could also increase the throughput during extrusion of the compounded composite mix. If rice hulls are heated beyond the ashes phase, the mass will produce tiny spheres of silica, which can be used as fillers in many plastic compounding operations. *3M/Zeelan Industries* offers hollow glass microspheres, which have interesting applications as fillers. These tiny microspheres reduce viscosity; lighten weight; reduce costs; enhance properties; and form a barrier against moisture.

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10.3 Extrusion of polymeric composites with rice hulls

Extrusion has been discussed in detail in previous chapters, so I will not dwell too much on it other than to say that extrusion comprises the drying of rice hulls followed by particle reduction and compounding with the polymer matrix and additives. This mixture is then processed through an extruder, with the extruder head having a profiled die of choice. The extrudate coming out of the die will then undergo cooling and be cut into desired lengths by a cutting system downstream, which can be operated manually, semi-automatically or automatically.

In the composite industry, WPC is the general term applied for composites with wood fibre, rice hulls or others. This may be because whichever fibres are used in a composite combining a polymer matrix and natural fibres, the resulting end products resemble and feel like wood. When WPC first appeared on the market, they showed very interesting possibilities as new materials with worldwide market potential. Awareness that the use of other natural fibres was also feasible as a possible substitute for natural wood applications made some of the top plastic engineering machinery manufacturers (e.g., *Reifenhauser, Cincinnati Milacron, Maplan Corporation, Harden Industries Ltd.*) begin to develop standard and tailored WPC extrusion solutions. One of the major breakthroughs is extrusion systems for PCRH, the products of which are superior to any in the market so far. These suppliers of extrusion systems not only supply suitable systems but also provide full technology and work closely with customers to ensure successful and profitable ventures.

Although composites with rice hulls stand out among the others, systems are now available for polymeric composite mixtures with all kinds of natural fibres. In this context, fibre quality with regard to size and moisture content can have an enormous effect on the entire extrusion process. The following basic features are important:
- Average size of fibre (mm)
- Distribution of fibre size
- Average moisture content of mass (%)
- Fibre type (name of plant or tree)

Recommended specifications for the use of fibres to achieve the best material properties and highest production speeds (output rates) are:
- *Fibre size*: 0.1–1 mm, ideally ≈350–500 µm, equal to mesh numbers 35, 40 or 45.
- *Moisture content*: <12% for direct extrusion or <3% for compounded, pelletised extrusion.
- *Fibre types*: generally a wide range of natural fibres are possible but softwood fibres are the easiest to process. In the case of rice hulls, specially designed screws are used.

Fibres with other specifications can also be used but with limitations regarding the maximum line-speed (output) and end-product properties. Composite

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manufacturers also have the option of having a 1–3-kg sample of the fibres analysed by most machinery suppliers, free of charge, before usage in production.

Besides the fibre raw material, the polymer matrix to be used also has a significant effect on the production equipment. In general, the most popular and easiest-to-process composites are based on polyolefin (PP or PE) as the matrices for the following reasons:

- Higher fibre-filling ratios are possible (≤80% natural fibres).
- Reduced costs for raw materials.
- Final products have a more natural wood-like feel to touch.
- Recyclability of polyolefin conforms to the natural and environmentally friendly image of WPC/PCRH due to use of renewable and sustainable raw materials.
- PVC is (normally) not allowed to be energetically reused (burned) because it would be harmful to the environment.

Depending on the size and capacity of an extrusion system and thickness of a profile, it is generally accepted that profile widths ≤1,000 mm can be produced. For general composite lumber applications, widths ≈200 mm can be produced easily.

10.4 Extrusion systems for polymeric composites with rice hulls

The key to an ideal selection of an extrusion system for PCRH is the end products to be produced. For example, a producer may opt to manufacture only PCRH lumber for decking, fencing and other outdoor applications, or set himself/herself up to produce different composite products on the same system using different formulations. Also, planning may include the use of different polymer matrices. It is best to work closely with a selected machinery supplier who will recommend a system with maximum potential and also supply technological guidance backed up by his/her in-house laboratories. In the extrusion of PCRH profiles, screw designs need special attention because the composite mixture will contain silica, which is an abrasive component. The lifespans of screws used in PCRH extrusions will probably be different to standard ones. In a project of this nature, a manufacturer must pay attention to an effective lay-out plan, especially of the complete in-line system is to be installed. Other areas that need thought are heating, water, air, power, ventilation, and safety factor.

WPC/PCRH extrusion systems have different output rates depending on the extruder type and system selected. This factor will also depend largely on the end products to be manufactured and planned volumes of production.

Manufacture of PCRH products can be carried out in two stages (compounding, pelletising and extrusion thereafter of these pellets) or in one operation (compounding and direct feeding into the extrusion system). Figure 10.1 shows the first stage of a process flow of producing pellets. Figure 10.2 shows an extrusion system for producing profiles for outdoor applications.

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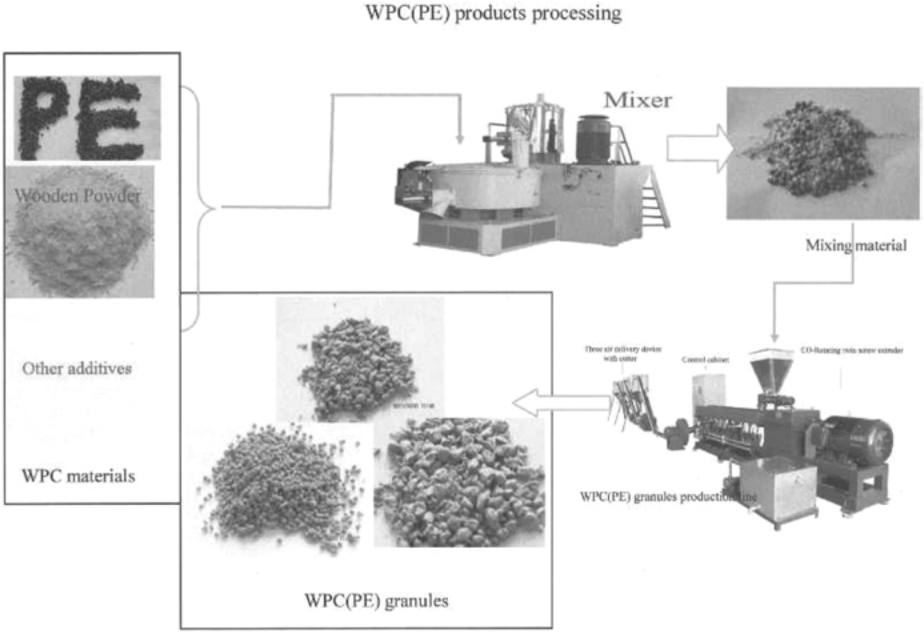

Figure 10.1: Process flow of production of PCRH pellets. Reproduced with permission from Wuhan Industries Ltd., China. ©Wuhan Industries Ltd.

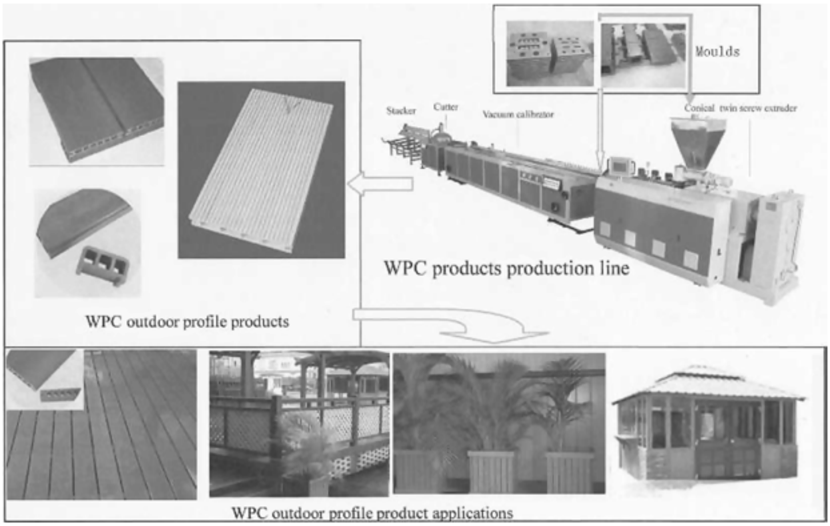

Figure 10.2: Extrusion of PCRH products for outdoor applications. Reproduced with permission from Wuhan Industries Ltd., China. ©Wuhan Industries Ltd.

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10.5 End applications of products of polymeric composites with rice hulls

As mentioned in previous chapters, PCRH products have a wide range of end applications. In North America and Europe, outdoor applications take precedence and are now spreading into the building construction and automobile industries in the East and Far East. For example, in China, the use of PCRH products have spread rapidly into sectors such as indoor and furniture industries. Due to the versatility of these products, other sectors are opening up and may have a booming market. The availability of rice hulls in abundance, the use of lower polymer content, and the ease of manufacture as technology and development advances, enhanced by cheaper costs and universal acceptance as an environmentally friendly product will no doubt sustain and increase the demand for these products. Figures 10.3–10.5 show some of the end applications of PCRH products.

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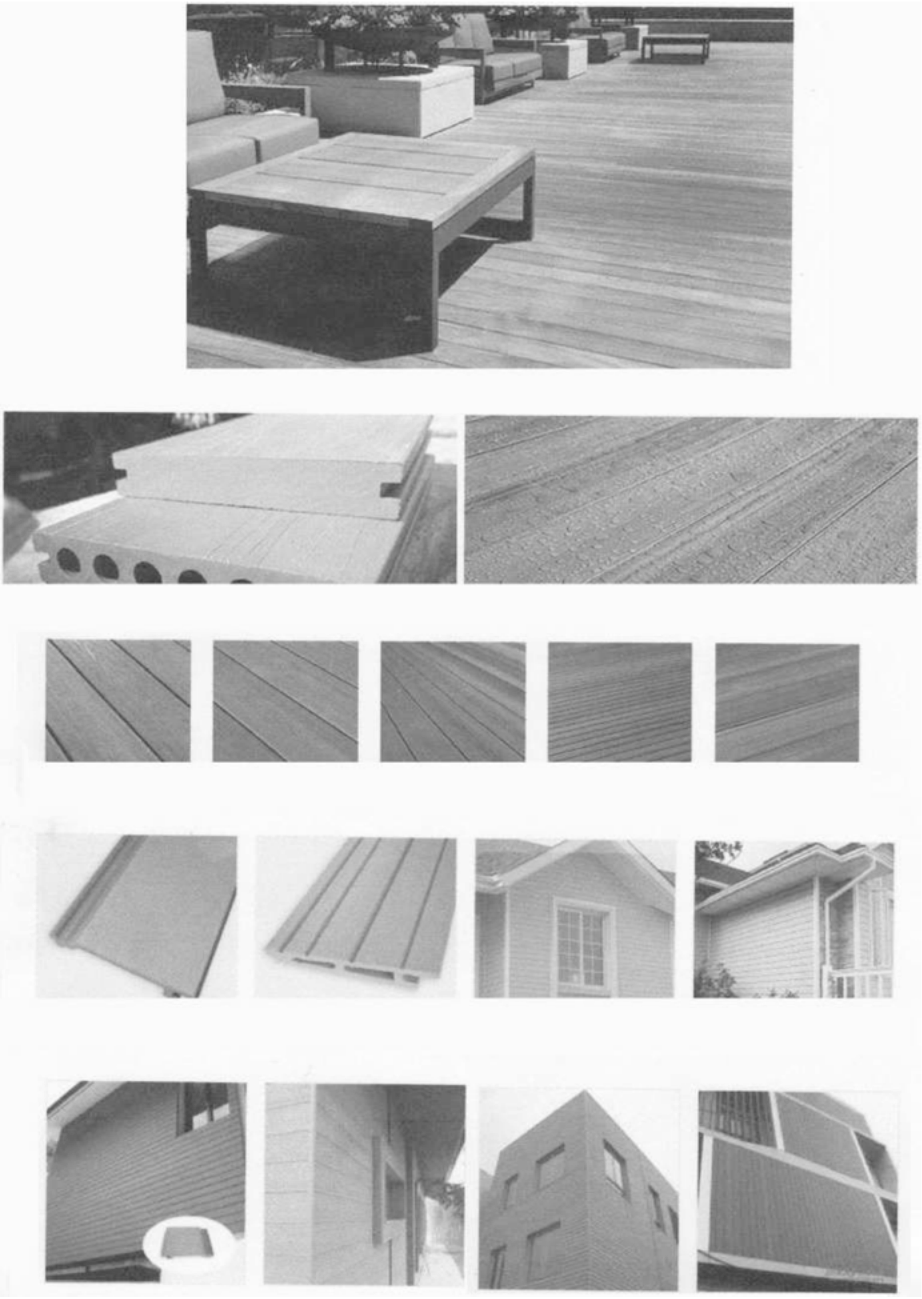

Figure 10.3: Outdoor applications for PCRH products. Reproduced with permission from Wuhan Industries Ltd., China. ©Wuhan Industries Ltd.

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Figure 10.4: Indoor and outdoor applications for PCRH products. Reproduced with permission from Wuhan Industries Ltd., China. ©Wuhan Industries Ltd.

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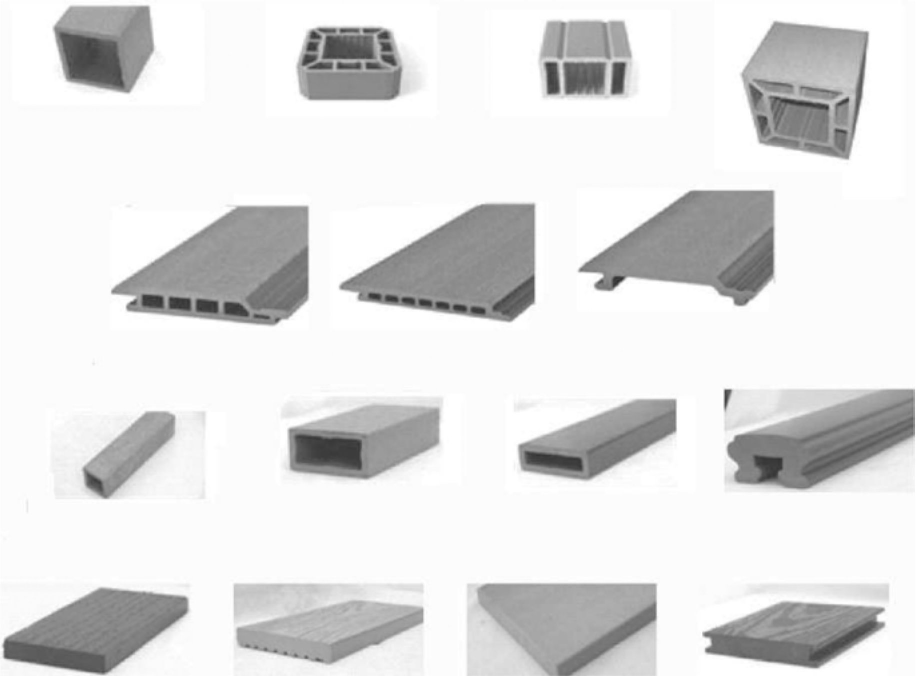

Figure 10.5: Extruded profiles. Reproduced with permission from Wuhan Industries Ltd., China. ©Wuhan Industries Ltd.

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11 Polymeric composite resins in injection moulding

11.1 Introduction to injection moulding

The plastics industry uses many processes to convert plastic resins into plastics products. Some of the popular ones are extrusion, blow molding, casting, and compression moulding but the most popular is *injection moulding*. The basics of injection moulding are introduction of a plastic resin into a heated barrel that contains a screw or a plunger (used in older machines). The hot melt is pushed forward into a nozzle of the injecting barrel and then forced by pressure into a closed mould in two halves. The mould may be single or multi-cavity and is designed in such a way so that the hot plastic melt flows freely into the closed mould and fills all the cavities. The mould is then cooled for a few seconds, the mould opens, and the moulded parts ejected. The cycle is repeated manually or automatically. Most large injection-moulding machines are operated horizontally but vertically operated machines for small parts (especially with inserts) are also used.

In the conversion of polymeric composites with rice hulls (PCRH) to final products, extrusion holds sway over other methods but injection moulders, realising the potential of these new composite resins, have started to use them widely. Injection moulding will soon be a vital sector using these composite resins, gradually replacing traditional petroleum-based polymer resins, so sound knowledge of injection moulding will greatly help in understanding how to use these composite resins to obtain the maximum benefit.

11.2 Injection moulding machine

From the early days when a material called a ‘plastic’ was created, the machines that processed these materials were injection machines that were hand-operated. The moulding principle has remained more or less identical over a decade of processing but from this humble operation injection-moulding machines have made great strides with screw feeds (instead of a plunger), automatic or semi-automatic operation and high-tech electronics. Modern machines operate on hydraulic systems or electric power and hybrids are also an option. The availability of ‘closed-loop’ automatic temperature and other controls on most machines is a big boost for operators and moulders.

An injection-moulding machine basically consists of a hopper connected to a barrel with a short screw inside. The barrel contains zonal heaters and also a detachable nozzle in front (screw type). The mould consists of a single cavity or multi-cavity, with an internal cooling arrangement with water or other liquids in circulation

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to cool the hot moulded parts. Two solid platens are mounted vertically on four strong steel bars with one platen stationary and the other movable. One half of the mould is mounted on the stationary platen and the other half on the movable platen, with the option of closing and opening it. The two halves of the mould must be precision-mounted and synchronised because a misaligned mounted mould causes serious damage. Moulds are generally of steel or aluminium, precision-made from computer-aided design/computer-aided machining and are very expensive. With constant use, one must expect a mould to have a lifespan and this is measured in the number of mouldings. For example, a mould-maker might say that a particular mould will last 30,000, 50,000 or even 100,000 mouldings. Hence, a customer quote for a part(s) by a producer will also include this consideration. A hydraulic or electric operating system for movement and a high-tech electronics system for other factors with a control panel will more or less complete the basics of an injection-moulding machine.

11.3 Polymer resins for injection moulding

Selecting the correct polymer resins for each end application can be quite a daunting task, requiring in-depth knowledge of the vast range of the injection-moulding resins available. Appropriate selection of the correct type and grade of resin hinges on thorough understanding of the application of the final product. All application characteristics need to be worked out carefully in addition to knowing the capabilities and limitations of the machine(s) to be used for injection before a determination is made. In large processing plants, the design engineers will decide and specify these selections but, for small processors, coordination and consulting the resin suppliers will be of great help. Also, for very intricate and special jobs, one may opt to use the services of a prototyping company where an actual product can be made, adjusted and finalised before a large production run. There are literally thousands of polymer resins available to moulders, which include standard ones, engineered resins and modified resins for special applications.

Polymer resins ready for moulding will generally be in the form of powders or pellets, with pellets being the first choice. They can be in their natural colour or coloured and packed in small- or large-volume packs. Each supply of material carries a data-processing guide of the material with any safety factors to be observed (if any) and also an indication of the melt flow index (which is very important to moulders). Thermoforming and thermosetting polymer materials can be injection-moulded but the emphasis is on thermoforming polymers.

Some of the common polymer resins used by injection moulders are: polyethylene (PE); polypropylene (PP); polyvinyl chloride (PVC); polystyrene (PS); acrylonitrile-butadiene-styrene; nylon and many others, including recycled materials. However, PCRH are offered as composite resins and the technology is quite new, so this chapter

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will discuss only composite resins made with PE and PP as the most popular composite productions on the market Later on in this chapter I will present a practical model with specifics on injection moulding with polymeric composite resins based on PE or PP as the matrix and rice hulls as the constituent reinforcement.

11.4 Injection moulding process

Injection moulding is primarily done with thermoforming (soften on heating and can be reused) polymers. However, smaller volumes of thermosetting (harden on heating and cannot be re-used) polymers, biodegradable plastics, and elastomers are also subjected to this process. There are several advantages in the injection-moulding process to produce a plastic part: high production volumes; little need to finish moulded parts; costs are lower than other processes despite the initial high cost of tooling. Injection moulding can be used to produce very complex parts and is often used as the preferred method if other processes are not practical. Other advantages of the injection-moulding process include efficient use of materials and energy, precision-formed parts and a negligible amount of waste generated that can go back into the production cycle.

Once the mould in two halves is mounted carefully on the platens on opposite sides, the set-up technician will test and synchronise its opening and closing by slow movement of the large operating door that controls this movement. The injection-moulding machine hopper is then filled with the polymer resin. The hopper will have a ‘throat-gate’ or valve that will give access to the screw barrel on which it is mounted. The hopper is designed to allow gravity feed of the polymer pellets or granules freely into the barrel. However, sometimes it is important to have a uniformity of resin pellet size and absence of contaminants to prevent constriction at the ‘throat’ of the hopper to ensure a smooth and continuous flow of material into the heated barrel, which has zonal heating for precise control of temperature. Modern machines have ‘closed-loop’ operations (i.e., the machine works to pre-set parameters and fluctuations will be negated within pre-set tolerances).

Plastic pellets will be subjected to heat for softening and the screw produces a hot homogenous melt that is carried along the screw and injected under pressure into an opening in the closed mould *via* an injection nozzle. The quantity of plastic material to be injected into the mould is pre-calculated and controlled by a ‘cushion’ (pre-set gap between the tip of the nozzle opening and the tip-end of the screw). This ensures that only a certain amount of hot material is injected. After pushing the material through the nozzle into the mould, the screw withdraws to wait for the next cycle. The flowing material inside the mould forms a frame-like structure, with the ‘sprue’ as the main supply line, and the multi-cavities are fed with hot plastic material through ‘runners’ and ‘gates’, which are part of the frame. This feed system can be cut-off and recycled. Some moulds are designed in such a

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way that it is stripped automatically from the parts on de-moulding. The mould undergoes a cooling cycle, after which the moulded parts are ejected from the mould. This same cycle is then repeated.

The quality of the moulded parts will depend to a great extent on: the quality of the mould; correct processing parameters such as temperature, pressure and cooling cycle; the mould design. The closed mould halves must fit exactly with no gaps otherwise small leakages of the hot material can cause ‘flash’. If filling a new or unfamiliar mould for the first time, in which the required shot-size is not known, a technician should reduce the nozzle pressure so that the mould fills but does not produce a flash with excess material. Sometimes this may have to be done gradually by trial and error, especially if dealing with very expensive or intricate moulds. An operator will have an electronic console in which readings can be taken periodically of the pre-set parameters. If a statistical process control (SPC) system is used, recording of the ‘cushion’ and related calculations will be of great importance to ensure the process is in ‘control’ and within the tolerances to ensure good parts.

Probably the most common injection-moulding machines are hydraulic oil machines that use the force of hydraulic fluids to move the mould through the mould. Also popular are the toggle injection-moulding machines that use mechanical links to open and close the mould. In addition, hybrid hydraulic/toggle machines have come on the market and become popular. These hybrid machines can eliminate some of the problems of the standard machines and also increase moulding rates as well as the rapid wear and tear of machines. With ongoing research, newer models with improved concepts are emerging for the benefit of moulders. Whatever the design, the basic principle of injection moulding has not changed.

11.5 Guidelines for injection moulding with composite resins

When polymer composite resins with wood fibre appeared on the market, injection moulders were cautious in their approach to these new composite materials. However, as they became more acquainted with them and considered the advantages of using these environmentally friendly materials and with constantly improving material quality and processing techniques, they are now using these composite resins with confidence. The availability of PCRH is opening up a whole new frontier with exciting possibilities.

Wood fibre blends have made a name for themselves and have been in use for some years in extrusion. Now they are moving effectively into injection moulding and compression moulding, though some moulders may be hesitant to use these new composite resins instead of the traditional resins with which they are more familiar with. A good example is PCRH.

However, with growing environmental concerns, rising petro-based resins costs, bio-degradable problems and other factors, injection moulders are showing a

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great interest in these new materials. Constant research and recent developments in the manufacture of these composite resins have significantly improved the quality, processing techniques and capabilities of these new materials. In fact, the latest generation of these composite resins can be processed efficiently on traditional equipment with minimal adjustments in process settings and with no other physical modification of hardware.

These PCRH can be made with various plastic resins such as low- and high-density PE; PP; PS; PVC; and others. They can be classified as a category of an emerging family of materials that can be termed ‘thermoplastic biocomposites’. It is a huge advantage for injection moulders that these resins are now available in different grades and properties. In general, the processing parameters for all grades are more or less the same and very similar to wood polymer composites.

Why use these composite resins? There are many compelling reasons to create products or to use them as an alternate material for products from these polymer rice hull resins. Because they contain ≥50% organic fibre, these materials offer injection moulders a material option that is more environmentally friendly than petrochemical-derived polymers. In addition to the ‘green’ factor, these composite resins reduce the moulder’s exposure to petroleum prices and reduce the energy costs associated with production while producing components with great structural rigidity, aesthetically pleasing finishes and highly marketplace-oriented end products. PCRH tend to be lower in cost and weight than unfilled or glass-filled resins, and are even competitive with resins filled with calcium carbonate or talc. An added advantage is lower density, which reduces costs and is beneficial in uses in which a premium is placed on lightweight applications such as in transportation, automotive, sports, toys, aviation and other consumer products.

Rice hulls are abundantly available in most countries at virtually no cost and are basically made up of opaline silica and a polymer called lignin. From the rice-milling process emerges two basic grades of hulls: coarse and fine. The particle size of hulls is important, as is the moisture content. Effective drying of hulls and further reduction of particle size is needed before the manufacture of composites. According to research and tests, rice hulls do not flame, smoulder transfer heat, or emit odours.

11.6 Selection of polymeric composite resins

Processing composite resins (and especially injection moulding composite resins) have had teething problems but over the years have settled down and these difficulties have been overcome. Although PCRH may be accepted as better composite resins, processing them needs a little more caution. For starters, one must be aware of the extra inherent heat-generating property and its natural abrasiveness as compared with standard polymer resins. Also, the probability is that rice hulls

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at the initial stages may contain a high content of moisture due to exposure to the weather. For ease of processing and to achieve good-quality products it is important to use high-quality pellets. Sections 11.6.1–11.6.3 describe some of the basic areas vital for selection of these pellets.

11.6.1 Moisture content

Surface moisture content should be <1.5%. Moisture content within the pellet should ideally be <1.0%. Increased moisture content and failure to control moisture content during processing results in ‘splay’ (whitish patches) and excessive brittleness.

11.6.2 Pellet characteristics

Pellets should be clean and relatively consistent in size and shape. There should be no chads or streamers. Powdery residues indicate the use non-standard pellet manufacturing equipment and poor maintenance of the equipment on the part of the manufacturer. Generally, a supplier of composite resins will include information in his/her datasheets. Large-volume producers may have their own *in situ* laboratories where tests can be carried out.

11.6.3 Correct grades

One of the benefits of PCRH is that they can be blended with additional pure resins while maintaining levels of polymer rice hulls. Through blending, moulders also can achieve different performance characteristics in addition to what is basically offered, such as flame-retardants, colouring, and extra-glossy grades. Thus, moulders have the option of selecting the correct grade(s) of these composite resins to suit particular applications.

11.7 Recommended processing guidelines

Injection-moulded finished products with these PCRH, if moulded appropriately with correct temperatures, speeds and a non-resistant flow path, will exhibit minimal stress, smooth surfaces, uniform colour distribution and no evidence of gassing. The two most important principles to remember if moulding with these composite resins are to avoid excessive heat and shear stress.

Some people may think that the rice hulls in composites will act as inhibitors but tests have shown that actually the reverse is true. For example, rice hull-propylene

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composites flow very quickly at relatively low temperatures and pressures, as a result of which injection moulders can achieve significant energy savings. An added feature is shorter cycle times and higher productivity due to the reduced mould filling and cooling times (less polymer content).

Temperature guidelines for moulding with PCRH resins are:
- Rear zone: 171.1–187.7 °C
- Middle zone: 182.2–198.8 °C
- Front zone: 193.3–210 °C
- Nozzle tip: 198.8–210 °C

Injection moulders have to adjust these parameters if using different grades to achieve the best results. Moulding pressures will depend on the part design as well as the runner system and gate design. In principle, moulding with these composites will require less pressure than moulding with traditional materials. However, moulders should be careful with mould-filling speeds. The hot material will tend to flow quickly, but avoiding excessive shot fill times is important because these materials are sensitive to shear stress. If streaking occurs, it can be remedied by slowing down the injection rate. Given that lower temperatures are suitable for moulding, hold times are often lower than for standard materials.

The nozzle tip used in processing these composites should have an orifice as close as possible to the diameter of the sprue to minimise shearing. Smaller orifices may cause increased shear as well as discolouration resulting from overheating of the material as it enters the mould. Injection-moulded parts with PCRH resins are ‘natural’ in colour with a very light-brown tone and uniform grain. However, they can be easily coloured and also have a matt or high-gloss finish as desired.

With the abundance of rice hull biomass available the world over and newer polymers from non-petrochemical sources being offered in the marketplace as well as ongoing composite development taking place, one could conclude that these exciting polymeric rice hull composites are materials with a great future for injection moulders. The availability of training programmes by some well-known manufacturers of these composite materials to assist injection molders can only enhance and establish the advantages of using them in comparison with traditional petrochemical-based materials.

11.7.1 Causes for rejection of parts in injection moulding

As in any manufacturing process, injection moulding is also subject to rejection of parts due to moulding faults. Some of the basic ones are:
- *Warp*: Insufficient cooling, de-moulding too fast
- *Blooming*: Colour not mixed properly, excess water present
- *Shrinkage*: Insufficient material, insufficient cooling, mould fault

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- *Splay*: Excess colour, colour not mixed properly
- *Streaking*: Excess material shear
- *Under-filled*: Insufficient material

In general, injection moulders employ strict quality-control methods, one of which is using SPC with International Organization for Standardization (ISO) standards such as ISO 9001, 9002 or the more sophisticated QS 9000 as required by the automotive industry.

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12 Polymeric composite resins in compression moulding

In the plastics moulding industry, in compression moulding, traditionally the polymer resins used have been virgin or recycled thermosets (harden on heating and cannot be reused) or thermoplastics (soften on heating and can be reused). Polymers in powder form, pellets or pre-pregs can be compression moulded easily. This process is generally used for moulding large solid parts, mostly for the industrial and automobile sectors. As discussed is Chapter 9, now PCRH are available and these can be moulded to produce large parts using conventional equipment and machinery. These new resins are available in their natural colour or in colour, and moulders also have the option of colouring *in situ*. Some of the advantages of using these composite resins include better properties and reduced material costs. Also, polymeric thermosetting composites with *rice ash* are available for compression moulding.

12.1 Uses of rice hull ash

I feel compelled to present some information on this valuable emerging commodity for the benefit of the reader. The very high content of silica in the ash mass, the availability in abundance in many countries and its cost-effectiveness has led to its use in many industrial applications and will no doubt create many new and diverse possibilities for the future.

12.1.1 Steel industry

Rice hull ash is used in the steel industry for producing high-quality flat steel, a plate product or a hot rolled strip product, which are usually employed in automotive body panels. The ash also finds application as an excellent insulator, having low thermal conductivity, a high melting point, low bulk-density and high porosity. This fine powder is used to insulate a container for pouring molten metal into a mould, enabling the prevention of rapid cooling of the steel pour and ensuring uniform solidification in a casting process.

12.1.2 Cement industry

Rice hull ash is used in the manufacture of low-cost building blocks and in the production of high-quality cement. Standard Portland cement is one of the most

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expensive components of concrete. The replacement of a portion of Portland cement with rice hull ash often improves affordability, particularly for low-cost housing. Addition of this ash to the cement speeds up the setting time of the concrete. At ≈35% replacement, the ash improves the compressive strength because of the higher content of silica. This ash cement will also have improved resistance to acid attacks as compared with ordinary Portland cement.

12.1.3 Other uses

With such a high content of silica in the ash, it is economical to extract the silica for various types of manufacture. The silica can also be precipitated in customised forms to meet the requirements of various uses. Some of these uses are in the rubber industry as a reinforcing agent, in cosmetics, in toothpastes as a cleaning agent, and in the food industry as an anti-caking agent.

Rice hull ash is used in the manufacture of refractory bricks because of its insulating properties. It is used in the production of low-cost and lightweight insulation boards. It can be used as an effective oil-spill absorbent and for use in waterproofing chemicals, flame retardants and as a carrier for pesticides and insecticides.

12.1.4 Rice hull ash in road building

In a little known rural village in India, some enterprising entrepreneurs, without any knowledge of science or chemistry, came up with a novel idea of using the abundant and difficult to dispose of plastic scrap. First the scrap was granulated into small pieces and introduced into a hot melt of bitumen, ≤60% of the total mass. The high temperature melted the plastics and a homogenous mix was the result. When this mix was used in road building, it was found to give a better, smoother and tougher surface. Vigorous tests carried out by officials proved that this surface could bear higher loads, did not crack, and rainwater had no effect on it. Moreover, the cheaper cost and a solution to the environmental concerns of how to dispose of these large amounts of plastic scrap were important. This impressive solution has been recognised by the Indian government and put into practice.

This technology is now spreading to other countries. For example, in Vancouver Canada, this technology is being used successfully. Here, I suggest that an addition of 10–15% of rice hull ash to the mix would give a better mix with improved compression strength (load bearing), smoother surface and a tougher product that will last much longer than the traditional bitumen only construction.

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12.2 What is compression moulding?

Compression moulding is a simple and cost-effective way to manufacture many large parts, especially for the industrial, automotive and air-travel sectors. It is similar to many other forms of moulding parts, whereby a polymer resin is put into a mould, heated, compressed and then cooled, with the end result virtually the same. This process is very common in industrial moulding.

There are many types of compression-moulded parts and processes. These parts distinguish themselves by the type of material used, the length of the reinforcing fibres, their size and surface quality. Each type of material and part has its own unique variation of a compression-moulding process. Here, we will discuss three of the widely used processes: compression moulding of sheet-moulding compound (SMC) parts; the injection–compression moulding of bulk-moulding compound (BMC) parts; and the compression moulding of long fibre-reinforced thermoplastics. SMC and BMC are fibre-reinforced thermosetting materials. The common matrix in SMC and BMC is unsaturated polyester crosslinked with styrene. The automotive industry is the largest user of SMC/BMC materials and parts. Phenolic polymers (probably the oldest synthetic polymers) are used for parts that require excellent part stability at elevated temperatures and high creep resistance. Furthermore, phenolic polymers deliver these qualities at prices that are comparable with acrylonitrile-butadiene-styrene.

The heart of the compression-moulding process is mould filling. From hand filling, this phase has advanced to specialised moulds in which charge weight is measured exactly before it is introduced into a mould. There is some variation in SMC, so it is often necessary to place small pieces of SMC on the centre of the charge to complete the full-weight of the part. The automotive industry has moved beyond using just compression-moulded parts to manufacture fibre-reinforced components to reduce weight to increase fuel efficiency. The versatility of PCRH, for example, to produce high-strength, lightweight and cosmetically superior parts has led to its use for critical structural parts and body panels, showcased in most of the high-end automobiles, such as sports cars and luxury cars.

Compression moulding usually functions by using a mould in two halves. The bottom half is fixed and stationary, whereas the top half of the mould moves up and down vertically. An electrically or hydraulically operated press is used with provision for heating both halves of the mould. If using thermosets, these raw materials must be heated before introduction into a mould to remove moisture content. These moulds can be simple designs or have intricate patterns. If choosing a press, it is important to ensure that the platens and daylight (mould-opening height) can be accommodated. The hot material becomes malleable and takes the set pattern of the mould easily. The moulded part is cooled inside the mould and then removed. If the raw material is in powder form there could be flash (excess material) that must be trimmed or buffed. Most presses are usually hydraulic because high pressure is often required for moulding.

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In general, only solid parts are moulded so the density and material distribution will be consistent throughout each moulded part. It is also possible to have a multi-cavity mould to produce many smaller parts that can be assembled into one large part later.

12.3 Brief history of compression moulding

In 1847, a plastic processing company was the first use compression moulding to mould small parts, particularly for domestic purposes. Undoubtedly, the machines would have been hand-operated ones and steam would have been heating medium. By the early 1900s, compression moulding had come a long way, with much-improved technology, and plastic product processors had begun to use thermosetting resins. Before that, the resin materials used in compression moulding were shellac-based thermoplastics. The first patented compression-moulding machine with a huge development in technology was in the 1930s. However, even these machines can be barely compared with modern machines, which are well advanced in technology, more efficient and available in manual, semi-automatic or automatic operation.

12.4 Raw materials for compression moulding

As the prices of polymer resins continue to increase, manufacturers of plastic products have been looking for more cost-effective pathways. For compression moulders, the availability of thermoplastic PCRH and thermosetting PCRH ash will solve this problem to a great extent. Both types of resins will give products with better properties and be less expensive.

12.4.1 Thermoplastic polymeric composite resins

It is more common to thermosetting resins than thermoplastic resins in compression moulding, but new technology is making it possible to use PCRH. For ease of moulding, these composite resins are available in the form of pellets in their natural colour or self-coloured. Moulders will also have the choice of polymeric composite resins with wood fibre. Excellent products can be made with these new types of resins.

12.4.2 Thermosetting polymeric composite resins

‘Rice hull ash’ is a general term describing all types of ash produced from burning rice husks used in various operations (e.g., steam-boiler fuel in agricultural

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projects). The nature of the ash produced depends on the burning conditions of rice husks. The silica in the ash undergoes structural transformations depending on the conditions, such as the duration and temperature of the burning process. The resulting ash will be of two types: (i) black and coarse powder, and (ii) grey and fine powder. Rice husks are high in ash compared with other biomass fuels. In the form of ash, the silica content can be ≥70–80%, highly porous and lightweight. This ash is absorbent and its insulating properties are useful for many industrial and building construction applications. Another use is the extraction of silica from rice hull ash for the manufacture of sodium silicate for adhesives.

Initially, compression-moulded products were made by virgin thermosetting polymer resins. Over the years, this trend has changed to the use of composites. Composite boards are commonly produced by combining a fibrous material (e.g., wood chips or flakes) as the reinforcement and a thermosetting synthetic resin (e.g., urea-formaldehyde) as the polymer matrix and curing the mass under heat and pressure. Further developments in this trend have produced composite resins with other thermosetting resins, such as phenol formaldehyde and melamine formaldehyde, combined with rice hull ash, as suitable for compression moulding. The ratio of polymer matrix to the reinforcing constituents depends on the end-product application. Many large parts can be made using these thermosetting composites with rice hull ash, but one important application is composite boards as walls and floors in the construction of buildings (enhanced strength and moisture resistance). They can also be used in the manufacture of furniture and many industrial applications.

12.5 Dangers and safety information

In general, compression-moulding machines are very large and dangerous if used inappropriately. These machines usually have safeguards that are activated if a part malfunctions. The safeguards must be installed appropriately, maintained regularly, and the heating systems checked often. Because the moulds mostly work with thermosetting plastics, the products can come out of the mould at high temperatures. Precautions must be taken at the time of part removal to prevent burns to operators.

Operators should also be alert at the time of opening and closing of the press platens. Probably the most common causes for accidents are improperly fitted guards, no guards, or negligence.

12.6 Compression-moulded products

Compression moulding is a versatile and popular processing method among plastic processors, especially for large parts. Compression moulding can be used in various sectors:

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- Automotive
- Construction
- Consumer
- Food services
- Industrial
- Medical

12.6.1 Compression moulding in the automotive industry

For decades, the automotive industry have been looking to compression moulders for supplies of parts needed for their motor vehicles. Although most parts may have been with thermosetting resins, thermoplastic resins are also an option if special properties such as light weight, high-strength and aesthetically pleasing parts are needed. For the latter, parts made from PCRH (in ‘leaf’ form) give a nice shiny ‘grainy’ finish. Transparent or translucent parts containing rice hulls would also have important uses. Simple compression-moulded automobile parts include light covers as well as coloured or transparent housings. Some of the automobile parts made with compression moulding are floor carpets, door handles, body panels, electrical housings, and consoles.

12.6.2 Compression moulding in the construction industry

Another big market for compression moulded parts is the construction industry. Small plastic concrete markers to large moulded door frames; partitioning panels; electrical boxes; and switch gear housings are made this way.

12.6.3 Compression moulding in the consumer sector

There is a wide range of products required by consumers, such as packs, containers, dust bins, boxes, and computer parts. Some of the most popular consumer products are melamine dinnerware made from melamine formaldehyde resin powder. Products range from plates, cups, saucers, and lunch boxes. These products are made in plain colour or with a print. They are cheap as compared with ceramic products, and thus a huge market exists. I have seen such production in India even as a ‘cottage industry’ in a small room, and the products were excellent.

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12.6.4 Compression moulding in the food services sector

Large and small trays; picnic boxes; boxes with compartments; large handles; handles for tools; and food-serving trays fall into this category.

12.6.5 Compression moulding in the industrial sector

Large computer housings; computer keyboards; musical keyboard bases; electrical wire housings; safety boxes; and products needing intricate patterns fall into this category. Flat-sheet laminates; laundry tubs; shower assemblies; structural frames; large electrical insulation parts; plug tops; electrical bases; insert moulded parts; bus supports; electrical insulators; electrical barrier parts; and airport/sports stadium seats are also made this way. In industrial applications, the compression-moulding possibilities are almost limitless.

12.6.6 Compression moulding in the medical sector

The medical sector is highly technical and calls for special plastic materials. Polymeric composite resins may have only limited applications but, because of the wide range of products needed in the medical sector for critical and non-critical applications, certain products such as safety disposal boxes; trays; laboratory equipment housings; first-aid boxes; and parts for wheelchairs can be made.

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Abbreviations

3D	Three-dimensional
ABS	Acrylonitrile-butadiene-styrene
BMC	Bulk moulding compound(s)
CFA	Chemical foaming agent(s)
CMC	Ceramic matrix composite(s)
DMC	Dough moulding compound(s)
EBS	Ethylene bistearamide
EPS	Expanded polystyrene
FRC	Fibre-reinforced composite(s)
FRP	Fibre-reinforced polymer(s)
GRP	Glass-reinforced plastic(s)
HDPE	High-density polyethylene
HIPS	High-impact polystyrene
ID	Inner diameter
IR	Infrared
ISO	International Organization for Standardization
L/D	Length:diameter ratio
LDPE	Low-density polyethylene
LFRT	Long fibre-reinforced thermoplastics
LLDPE	Linear low-density polyethylene
MDPE	Medium-density polyethylene
MFI	Melt-flow index
MW	Molecular weight
OD	Outer diameter
PA	Polyamide
PC	Polycarbonate
PCRH	Polymeric composites with rice hulls
PE	Polyethylene
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
RYB	Red, yellow and blue
SMC	Sheet moulding compound
SPC	Statistical process control
Tg	Glass transition temperature
uPVC	Unplasticised polyvinyl chloride
UV	Ultraviolet
WPC	Wood plastic composite

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Glossary

Accelerator chemical substance (catalyst) that increases the rate of chemical reaction.
Acoustic applications some composites are made to absorb sound.
Acoustic composites composites designed to dampen vibrations or sound.
Additive a substance added to a foam mixture to enhance or achieve a property.
Adjustable speeds ability of pumps and mixers of machines to work at different speeds.
After-cure period of time for further cure after all chemical reactions have ceased.
Ageing accelerated tests to determine changes in properties over time.
Agitators mechanisms that mix chemical components in tanks before mixing together.
Airflow a measure of the ease with which air passes through a foam sample.
Aliphatic division of organic compounds containing carbon with open-chain structures.
Ambient normal temperature of a room or environment.
Amine catalyst compound used to accelerate a blowing reaction.
Antioxidants materials added to foam to resist oxidation and improve properties.
Antistatic agents chemicals added to prevent accumulation of electrostatic charges.
Aromatic organic compounds containing a benzene ring.
Auxiliary blowing agent additive used in the production of foams that supplements the primary blowing agent to make foam softer or lighter.

Ball rebound an American Society for Testing and Materials (ASTM) test used to measure the surface resilience of a foamed product.
Batch mixer machine with a dispensing head in which all chemicals are mixed.
Batch mixing process in which all measured chemicals are mixed in one container.
Batch tank large containers in which two or three chemicals are mixed separately.
Blanket heater provides heat at desired levels for tanks containing chemicals.
Blowing agent a chemical compound that provides gas for foam expansion.
Blowing reaction a chemical reaction resulting in the release of carbon dioxide.
Board foot a unit of measurement (square foot by one inch).
Boiling gas generated during foaming that is not contained inside and escapes.
Bonding synonym for gluing, laminating or re-bonding.
Bulking agent material added to increase the volume of a mixture.
Bulk storage large tanks or containers to store components in large volumes.
Burp condition in which a ‘puff’ of gas is released during foaming.

Calibration synonym for controlled metering of components into a dispenser.
Catalysts compounds capable of increasing the speed of chemical reaction.
Catalyst mix a combination of catalysts to help balance blowing/gelation reactions.
Cell count the number of cells per linear inch or centimetre.
Cell membrane thin intact polymer film that forms a cell.
Cell size average diameter of pores (often referred to as ‘fine’, ‘medium’ or ‘coarse’).
Cellular plastic expanded or foamed plastic such as expanded polystyrene (EPS).
Centipoise 1/100th of a poise (viscosity is commonly expressed in poise).
Chain extension end-to-end lengthening of main polymer molecules chains.
Charging process of filling machine tanks with chemicals.
Chiller method of maintaining chemical components at desired temperatures.
Chopper device used to cutoff composite trims to small pieces.
Closed cells foam cells closed completely (e.g. semi-rigid or rigid foams).
Closed loop electronic automatic control system for set parameters.
Collapse sudden or complete loss of foam height after foam has risen.

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Colourant pigment or dyes used for colouring plastics.
Complete package a complete continuous processing line.
Components different constituents used in a composite mix.
Composite a material consisting of two or components combining to give more strength than each component separately.
Compression loss of initial height of foam due to body weight.
Compression load deflection resistance to compression of a composite sample.
Compressive strength resistance of a composite to compression.
Continuous mixing head mixing device such as on a continuous compounding machine.
Constituents the reinforcing components of a composite material.
Converting cutting and fabrication of composites as saleable items.
Conveyor belt moving surface of material (metal, rubber or other) used to move extruded profiles.
Core density density at the centre of a composite.
Cracks long, narrow openings or cavities due to faulty formulation or weighing.
Cross-section can refer to shape or area of a profile (e.g., round, square).
Crosslinking setting-up of chemical links between polymer molecules.
Crumbs very fine pieces of composites from shredding, milling or ground scrap.
Cubic centimetre measure of volume in the metric system.
Cubic metre cubic measurement in which length, width and height are all one metre.
Cure completion of a chemical reaction.
Curing time the time required to achieve the desired level of curing.
Cushion as used in injection moulding: distance set between the nozzle-end and screw tip.
Cutoff saw composite lumber device to make vertical cuts on a continuous line.

Day tanks batch or machine tanks for daily production.
Degree of polymerisation number of structural units (‘mers’) in the average polymer.
Density measurement of mass per unit volume (lb/ft^3 or kg/m^3).
Differential thermal analysis test used to assess the behaviour of composites exposed to high temperatures.
Dilantic a liquid that resists being moved but is fluid at rest.
Diluent a material used to extend or bulk-up another material without changing reactivity.
Dimensional stability ability of a plastic part or product to retain its original shape.
Dimer a substance comprising molecules formed from two molecules of a monomer.
Discharge orifice the opening through which the composite mix is discharged.
Discolouration the gradual yellowing of composites due to exposure.
Dryer heating device to remove moisture from fibres.
Dry heat ageing an accelerated aging test for formulation materials.
Durability how well a composite product retains its support and shape with use.
Dynamic balance describes the stability achieved on operating variables.
Dynamic fatigue a durability test undertaken in the laboratory using roller-shear or pounding-type mechanisms.

Elastic component viscosity resistance of some fluids to flow under shear force.
Elastic limit the point of deformation beyond which a material deforms permanently.
Elastic modulus the ratio between the force applied to cause deformation and the resistance.
Elastomer a rubber-like material (but not necessarily made of rubber).
Electric motor electrically driven motor (generally expressed as horse power (HP)).
Elongation the percentage of its original length to which a specially shaped sample will stretch.
Emulsifiers additives to a formulation that help in stabilising a mixture between the time of mixing and pouring.

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Emulsion a suspension of fine droplets of one liquid in another.

Equivalent weight the molecular weight of a chemical divided by the number of functional groups.

Exothermic heat-giving/generating chemical reaction (e.g. urethane foam reaction).

Extruder a machine with a screw for heating and mixing polymers.

Extrusion die a die with a profiled orifice set in an extrusion head.

Fast heat intense heat supplied to a mould to improve the skin quality and physical properties of a product.

Fast heat oven an oven that can supply the intense heat required for the ‘fast heat’ process.

Fibre natural or synthetic fibres such as rice hulls, hemp and wood fibres.

Fibre flour a very fine powder (e.g. rice hulls, wood fibres).

Filler an inert material added to a foam formulation to reduce costs/change physical properties.

Filter a device used to remove unwanted particles from liquid chemical streams.

Fine cells foam cells having a cell count of >80 per linear inch.

Fixed calibration time process of metering chemical liquids by a time limit (usually in seconds).

Fixed ratio having all components with a fixed throughput without variations.

Flak a slang term used to describe many small splits scattered widely.

Flame lamination sticking together composites and other material by heating/ melting.

Flame retardant composite material imparting a certain degree of resistance and slow burning.

Flammability degree of burning in various situations.

Flaps usually semi-circular internal blows or voids on the skin surface and connected inside also.

Flashing continual release of tiny bubbles of gas in a continuous foaming process.

Flex fatigue the loss of physical properties of a composite sample undergoing continuous flexing.

Flow lines pattern of high-density streaks or ridges radiating from bottom of composite.

Flow meter device used to gauge the flow of liquids.

Flow rate quantity of chemicals delivered to metering port.

Foam material produced with a gas reaction with open or closed cells.

Formula a list of components for the production of composites.

Formulation working out correct quantities of chemicals/components to achieve the desired results.

Functionality the number of reactive groups attached to a single molecule.

Gas loss net weight loss between chemicals used and final weight of foam.

Gelation rate the speed with which chain extensions and crosslinking reactions occur.

Gel strength the stability of the foaming mass.

Gelling reaction the increase in viscosity of the foaming mass caused by polymerisation of the liquids.

Grinders machines that produce small particles (also called shredders, cutters and hammer mills).

Hand batching the practice of weighing all ingredients by hand separately.

Hard spots high-density areas formed in a moulded composite product.

Haze smoke or fumes released from the foaming mass during the reaction.

Helix mixer a mixer that uses a helical spiral mixing technique.

High shear mixer a mixer with a blade or impeller that transfers a large amount of mechanical energy to a chemical mix in the form of heat.

Holding tanks storage tanks in which stable premixes are made and stored before use.

Humid ageing accelerated aging test for composites under high humidity and temperature.

Hydraulic a system by which energy is transferred from one place to another by compression and flow of fluid.

Hydraulic mixing head a mixing device in which the primary mixing is the turbulence created by the flowing streams of chemical components.

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Hydrophobic water repellent.

Hydrophilic affinity for water (composites with large open cells are more absorptive sponges).

Hydroxyl group the combined oxygen and hydrogen radical that forms the reactive groups on polyols.

Indentation force deflection index indicates support value of a foam based on compression. This value is the ratio of 65% divided by 25% (compression value). Index values >2 are considered good and values <1.75 considered poor for urethane foam.

Indentation force deflection value formerly called the RMA value. Taken as 25% compression.

Inhibitor a substance that slows down a chemical reaction. Sometimes used to prolong shelf-life.

Impeller the power-driven blades used to mix chemicals.

In-line cutters cutting machines installed directly on a continuous extrusion.

In-line mixer a special mixer that has been added to pre-mix one or more minor components before entering the main stream.

Integral skin foam a moulded composite foam product having a dense outer skin and soft core.

Inter-locked system practice of using a single power source to drive two or more fluid metering systems.

Internal mix practice of mixing the various components inside a mixing vessel and then discharging them through one or two ports.

Irregular cells a foam having a mixture of widely varying cells.

Isotropic foam characterised by having the same strength in all directions.

Jacketed tank a tank having an additional shell with cooling or heating devices.

K factor a measure of the insulation ability or thermal conductivity of a composite material.

Lag the delay or reduction in flow that occurs if a restriction in flow causes a build-up of pressure.

Lamination adhering two or more sheets together to form a thicker product.

Lead lag the problem of non-uniform flows of components at start-up.

Lead time the time between the end of mixing and extrusion.

Linear molecule a long-chain molecule in contrast to one having many side chains or branches.

Machine tanks tanks that form a part of a composite machine with metering pumps.

Manual flush a manual operation to clean the mixing head with solvent.

Mass effect the influence the total amount of chemicals poured has on the density.

Masterbatch a mixture resulting from premixing as many minor ingredients as possible.

Matrix a polymer acts as the matrix in polymer composites.

Mechanical mixing head a mixing device with a power-driven rotor and impeller.

Mer a basic unit in a plastic and the repeating structural unit in a polymer.

Mesh pack a set of fine steel mesh placed at the head of an extruder to prevent foreign matter entering.

Metering the calibrated flow of a composite mix through the extruder.

Metering system the pumping system used to accurately control the flow of a mix.

Methylene chloride a chlorinated hydrocarbon commonly used as a secondary blowing agent and as a cheap cleaning solvent in the plastics industry.

Mill in industry a ‘hammer mill’ is used to produce fine particles.

Mixer a mechanical device that can mix two or more materials together homogenously.

Modified pre-polymer a polymer system that has been modified by diluting the catalyst system with plasticisers and additives.

Modulus of elasticity the ratio of stress-to-strain in a material that is elastically deformed.

Monitoring checking of a process at various stages of production and afterwards.

Mould packing small percentage of excess total liquid poured to counter weight loss due to gas.

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Mould release agents chemical compounds applied to the insides of a mould to prevent cured products from sticking to the mould.

Moulding whereby a mix is put into a mould cavity to mould a shaped product (used in injection or compression moulding).

Nominal throughput range a throughput or flow rate capacity of a particular machine designed to handle normal formulations.

Nozzle a very general term used to describe the discharge opening or discharge port of the mixing head.

Nucleation generation of small uniform bubbles by an injection of air or other liquid chemicals to improve quality or for light weight.

Organotin catalysts a family of foam catalysts used to help in blowing and gelation.

Overfill the amount of unwanted excess of a composite mix poured into a mould intentionally or otherwise.

Permeability the rate at which a liquid or gas can penetrate through a material.

Pin impeller a rotating mixing blade having a straight shaft having a series of round, square or hexagonal shaped ‘pins’ mounted at right angles to the shaft. Other variations are possible.

Pin mixer a mixing head that uses a pin impeller.

Plastic one of many high polymeric substances, including natural and synthetic products but excluding rubbers.

Plasticiser chemical used as an additive in a formulation to increase the flexibility of a plastic product.

Pneumatic drive better known as air-actuated motion drives (e.g. a pneumatic cylinder).

Poise a measure of the specific viscosity (thickness) of a fluid.

Polycone a cone-shaped nozzle used to control the dimensions of the liquid stream coming from a mixing head.

Polymer a high-molecular-weight organic compound (natural or synthetic) whose structure is made up small repeating units (mers).

Polymerization the chemical reaction by which larger molecules are formed by the joining of smaller molecules.

Pore diameter cell size.

Portable cutters small, lightweight devices/machines used for cutting thin sheets.

Positive metering the ability to control the flow rate of a particular fluid with accuracy.

Post-cure the period of curing time after extrudates have been removed from the machine or conveyor.

Pour-in-place practice of pouring a liquid mix into a cavity and having it filled with the mix.

Pouring head a mixing and dispensing head designed for chemical liquids.

Pre-cure the time interval between pouring the chemical mix into a mould and removing the product without damage. Sometimes called the ‘handling time’.

Pre-cure oven an oven in which heat can be supplied to accelerate curing.

Pre-heat technique of heating moulds or cavities to desired temperatures before pouring.

Premix used synonymously with masterbatch or a composite mix.

Premix tanks tanks used for making batches of premix, separate from the machine.

Pressure force applied.

Pressure gauge a device for measuring/checking pressure. All processing machines are equipped with accurate pressure gauges in all flow circuits for process safety.

Profiles different shapes.

Powered conveyor a conveyor having the moving surface powered by a drive motor.

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Process variables factors in the chemical foaming process (e.g. the machine, room temperature) that could affect the quality of the final product.

Pumping impeller a blade designed to accurately move the liquids being mixed through the mixing zone and through the discharge orifice with uniform force.

Rat holes the large, irregular, normally elongated gas pockets usually found in foam in a foamed composite.

Ratio control the ability to change and regulate the ratio or proportion between two or more fluid components.

Raw materials the chemical ingredients used in the manufacture of polymeric composites.

Reactants general term for any of the raw material or intermediates used in a manufacture.

Reaction balance the important balance between the relative reaction rates of gas generation (blowing) and gelation (polymerisation).

Regulator a device used to control the flow of fluids.

Remote drive a drive motor (usually for a mixing head) that is located separately.

Reodorant a powerful, pleasant-smelling chemical that is added to a formulation to mask unpleasant odours (sometimes associated with amine catalysts).

Resilience an indicator of the surface elasticity or ‘springiness’ of a sample of composite.

Resin unsaturated polymers or monomers. Also called ‘plastic resins’.

Rheology the study of flow and deformation of matter.

Schematic diagram drawing that illustrates the design and layout of a machine, circuit or process in an abstract or symbolic manner.

Scrap generally refers to waste from a plastic manufacturing process and is an inherent waste-generation.

Screw a grooved or specially designed rotating steel shaft that transfers the heated material forward in injection moulding and extrusion.

Self-extinguishing the ability of a material to stop burning after it has started burning.

Shaping saws cutting devices that can produce any special shape desired.

Shear resistance the ability of a composite to resist laterally applied forces.

Shiny foam foams with high proportion of uniform cell membranes that glitter from reflected light.

Shot the total amount of a composite resin dispensed from an injector during one cycle.

Shot cycle the total time spent on ‘on’ and ‘off’ in a single unit of operation.

Shot cycle timer – a timing device used for automatic control of a shot cycle.

Shredder – a mechanical device used to reduce waste to small pieces.

Shrinking the loss in size that occurs during production. Can be due to excess heat and faulty formulations.

Silicones complex chemicals formed from a combination of silicon and organic groups. These are used widely in urethane foam formulations for cell structures.

Skins describes the high-density outer surface of an extruded composite profile.

Solid elastomer rubber-like compounds that have no internal cavities or gas bubbles.

Solid filler an insoluble additive used in foam formulations. Adds weight and reduces the cost of foam products.

Solvent a substance, usually liquid, used to dissolve another substance.

Solvent flush the cleaning of mixing tanks, chambers or mixing heads after each production cycle. Done manually or automatically.

Solvent flush timers timers used to control auto flushing systems.

Specific gravity the density (mass per unit volume) of any material divided by that of water.

Splashing a splattering that occurs if a mixed liquid is poured into a mould or onto a moving conveyor.

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Spreader a device used to assist in placement of a uniformly distributed layer of mixed liquids.

Stabilisers additives such as antioxidants and ultraviolet absorbers that help to maintain the quality of a foam. Silicone stabilisers add stability and control the semi-liquid foaming mass.

Stannous octoate one of the commonly used organotin catalysts used in the manufacture of flexible foams.

Stannous oleate an organotin catalyst less active than stannous octoate.

Static fatigue the loss in load-bearing properties of a composite sample after being under constant compression.

Stator blades non-rotating or non-moving baffles in a mixing chamber that assist mixing components.

Stoichemistry the relationship of the various combining weights of several interacting chemicals.

Stream the flow of liquid of one of the components in a formula.

Surfactants chemical compounds used in a foam formulation to help and control cell formation during foaming.

Surface active agent an additive to a foam formulation that helps or hinders the formation of a fine, uniform cell structure in the resulting foam.

Swelling excess moisture in a composite mix causes swelling of extrudate during extrusion.

Synergism the property exhibited by a blend of some materials having a greater effectiveness or chemical activity as a mixture than would ordinarily be expected from the sum of their independent abilities.

System an ambiguous term used to describe almost any combination or method of mechanical parts or chemicals that have some relationship with each other.

Tachometer a device used to indicate the speed of a mechanism (usually the number of revolutions per minute).

Tacky surface the condition of the surface of a processed composite that is still sticky. This feature could be due to insufficient cure time or faulty weighing or a faulty formulation.

Tear resistance the ability of a sample to resist tearing after a tear has been made.

Tear strength a measure of the force required to continue to tear a sample after it has been torn.

Tensile strength a measure of force required to stretch a standard sample of material to its breaking point.

Tertiary amine an amine catalyst used in foaming. Tertiary amines are more powerful than primary or secondary amines.

Thermal conductivity the ability of a material to conduct heat. Measured by the quantity of heat that passes through a unit cube of a substance in unit of time if the difference between the two faces is 1^o.

Thermal gravimetric analysis analysis of weight loss of a material sample at different temperatures through a decomposition point or decomposition zone.

Thermoplastic a material that can soften or melt at elevated temperatures without degradation and, upon cooling, retain its original condition. Material can be re-used (e.g. polyethylene and polystyrene plastics).

Thermosetting a material that is fully cured by elevated temperatures into a solid condition and cannot be recovered by re-heating. Material cannot be used again (e.g. polyurethane).

Thixotropic the ability of a fluid to be semi-solid at rest but revert to a liquid upon agitation or stirring.

Throughput control being able to vary the flow rate of a metering machine.

Throughput indicators any one of the several devices that have been calibrated for flow rates, such as tachometers and flow meters.

Throughput rating applies to metering machines and mixing heads that indicates the maximum flow rate that can be metered.

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Tolerance a specified acceptable allowance for deviations in measurements.
Top cracks cracks that appear in the top surface of a composite slab that extend across the width of the conveyor.
Top cure shortening the tack-free time of composite products or slabs by heat.
Transfer pumping the method of filling the processing machine tanks or keeping them filled.
Trichlorofluoromethane a chemical name for a fluorocarbon. It is a blowing agent or auxiliary blowing agent.
Trim results from the trimming of products that have been compressed-moulded or are slabs before conversion to products. After shredding, these products can be converted into saleable products.

Ultraviolet zone of invisible radiations beyond the violet end of the spectrum.
Ultraviolet stabiliser chemical compounds used to counter degradation by ultraviolet light.
Undercutting a condition that can result in flow lines, side and top cracking, and entrapment of large bubbles in the centre of a foamed composite.
Underfill insufficient pour of a chemical mix resulting in not filling a mould fully.

Velocity balance a lead-lag problem under some conditions of metering and mixing machine operations in which pressures are balanced exactly.
Vertical cutting saws special cutting bandsaws in which the blades used for cutting are in the vertical plane.
Vertical pour pour-in-place operations.
Viscous a flow condition of any fluid or mix more resistant to flow than water.

Water absorption degree of water absorption if composites are exposed to the weather.
Weathering when a material is exposed to the weather.

Yield point in compression or tension loading of a composite sample, the point at which permanent deformation takes place.
Yield strength the force required to bring a specified sample of a composite to the yield point.

Zones in processing machines, there are different zones such as a feed zone and metering zone.

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Appendices

Appendix 1 Conversion table of units commonly used in industry

	To convert	Into	Multiply by
Airflow	ft^3/min	litre/sec	0.4719
	ft^3/min	m^3/sec	0.0004719
Coating	g/m^2	oz/yd^2	0.0295
	ounce/yd^2	ounce/m^2	33.90
Density	lb/ft^3 (pcf)	kg/m^3	16.018
	kg/m^3	pcf	0.0624
	pcf	g/cc (g/cm^3)	0.016
	g/cm^3	pcf	62.43
	g/L	pcf	0.0624
Energy	joule	ft-lb	0.7573
	joule	in-lb	8.85
	ft-lb	joule	1.355
	in-lb	joule	0.113
	Btu	joule	1.055×10^3
ILD or IFD (load-bearing)	lb/50 in^2	N/323 cm^2	4.448
	N/323 cm^2	lb/50 in^2	0.225
	lb/50 in^2	kg/323 cm^2	0.4536
	kg/323 cm^2	lb/50 in^2	2.2
Length	angstrom	metre	1×10^{-10}
	metre	micron	1×10^6
	micron	angstrom	1×10^4
Pressure and stress	lb/in^2 (psi)	(kpa)kN/m^2	6.895
	kN/m^2 (or kPa)	lb/in^2	0.145
	kg/cm^2	kPa	98.07
	kg/cm^2	psi	14.223
	psi	kg/cm^2	0.0703
	psi	Pa	6895
	Pa	psi	0.000145

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(continued)

	To convert	Into	Multiply by
	g/cm^2	psi	0.01422
	psi	$dyne/cm^2$	68965
	$dyne/cm^2$	psi	0.0000145
	bar	atm	0.987
	bar	kg/cm^2	1.02
	bar	Pa	1×10^5
	$dyne/cm^2$	atm	9.869×10^{-7}
	psi	atm	0.068
	Pa	$dyne/cm^2$	10
	MPa	psi	145
	atm	Pa	1.013×10^5
	$dyne/cm^2$	Pa	0.1
Tear strength	ib/in	N/cm	1.75
	N/cm	lb/in	0.571
	N/m	lb/in	0.00571
	lb/in	N/m	175.1
	lb/in	kg/cm	0.1786
	kg/cm	lb/in	5.6
	kN/m	N/cm	10
	kg/cm	N/cm	9.798
Temperature	°C	°F	9/5 (°C) + 32
	°F	°C	(5/9) (°F – 32)
	°C	K	°C + 273.15
Volume	litre	in^3	61.023
	litre	US gallon	0.264
	litre	ft^3	0.0353
	US fl oz	ml	29.6
	US fl oz	m^3	2.957×10^{-5}
	US gallon	litre	3.79
	litre	m^3	0.001
	m^3	litre	1,000
	litre	US fl oz	33.819

(continued)

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(continued)

	To convert	Into	Multiply by
	US fl oz	British fl oz	1.0408
	Board foot	m^3	2.359×10^{-3}
Viscosity	Centipoise = centistrokes × density		
	Pascal second (Pa·s)	centipoise	1,000
	centipoise	Pa·s	0.001
	mPa·s	centipoise	1
Weight	g	metric tonnes	1×10^{-6}
	g	kg	0.001
	g	ounces (avdp)	0.0352739
	g	lb (avdp)	0.0022026
	ounces (avdp)	g	28.3495
	ounces (avdp)	metric tonnes	2.83495×10^{-5}
	metric tonnes	kg	1,000
	metric tonnes	lb	2,240

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Appendix 2 Suppliers of polymers, additives, machinery and rice hulls

There are many suppliers for polymers and additives from sources in North America, Europe and Asia. However, polymer composite technology is virtually new, so the list shown below represents a few of the machinery suppliers who specialise in composite extrusion technology. The names of suppliers of rice hulls are provided for the benefit of the reader but other sources should also be researched for maximum benefit.

A2.1 Polymer suppliers

- BASF AG, Germany
- Dow Corporation, USA
- Bayer AG, Germany
- Union Carbide (Canada) Limited, Canada
- Hoechst AG, Germany
- Celanese Corporation, USA
- Eastman Chemical Company, USA
- Georgia-Pacific Chemical Division, USA

A2.2 Suppliers of additives

- Acme-Hardesty Company, USA
- Americhem Incorporated, USA
- Clariant Masterbatches Division, USA
- Eastman Chemical Company, USA
- Colors for Plastics Incorporated, USA
- Color Master Incorporated, USA
- Techmer PM, USA
- Rockwood Specialities, USA
- Ferro Corporation, USA
- Plasticoncentrates Incorporated, USA
- National Plastic Colors Incorporated, USA
- Lonza Incorporated, USA
- International Speciality Products, Germany
- Honeywell Specialty Additives, USA

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A2.3 Suppliers of machinery

- Reifenhauser GmbH & Company, Germany
- Maplan Corporation, USA
- Harden Industries Limited, China
- Wuhan Plastic Machinery Products Company Limited, China
- Davis Standard LLC, USA
- Coperion K-Tron, USA
- Crown Machines UWP Incorporated, USA
- Cincinnati Milacron, USA

A2.4 Suppliers of rice hulls

- Rice Hulls Specialty Products Incorporated, USA
- Al Maryam International, Pakistan
- Yuvaraj Agro Impex, India
- Gia Gia Nguyen Company Limited, Vietnam
- Wagasa PTE Limited, Singapore
- Psalm Agency, Malaysia

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