Recent Development of Fiber Reinforced Composite Materials

CHAPTER · JULY 2014

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Recent Development of Fiber Reinforced Composite Materials

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Abstract

Natural fibers such as jute, coir, sisal, pineapple, ramie, bamboo, banana, etc., have been the focus in the development of natural fiber composites; primarily in value added application. The versatile material system so developed has potential for wood substitute applications like door shutters, flooring tiles, roofing sheets, partitions, etc., and is envisaged to significantly contribute towards forest conservation and environmental protection. Polyester resin of fire retardant grade was used for preparing the composite. In the polymerization process, cobalt naphthonate and methyl ethyl ketone peroxide (MEKP) as catalyst were used. The study reveals that the developed polymer–natural fiber–industrial (inorganic) wastes (fly ash, red mud) composites attain far superior mechanical properties and resistance to abrasive wear, fire, water absorption, weathering and chemical attack, as compared to their conventional counterparts such as wood, medium density fiber (MDF) boards, particle boards, etc. Relevant engineering properties such as physical and mechanical resistance to abrasive wear, weathering, fire, etc., of the plant fiber-reinforced polymer matrix composites so synthesized were characterized. The effects of fiber content, matrix type and interfacial bonding on the tensile and flexural properties of these composite materials have been determined through extensive testing at different conditions. The mechanical properties of natural fibers were improved by using a chemical treatment process and improved the mechanical properties of composite materials. Shrinkage of fibers during this process has significant effects on the fiber structure, as well as on the mechanical fiber properties, such as tensile strength and modulus. The tensile strength, initial modulus and elongation at break were evaluated for untreated and treated fibers. One of the current studies, which focused on thermoplastics, utilizing natural fiber compounded with a thermoplastic resin (polyethylene, polypropylene, PVC, etc.), has yielded

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excellent wood substitute. The development of green reinforced composites for a wide range of applications is also a recent trend. There have been efforts to develop new pathways to produce natural polymers with better mechanical properties and thermal stability using nanotechnology; and to use natural polymers to make biodegradable plastics and their composites with lignocellulosic fibers. In the production of composite board, phenol formaldehyde and urea formaldehyde are the most used thermosetting resins and many researchers have produced particle boards from lignocellulosic materials. The suitability of particle board for interior and exterior use is based on the water absorption and swelling in water. From the increase in mass and dimensions, the percent water absorption and percent swelling along surface and thickness were calculated. Board prepared with a mixture of UF and PF resins in different proportions gave variable MOR and water absorption properties. Studies strongly suggest that newly developed plant fiber or industrial waste-reinforced polymer composite materials are quite capable of serving as a potential cost and energy effective, technologically viable and attractive option to conventionally used wood and other identical materials. This chapter includes an overview of the developments made in the area of fiber reinforced composites, in terms of market, processing methods, matrix-reinforcement systems, morphology, properties and product development. Some critical issues and future works are also discussed.

**Keywords:** Medium density fiber (MDF), MOR, UF and PF resins, matrix-reinforcement

### 13.1 Introduction

Three-thousand years ago natural fibers were used for the first time in composite systems in ancient Egypt, where straw and clay were mixed together to build walls. Over the last decade, polymer composites reinforced with natural fibers have received ever-increasing attention, both from the academic world and from various industries. There are a wide variety of different natural fibers which can be applied as reinforcement or fillers. Increased environmental consciousness throughout the world has developed an increasing interest in natural fibers and their applications in various fields. Natural fibers are now considered an important field.

Environmental and economical concerns are stimulating research in the development of new materials for construction, furniture, packaging and automotive industries. Particularly attractive are the new materials, a good part of which are based on natural renewable resources, thereby preventing further stresses on the environment caused by the depletion of dwindling wood resources from forests. Examples of such raw material sources are annual growth native crops plant fibers, which are abundantly available
in tropical regions. These plant fibers (like jute and sisal) have been used for hundreds of years for many applications such as in ropes, beds, bags, etc. If new uses of fast growing, native plants can be developed for high-value, non-timber-based materials, there is a tremendous potential for creating jobs in the rural sector. These renewable, non-timber-based materials could reduce the use of traditional materials such as wood, minerals and plastics for some applications.

Research on natural fiber composites has existed since the early 1900s but has not received much attention until late in the 1980s. Composites, primarily glass but including natural reinforced composites, are found in countless consumer products including boats, skis, agricultural machinery and cars [1–3]. A major goal of natural fiber composites is to lessen the need to use expensive glass fiber ($3.25/kg), which has a relatively high density (2.5 g/cm³) and is dependent on nonrenewable sources [1, 3].

Plant waste fibers can be described as lignocellulosic, i.e., resources comprised primarily of cellulose, hemicelluloses and lignin. Lignocellulosics include wood, agricultural residues, water plants, grasses and other plant substances [4]. In the building materials industry, the “term” composite is often used in a board sense to describe woody materials bonded together by adhesives covering the entire gamut of plywood, oriented strand board, wafer board, fiber board and other types of paneling products. Such natural fiber thermoplastic composites find a wide array of applications in the building and construction industry such as door and window frames, decking material, railings for parapet wall systems, furniture sections (park benches, etc.) and others. These can also cater to a number of industrial applications. All such products are fabricated by extrusion through properly designed dies. Thermoplastic composite is consistent and uniform in properties due to intimate compounding of resin and natural and natural fiber/filler. While positioned against wood, they score much better in terms of dimensional stability, no water absorption and hence, no swelling in moist weather, better fungal resistance, reduced thermal linear expansion, etc. The workability of the composite is also quite good in terms of its ability to be sawn and nailed or screwed by conventional methods.

Plant waste fibers have the composition, properties and structure that make them suitable for uses such as composite, textile and pulp and paper manufacture. Biomass, including agricultural crops and residues, forest resources and residues, animal and municipal wastes, is the largest source for cellulose in the world. Organic plant waste such as oil palm, pineapple, banana and coconut fiber are annually renewable, available in abundance and of limited value at present. These lignocellulosic by-products could be a principle source for fibers, chemicals and other industrial products [5].
The use of natural fibers as reinforcing materials in both thermoplastics and thermoset matrix composites provides positive environmental benefits with respect to ultimate disposability and best utilization of raw materials [6, 7].

Natural fiber-reinforced resin matrix composites have to overcome many challenges in order to be commonly used as engineering materials. A common drawback of these composites is the large variability of their mechanical properties, in many instances associated with low mean values for their properties [8, 9]. These characteristics are due to the intrinsic variability of the properties of the fibers, the susceptibility of natural fibers against moisture, and poor wetting of the fibers by the resin matrix. Considerable work has been done in order to improve the strength of fiber/matrix interface [10–13], but much work has yet to be done in order to guarantee the reliability of natural fiber composites.

Recently much work has been devoted to the use of agricultural fibers, particularly cellulose fiber derived from plants in reinforcement of commodity thermoplastics such as polyethylene (PE) [14–16] and polypropylene (PP) [17–20]. Agricultural fibers are interesting materials to use for the reinforcement of polymer because they are usually of lower density than inorganic fibers, environmentally friendly and relatively easy to obtain [21]. It is anticipated that the fibers would not contribute to the wear of polymer processing equipment and may not suffer from size reduction during processing, both of which occur when inorganic fibers or filler are used. Although the absolute property increase when using organic fibers is not anticipated being nearly as high as inorganic fibers, the specific properties are anticipated to be high owing to the much lower density of the organic fibers [17].

Ecological concerns and the impending depletion of fossil fuels are driving the development of new biobased, green product. Over the past few decades, the possibility of exploiting natural fibers (biofibers) as load bearing constituents in composite materials has been exposed and has produced encouraging results [22–25]. Industrial use of these natural fiber-reinforced composites is increasing due to their relative cheapness compared to conventional materials and their potential to be recycled. As a result, natural fiber-reinforced plastics are of interest as a replacement for synthetic fiber-reinforced plastics in an increasing number of industrial sectors, including the automotive and packaging industries, and in furniture production.

New environmental legislation as well as consumer pressure has forced manufacturing industries to search for new materials that can substitute for conventional non-renewable reinforcing materials, such as carbon and
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glass fibers. On account of this, in recent years, the use of natural fiber including banana, sisal, hemp and flax, jute, coconut and oil palm have attracted scientists and technologists for application in consumer goods, low-cost housing and other civil structures [26–28]. Natural fibers are very attractive for composite material because of their advantages compared to synthetic fibers; these include lower levels of skin and respiratory system irritation during handling, reducing tool wear during processing, good recyclability, abundant supply, low cost, low density, high specific strength-to-weight ratio, nontoxicity and biodegradability [27, 29, 30].

Jute, sisal, banana and coir (coconut fiber) are the major sources of natural fibers. Sisal and banana are cellulose rich (> 65%) and show tensile strength, modulus and failure strain comparable with other cellulose rich fibers like jute and flax, whereas the lignin rich (> 40%) coir fiber is relatively weak and possesses high failure strain. These fibers are extensively used for cordage, sacks, fishnets, matting and rope and as filling for mattresses and cushions (e.g., rubberized coir). Cellulose fibers are obtained from different parts of plants, e.g., jute and ramie are obtained from the stem, sisal, banana and pineapple from the leaf, cotton from the seed and coir from the fruit and so on.

Two major factors currently limit the large-scale production of natural fiber composites. First, the strength of natural fiber composites is very low compared to glass. This is often a result of the incompatibility between the fiber and the resin matrix. The wettability of the fibers is greatly reduced compared to glass and this constitutes a challenge for scale up productions. Though when comparing specific strengths, natural fibers are not much less than glass fiber composites.

The second factor limiting large-scale production of natural fiber composites is water absorption. Natural fibers absorb water from the air and direct contact from the environment. This absorption deforms the surface of the composites by swelling and creating voids. The result of these deformations is lower strength and an increase in mass. Additionally, with water absorption rates as high as 20 wt%, the light weight advantage is often nullified.

At the present time, technology is used to manufacture materials from agricultural waste which is considered a substitute for natural wood. Natural fibers are rapidly emerging in composite applications where glass fibers (predominantly E-glass) have been traditionally used. This is particularly true within the automotive and construction industries. These natural fibers provide several benefits: low cost, “green” availability, lower densities, recyclability, biodegradability, moderate mechanical properties, and their abundance. Their uses have found entry into both the thermoset and thermoplastic composites market places. Industries are rapidly learning how
to effectively process these natural resources and use them in numerous composite applications. Typically they are used with well-recognized thermoset resin families: polyesters, vinyl esters and epoxies. Thermoplastic resin matrices are also commonly seen within the commercial markets: polypropylene, low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene, Nylon 6 and Nylon 6, 6 systems [31].

In recent years, there has been great interest in the development of biodegradable polymers as a key solution to environmental problems [32, 3]. These biodegradable polymers are mainly the aliphatic polyesters produced by microbiological and chemical synthesis, natural polymer-based products, and their blends [33–40]. Among them, poly(lactic acid) (PLA), polycaprolactone (PCL), polybutylenesuccinate (PBS), and polybutylene succinate– butylenecarbonate (PBSC) are commercially available at present. The main effort of this study is to develop a completely biodegradable composite using wood fiber, with PCL or PBSC as the matrix polymer. In fact, the interest stems from the fact that the biodegradable polymers used in the study show relatively rapid biodegradability in soil, and hence composites with wood fibers would be biodegradable. Polycaprolactone is being widely used as a soft plastic in the field of film and packaging. Microorganisms and enzymes to assist in degradation have already been found. Blends of PCL and various other polymers, including composites with starch, have been developed, and compatibilizers for improving their interfacial adhesion have also been reported [33, 34, 38, 39]. Another possible matrix polymer, PBSC, is a crystallizable thermoplastic with polyester and polycarbonate units that possesses properties similar to common thermoplastics such as polypropylene and polyethylene. The biodegradability, processibility, and mechanical properties of PBSC can be controlled by changing the carbonate unit ratio [40–42]. Table 13.1 shows the average global production volume of different natural fibers.

13.2 History of Natural Fiber Use

Natural fibers have traditionally been used in all cultures of the world to meet basic requirements of clothing, storage, building material, and for items of daily use such as ropes and fishing nets. People in olden times used various kinds of natural fibers depending on their local availability. The first composite material in history was apparently made with clay and straw 3000 years ago in Egypt to build walls. Hemp was cultivated in China in 2800 BC and is considered one of the oldest natural fibers used for making products, along with linen. Hemp in Greek and Latin terminology was
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Table 13.1 Estimated global production volume averages of different natural fibers (in million metric tonnes per year average over the recent years) [43].

<table>
<thead>
<tr>
<th>Fibers</th>
<th>Mill. tonnes</th>
<th>Main producer countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>25</td>
<td>China, USA, India, Pakistan</td>
</tr>
<tr>
<td>Kapok</td>
<td>0.03</td>
<td>Indonesia</td>
</tr>
<tr>
<td>Jute</td>
<td>2.5</td>
<td>India, Bangladesh</td>
</tr>
<tr>
<td>Kenaf</td>
<td>0.45</td>
<td>China, India, Thailand</td>
</tr>
<tr>
<td>Flax</td>
<td>0.50</td>
<td>China, France, Belgium, Belarus, Ukraine</td>
</tr>
<tr>
<td>Hemp</td>
<td>0.10</td>
<td>China*</td>
</tr>
<tr>
<td>Ramie</td>
<td>0.15</td>
<td>China</td>
</tr>
<tr>
<td>Abaca</td>
<td>0.10</td>
<td>Philippines, Equador</td>
</tr>
<tr>
<td>Sisal</td>
<td>0.30</td>
<td>Brazil, China, Tanzania, Kenya</td>
</tr>
<tr>
<td>Henequen</td>
<td>0.03</td>
<td>Mexico</td>
</tr>
<tr>
<td>Coir</td>
<td>0.45</td>
<td>India, Sri Lanka</td>
</tr>
<tr>
<td>Wool</td>
<td>2.2</td>
<td>Australia, China, New Zealand</td>
</tr>
<tr>
<td>Silk</td>
<td>0.10</td>
<td>China, India</td>
</tr>
</tbody>
</table>

*China has announced a substantially increase in hemp production for textiles in the coming years to 1.5 million tonnes of fiber per year.

cannabis, which led to the word canvas, as hemp was used for making sails of boats. Flax or fine linen was used for burial shrouds of Egyptian pharaohs. Similarly, nettle was used for making fishing nets in olden times. India is rich in plant resources and the use of a variety of natural fibers such as banana, pineapple, sisal, hemp, coconut, palm, grasses, etc., was prevalent in olden times. Their use became limited once cotton acquired prime status in plant fibers. In cotton production, organic cotton accounts for a very small percentage of total cotton production. Silk, linen and jute are other natural fibers that have continued to enjoy popularity.

Asian markets have been using natural fibers for many years. For example, jute is a common reinforcement in India. While in Europe, natural fibers are increasingly being used in the automotive industry. In 1999 consumption was 21,300 tons and by 2000 this had risen to 28,300 tons. Packaging is a further application in Europe, particularly in Germany. In
North America, polymer composites amount to a 300,000 ton/year market for use in building and garden products, particularly decking.

13.3 Characteristics and Uses of Natural Fibers

Natural fibers are typically about 30–50 percent lower in density when compared to E-glass fibers, and roughly the same as the aramid commercial grade systems. This advantage has made natural fibers quite attractive to use within the automotive industry across a wide range of applications with both thermoset and thermoplastic resin matrices. In fact the stiffness of some of these natural fibers can be higher than or equivalent to that of E-glass. Flax, sisal and kenaf fibers also tend toward a higher stiffness. Hence, for stiffness-driven designs, these fibers are reasonable options. Their abundance, and a growing understanding of their processibility, makes them attractive to engineers.

Natural cellulose-based fibers are gaining increasing attention in the engineering of composite material where light weight is required. Beside their light weight, plant fibers have the advantages of low cost and little tool wear during processing. Cellulose fibers exhibit a highly polar surface due to the presence of hydroxyl groups. These hydroxyl groups enable the formation of hydrogen bonds in the interface of reinforced composite materials. But in order to get access to these hydroxyl groups, a cover of pectin and other waxy substances must be removed. On the other hand, the high polarity of the cellulose fiber surface is the reason for their hydrophilic behavior, which induces fiber swelling. Intense surface treatment is therefore required for fiber cleaning and preparation for interfacial bonding.

Coir is a natural fabric which is obtained from the fibrous husk of a coconut. It is stress resistant, biodegradable and buoyant. Coir is used to make sacking, twine, doormats and items such as bags and ropes. Coir can also be used in construction and to improve clays. It is a good fabric to control soil erosion.

Cotton is one of the best known natural fabrics. The fiber grows around the seeds of the cotton plant and has been used since about 3000 BC. Cotton is soft, strong, flame retardant, hypo-allergenic and easy to wash. It is the most popular natural fabrics used in making clothing. It is also used to make home furniture, bags and medical products. Heavyweight cotton fabric can be used to make items such as shoes and tents.

Hemp is quite unusual in that it is both very soft and durable. It can be used for many things, from work clothing to home decoration such as table linens, dish towels and sheets. It has a great luster and dyes easily.
Another widely used natural fabric is jute. It is economical and strong, reusable and repairable. Jute fabric comes in a number of varieties including hessian, CBC, sacking, a heavy fabric variety, jute yarn, webbing and nonwoven felt. It is a good insulator of electricity and heat. Examples of items made from jute fabric include fashion apparel, soft luggage, backing for carpets, inner spring webbing for car seats and bags or sacks for packing.

Linen is hypoallergenic and protects against sun radiation. It has been used for over 10,000 years and is luxurious and comfortable. Linen is obtained from the flax plant. It is strong and can absorb up to 20 times its own weight in liquid. It is used for rugs, painting canvases and apparel.

Ramie is stronger than linen or cotton. It is obtained from the ramie plant. Ramie is strong, absorbent and can be easily dyed. Its uses include clothing, pillow cases, tablecloths, sacks and cable insulation.

The strength characteristics of fiber depend on the properties of the individual constituents, the fibrillar structure and the lamellae matrix [44]. Natural fibers exhibit considerable variation in diameter along with the length of individual filaments. Quality and other properties of fibers depend on factors such as size, maturity and processing methods adopted for the extraction of fiber [45]. Properties such as density, electrical resistivity, ultimate tensile strength and initial modulus are related to the internal structure and chemical composition of fibers [45]. The structure, microfibrillar angle, cell dimensions, defects, and the chemical composition of fibres are the most important variables that determine the overall properties of the fibers.

### 13.4 Advantages of Natural Fibers

- Low specific weight, which results in a higher specific strength and stiffness than glass. This is a benefit especially in parts designed for bending stiffness.
- It is a renewable resource, the production requires little energy; CO$_2$ is used while oxygen is given back to the environment.
- Producible with low investment at low cost, which makes the material an interesting product for low-wage countries.
- Friendly processing, no wear of tooling, no skin irritation.
- Thermal recycling is possible, where glass causes problems in combustion furnaces.
- Good thermal and acoustic insulating properties
13.5 Disadvantages of Natural Fibers

- Variable quality, depending on unpredictable influences such as harvesting time, age and body of the plant from which they are extracted, the extraction techniques and the environmental conditions of the site.
- Lower strength properties, moisture absorption, which causes swelling of the fibers and decreases fiber’s mechanical properties
- Restricted maximum processing temperature, i.e., possibility of degradation at moderate temperature (230–250°C).
- Hydrophilic nature of fiber surface, due to the presence of pendant hydroxyl and polar groups in various constituents, which lead to poor adhesion between fibers and hydrophobic matrix polymers [46, 47]. The hydrophilic nature can lead to swelling and maceration of the fibers.
- Lower durability, fiber treatments can improve this considerably.
- Poor fire resistance.

13.6 Natural Fibers and Their Chemical Composition

Natural fibers primarily consist of: cellulose, hemicelluloses, pectin and lignin. The individual percentage of these components varies with the different types of fibers. This variation can also be affected by growing and harvesting conditions. Cellulose is a semicrystalline polysaccharide and is responsible for the hydrophilic nature of natural fibers. Hemicellulose is a fully amorphous polysaccharide with a lower molecular weight compared to cellulose. The amorphous nature of hemicelluloses results in it being partially soluble in water and alkaline solutions [21]. Pectin, whose function is to hold the fiber together, is a polysaccharide like cellulose and hemicellulose. Lignin is an anamorphous polymer but unlike hemicellulose, lignin is comprised mainly of aromatics and has little effect on water absorption [48, 49]. The chemical compositions of some natural fibers are summarized in Table 13.2.

13.7 Mechanical Behavior of Natural Fiber

The mechanical properties of natural fibers can depend on the source, age, growth, origin, cellular morphology and chemical composition and
**Table 13.2** Chemical compositions of various natural fibers [50].

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Cellelose (wt %)</th>
<th>Hemicellulose (wt%)</th>
<th>Lignin (wt%)</th>
<th>Waxes (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaca</td>
<td>56–63</td>
<td>20–25</td>
<td>7–9</td>
<td>3</td>
</tr>
<tr>
<td>Alfa</td>
<td>45.4</td>
<td>38.5</td>
<td>14.9</td>
<td>2</td>
</tr>
<tr>
<td>Bagasse</td>
<td>55.2</td>
<td>16.8</td>
<td>25.3</td>
<td>–</td>
</tr>
<tr>
<td>Bamboo</td>
<td>26–43</td>
<td>30</td>
<td>21–31</td>
<td>–</td>
</tr>
<tr>
<td>Banana</td>
<td>63–64</td>
<td>19</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>Coir</td>
<td>32–43</td>
<td>0.15–0.25</td>
<td>40–45</td>
<td>–</td>
</tr>
<tr>
<td>Cotton</td>
<td>85–90</td>
<td>5.7</td>
<td>–</td>
<td>0.6</td>
</tr>
<tr>
<td>Caraua</td>
<td>73.6</td>
<td>9.9</td>
<td>7.5</td>
<td>–</td>
</tr>
<tr>
<td>Flax</td>
<td>71</td>
<td>18.6–20.6</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Hemp</td>
<td>68</td>
<td>15</td>
<td>10</td>
<td>0.8</td>
</tr>
<tr>
<td>Henequen</td>
<td>60</td>
<td>28</td>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>Isora</td>
<td>74</td>
<td>–</td>
<td>23</td>
<td>1.09</td>
</tr>
<tr>
<td>Jute</td>
<td>61–71</td>
<td>14–20</td>
<td>12–13</td>
<td>0.5</td>
</tr>
<tr>
<td>Kenaf</td>
<td>72</td>
<td>20.3</td>
<td>9</td>
<td>–</td>
</tr>
<tr>
<td>Kudzu</td>
<td>33</td>
<td>11.6</td>
<td>14</td>
<td>–</td>
</tr>
<tr>
<td>Nettle</td>
<td>86</td>
<td>10</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Oil Palm</td>
<td>65</td>
<td>–</td>
<td>29</td>
<td>–</td>
</tr>
<tr>
<td>Piassava</td>
<td>28.6</td>
<td>25.8</td>
<td>45</td>
<td>–</td>
</tr>
<tr>
<td>Pineapple</td>
<td>81</td>
<td>–</td>
<td>12.7</td>
<td>–</td>
</tr>
<tr>
<td>Ramie</td>
<td>68.6–76.2</td>
<td>13–16</td>
<td>0.6–0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Sisal</td>
<td>65</td>
<td>12</td>
<td>9.9</td>
<td>2</td>
</tr>
<tr>
<td>Sponge gourd</td>
<td>63</td>
<td>19.4</td>
<td>11.2</td>
<td>3</td>
</tr>
<tr>
<td>Straw(wheat)</td>
<td>38–45</td>
<td>15–31</td>
<td>12–20</td>
<td>–</td>
</tr>
<tr>
<td>Sun hemp</td>
<td>41–48</td>
<td>8.3–13</td>
<td>22.7</td>
<td>–</td>
</tr>
</tbody>
</table>
separating techniques of the fibers. When bundles of fibers, referred to as technical fibers, are tensile tested the tensile performance is almost completely linear elastic. This is believed to be caused because the pectin interface between the fibers prevents local rotations. The same mechanism is believed to be also valid in a composite where the adhesive prevents these rotations. The decreasing stiffness with increasing diameter was a consequence of the geometry of the dislocations. The dislocation was kinked in the tangential direction. Together with the helical structure of the cellulose, the effect of this assumption was that the angle of the dislocation increases for an increasing diameter of the fiber, which in turn gave a decrease of the tensile stiffness of the fiber [51]. Table 13.3 summarizes characteristic values for the density, diameter, and mechanical properties of natural as compared to conventional reinforcing fibers.

Table 13.3 Mechanical properties of natural fibers as compared to conventional reinforcing fibers [21,61,62].

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Density (g/cm³)</th>
<th>Elongation (%)</th>
<th>Tensile Strength (MPa)</th>
<th>Young's modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>1.5–1.6</td>
<td>3.0–10.0</td>
<td>287–597</td>
<td>5.5–12.6</td>
</tr>
<tr>
<td>Jute</td>
<td>1.3–1.46</td>
<td>1.5–1.8</td>
<td>393–800</td>
<td>10–30</td>
</tr>
<tr>
<td>Flax</td>
<td>1.4–1.5</td>
<td>1.2–3.2</td>
<td>345–1500</td>
<td>27.6–80</td>
</tr>
<tr>
<td>Hemp</td>
<td>1.48</td>
<td>1.6</td>
<td>550–900</td>
<td>70</td>
</tr>
<tr>
<td>Ramie</td>
<td>1.5</td>
<td>2.0–3.8</td>
<td>220–938</td>
<td>44–128</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.33–1.5</td>
<td>2.0–14</td>
<td>400–700</td>
<td>9.0–38.0</td>
</tr>
<tr>
<td>Coir</td>
<td>1.2</td>
<td>15.0–30.0</td>
<td>175–220</td>
<td>4.0–6.0</td>
</tr>
<tr>
<td>Softwood kraft</td>
<td>1.5</td>
<td>–</td>
<td>1000</td>
<td>40.0</td>
</tr>
<tr>
<td>E–glass</td>
<td>2.5</td>
<td>2.5–3.0</td>
<td>2000–3500</td>
<td>70.0</td>
</tr>
<tr>
<td>S–glass</td>
<td>2.5</td>
<td>2.8</td>
<td>4570</td>
<td>86.0</td>
</tr>
<tr>
<td>Aramide (normal)</td>
<td>1.4</td>
<td>3.3–3.7</td>
<td>3000–3150</td>
<td>63.0–67.0</td>
</tr>
<tr>
<td>Carbon (standard)</td>
<td>1.4</td>
<td>1.4–1.8</td>
<td>4000</td>
<td>230.0–240.0</td>
</tr>
</tbody>
</table>
Natural (plant) fibers are nonabrasive towards mixing and molding equipment, which can contribute to significant equipment maintenance cost reductions. They also present safer handling and working conditions compared to synthetic reinforcements, such as glass fibers. Their processing is environmentally friendly, offering better working conditions and, therefore, a reduction in risk of dermal or respiratory problems. The most interesting aspect of natural (plant) fibers is their positive environmental impact. Natural (plant) fibers are renewable resources, which mean they are biodegradable and their production requires little energy [52]. A major drawback of natural (plant) fibers compared to synthetic fibers is their non-uniformity, variety of dimensions, and their mechanical properties (even between individual natural [plant] fibers in the same cultivation) [53]. Therefore, the major task to be solved in order to boost the acceptance of natural (plant) fibers as a quality alternative to conventional reinforcing fibers, is to develop high-performance, natural fiber-reinforced composites [54, 55].

Natural (plant) fibers generally contain large amounts of the hydroxyl group, which makes them polar and hydrophilic in nature. However, most plastics are hydrophobic in nature. The addition of hydrophilic natural (plant) fibers to hydrophobic plastic will result in a composite with poor mechanical properties due to non-uniform fiber dispersion in the matrix, and an inferior fiber matrix interphase [56]. This polar nature also results in high moisture absorption in natural (plant) fiber-based composites, leading to fiber swelling and voids in the fiber matrix interphase. Moisture, if not removed from natural (plant) fibers prior to compounding by drying, will result in a porous product. High moisture absorption could also cause deterioration in mechanical properties and loss of dimensional stability [57, 58]. These problems are generally solved by fiber surface treatment or matrix modifications [57–59]. Another major limitation in exploiting the use of natural (plant) fibers is the limited thermal stability possessed by natural (plant) fibers. They undergo degradation when processed beyond 200°C; this further limits the choice of plastic materials to be used as matrix [53, 60].

13.8 Methods for Surface Modification of Natural Fiber

The largest advantages to using natural fibers in composites are the cost of materials, their sustainability and density. Natural fibers can cost as little as $0.50/kg, and can be grown in just a few months [63]. They are also easy
to grow and have the potential to be a cash crop for local farmers. Natural fibers are also significantly lighter than glass, with a density of 1.15–1.50 g/cm$^3$ versus 2.4g/cm$^3$ for E-glass [64]. Two major factors currently limit the large-scale production of natural fiber composites. First, the strength of natural fiber composites is very low compared to glass. This is often a result of the incompatibility between the fiber and the resin matrix. The wettability of the fibers is greatly reduced compared to glass and this constitutes a challenge for scale-up productions. Though when comparing specific strengths, natural fibers are not much less than glass fiber composites.

The treatment of fibers is currently an area of research receiving significant attention. The absorption of water is commonly thought to occur at the free hydroxyl groups on the cellulose chains. With a ratio of 3 hydroxyl groups per glucose repeat unit, the amount of water that can be absorbed is substantial. By capping the hydroxyl groups this ratio can be reduced. There are several promising techniques that have been studied by various groups [21, 48, 49, 65–69]. Among these treatments the mercerization (alkaline) treatment has had the most reviews [21, 48, 49, 65, 66]. Utilizing silanes as coupling agents is a treatment commonly used in glass composite production and is starting to find uses in natural fiber composites [21, 49, 65, 67, 68]. Acetylation is another treatment that is common with cellulose to form a hydrophobic thermoplastic and has the potential to have the same results on natural fibers [21, 48, 49, 69]. Reinforcing fiber can be modified by physical and chemical methods.

### 13.8.1 Physical Methods

Physical methods such as stretching [70], calendaring [71, 72], thermo treatment [73] and production of hybrid yarns [74, 75] do not change the chemical composition of the fibers. Physical treatments change structural and surface properties of the fiber and thereby influence the mechanical bonding to polymers.

Electric discharge (corona, cold plasma) is another way of physical treatment. Corona treatment is one of the most interesting techniques for surface oxidation activation. This process changes the surface energy of cellulose fibers [76] and in the case of wood surface activation, increases the amount of aldehyde groups [77].

The same effects are reached by cold plasma treatment. Depending on the type and nature of the used gases, a variety of surface modifications could be achieved. Surface crosslinking could be introduced, surface energy could be increased or decreased, or reactive free radicals [76] and groups [78] could be produced.
Electric discharge methods are known [79] to be very effective for “non-active” polymer substrates such as polystyrene, polyethylene, polypropylene, etc. They are successfully used for cellulose fiber modification to decrease the melt viscosity of cellulose-polyethylene composites [80] and improve the mechanical properties of cellulose-polypropylene composites [76].

An old method of cellulose fiber modification is mercerization [70, 81–84], which has been widely used on cotton textiles. Mercerization is an alkali treatment of cellulose fibers; it depends on the type and concentration of the alkaline solution, time of treatment, tension of the material as well as on the additives [81, 84]. At present there is a tendency to use mercerization on natural fibers as well. Optimal conditions of mercerization ensure the improvement of the tensile properties [81–83] and absorption characteristics, which are important in the composing process.

In recent years the use of plasma for treatment of natural fibers has gained more prominence since it provides a “greener” alternative for the treatment of natural fibers for the development of polymer composites, but is of particular interest to polymer composites incorporating biopolymer matrices, since this technique provides further credence to the whole idea of “green” materials [85]. Sustainability and end of life after use are important considerations to make when developing polymer composites from renewable resources; these considerations include the toxicity and environmental impact of using various chemical or physical methods for improving the properties of these materials. Some chemical techniques may be toxic, e.g., isocyanates are carcinogenic and, therefore, the use of such agents may not be feasible for the development of polymer composites from renewable resources. Physical methods involving plasma treatments have the ability to change the surface properties of natural fibers by formation of free radical species (ions, electrons) on their surfaces [86]. During plasma treatment, the surfaces of the materials are bombarded with a stream of high-energy particles within the stream of plasma. Properties such as wetting, surface chemistry and surface roughness of material surfaces can be altered without the need for employing solvents or other hazardous substances. Alternative surface chemistries can be produced with plasmas by altering the carrier gas and depositing different reactive species on the surfaces of natural fibers [87]. This can then be further exploited by grafting monomeric and/or polymeric molecules onto the reactive natural fiber surface, which can then facilitate compatibility with the polymer matrix.

13.8.1.1 Surface Modification by Plasma Treatment

Low-temperature plasma treatment is a quite new technology for natural fiber textiles; plasma is essentially a dry process providing modification of
the top nanometer surface [88]. The advantages of plasma technology are its potential environmental friendliness and energy conservation benefits in developing high-performance materials [88]. It offers many advantages against wet techniques: there are no harmful chemicals, wet processes, wastewater, and mechanical hazards to textiles, etc. In addition it has a specific impact on the surface and gives the surface some properties that cannot be obtained by conventional techniques [89].

Plasma treatment as an activation method for the surface of cotton fabric is used to improve copper adhesion to the fabric surface, followed by the deposition of the metallic layers by vacuum evaporation technology. The results of our previous research evince that plasma activation of the material's surface, followed by the deposition of the metallic layer by vacuum evaporation, positively influences copper concentration on the surface and evenness of copper coating [90].

In vacuum evaporation technology, plasma treatment and coating with copper is a two-stage process. It is possible to significantly simplify this process by the method of magnetron sputtering, which unites the two processes mentioned above in one. This is a quick, ecological process, yielding practically no waste, and is characterized by high repeatability, stability and efficiency.

### 13.8.2 Chemical Methods

Chemical treatments include treatment with the help of alkali, silane, acetylation, benzoylation, acrylation, isocyanates, permanganate, etc.

#### 13.8.2.1 Alkaline Treatment

Alkaline treatment, or mercerization, is one of the most used chemical treatments of natural fibers when used to reinforce thermoplastics and thermosets. The important modification done by alkaline treatment is the disruption of hydrogen bonding in the network structure, thereby increasing surface roughness. This treatment removes a certain amount of lignin, wax and oils covering the external surface of the fiber cell wall, depolymerizes cellulose and exposes the short length crystallites [45]. Addition of aqueous sodium hydroxide (NaOH) to natural fiber promotes the ionization of the hydroxyl group to the alkoxide [91].

\[
\text{Fiber– OH} + \text{NaOH} \rightarrow \text{Fiber–O–Na} + \text{H}_2\text{O}
\]

Thus, alkaline processing directly influences the cellulosic fibril, the degree of polymerization and the extraction of lignin and hemicellulosic
compounds [92]. In alkaline treatment, fibers are immersed in NaOH solution for a given period of time. Ray et al. [93] and Mishra et al. [94] treated jute and sisal fibers with 5% aqueous NaOH solution for 2 h up to 72 h at room temperature. Similar treatments were attempted by Morrison et al. [95] to treat flax fiber.

Garcia et al. [96] reported that 2% alkali solution for 90 s at 200°C and 1.5 MPa pressure was suitable for degumming and defibrillation to individual fibers. These researchers observed that alkali led to an increase in amorphous cellulose content at the expense of crystalline cellulose. It is reported that alkaline treatment has two effects on the fiber: (1) it increases surface roughness, resulting in better mechanical interlocking; and (2) it increases the amount of cellulose exposed on the fiber surface, thus increasing the number of possible reaction sites [97]. Consequently, alkaline treatment has a lasting effect on the mechanical behavior of flax fibers, especially on fiber strength and stiffness [92].

Van de Weyenberg et al. [98] reported that alkaline treatment gave up to a 30% increase in tensile properties (both strength and modulus) for flax fiber–epoxy composites and coincided with the removal of pectin. Alkaline treatment also significantly improved the mechanical, impact fatigue and dynamic mechanical behaviors of fiber-reinforced composites [99–101]. Jacob et al. [101] examined the effect of NaOH concentration (0.5, 1, 2, 4 and 10%) for treating sisal fiber-reinforced composites and concluded that maximum tensile strength resulted from the 4% NaOH treatment at room temperature.

Mishra et al. [102] reported that 5% NaOH-treated sisal fiber-reinforced polyester composite had better tensile strength than 10% NaOH-treated composites. This is because at higher alkali concentration, excess delignification of natural fiber occurs, resulting in a weaker or damaged fiber. The tensile strength of the composite decreased drastically after a certain optimum NaOH concentration.

### 13.8.2.2 Silane Treatment

Silane is a chemical compound with chemical formula SiH₄. Silanes are used as coupling agents to let glass fibers adhere to a polymer matrix, stabilizing the composite material. Silane coupling agents may reduce the number of cellulose hydroxyl groups in the fiber–matrix interface. In the presence of moisture, hydrolyzable alkoxy group leads to the formation of silanols. The silanol then reacts with the hydroxyl group of the fiber, forming stable covalent bonds to the cell wall that are chemisorbed onto the fiber surface [91]. Therefore, the hydrocarbon chains provided by the
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application of silane restrain the swelling of the fiber by creating a cross-linked network, due to covalent bonding between the matrix and the fiber. The reaction schemes are given as follows [91].

\[
\text{CH}_2\text{CHSi (OC}_2\text{H}_5)_3 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{CHSi (OH)_3} + 3\text{C}_2\text{H}_5\text{OH}
\]

\[
\text{CH}_2\text{CHSi (OH)_3} + \text{Fiber - OH} \rightarrow \text{CH}_2\text{CHSi(OH)_2} - \text{Fiber} + \text{H}_2\text{O}
\]

Many researchers applied silane treatment in surface modification of glass fiber composites [103–106]. Silane coupling agents were also found to be effective in modifying natural fiber–polymer matrix interface and increasing the interfacial strength. In one instance, 3-aminopropytrimethoxysilane with concentration of 1% in a solution of acetone and water (50/50 by volume) for 2 h was reportedly used to modify the flax surface [98]. Rong et al. [107] soaked sisal fiber in a solution of 2% aminosilane in 95% alcohol for 5 min at a pH value of 4.5–5.5 followed by 30 min air drying for hydrolyzing the coupling agent. Silane solutions in a water and ethanol mixture with concentration of 0.033% and 1% were also carried out by Valadez et al. [97] and Agrawal et al. [91] to treat henequen fibers and oil palm fibers. It was verified that the interaction between the silane coupling agent modified fiber and the matrix was much stronger than that of alkaline treatment, which led to composites with higher tensile strength from silane-treated than alkaline-treated fiber. Thermal stability of the composites was also improved after silane treatment.

13.8.2.3 Acetylation

Acetylation describes a reaction introducing an acetyl functional group (\(\text{CH}_3\text{COO}^–\)) into an organic compound. Acetylation of natural fibers is a well-known esterification method causing plasticization of cellulosic fibers. The reaction involves the generation of acetic acid (\(\text{CH}_3\text{COOH}\)) as by-product which must be removed from the lignocellulosic material before the fiber is used. Chemical modification with acetic anhydride (\(\text{CH}_3\text{C ( =O) - O - C ( = O) - CH}_3\)) substitutes the polymer hydroxyl groups of the cell wall with acetyl groups, modifying the properties of these polymers so that they become hydrophobic [108]. The reaction of acetic anhydride with fiber is shown as:

\[
\text{Fiber - OH} + \text{CH}_3\text{ - C ( = O) - O - C ( = O) - CH}_3 \rightarrow \\
\text{Fiber - OCOCH}_3 + \text{CH}_3\text{COOH}
\]
Acetylation can reduce the hygroscopic nature of natural fibers and increases the dimensional stability of composites. Acetylation was used in surface treatments of fiber for use in fiber-reinforced composites [107–110]. Acetylation treatment of sisal fiber was reported to improve the fiber–matrix adhesion. The procedure included an alkaline treatment initially, followed by acetylation. Mishra et al. [100] investigated the acetylation of sisal fibers. Dewaxed sisal fiber was immersed in 5 and 10% NaOH solution for 1 h at 30°C; the alkaline-treated fiber was soaked in glacial acetic acid for 1 h at 30°C; it was decanted and soaked in acetic anhydride containing one drop of concentrated H_2SO_4 for 5 min. Nair et al. [111] treated raw sisal fiber in 18% NaOH solution, then in glacial acetic acid and finally in acetic anhydride containing two drops of concentrated H_2SO_4 for a period of 1 h. The treated surface of sisal fiber reportedly became very rough and had a number of voids that provided better mechanical interlocking with the polystyrene (PS) matrix. A hypothetical model of interface between the sisal fiber and PS composites has been postulated. Meanwhile, the thermal stability of treated fiber composites was found to be higher than that of untreated fiber composite because of better thermal stability of treated fibers and improved fiber–matrix interactions in treated fiber composites [111]. It was also reported that acetylated natural fiber-reinforced polyester composites exhibited higher bioresistance and less tensile strength loss compared to composites with silane-treated fiber in biological tests [112].

13.8.2.4 Benzoylation Treatment

Benzoylation is an important transformation in organic synthesis [113]. Benzoyl chloride is most often used in fiber treatment. Benzoyl chloride includes benzoyl (C_6H_5C=O) which is attributed to the decreased hydrophilic nature of the treated fiber and improved interaction with the hydrophobic polystyrene (PS) matrix. The reaction between the cellulosic hydroxyl group of the fiber and benzoyl chloride is shown in the following equation [44].

\[
\text{Fiber} - \text{OH} + \text{NaOH} \rightarrow \text{Fibre} - \text{O}^- \text{Na}^+ + \text{H}_2\text{O}
\]

Benzoylation of fiber improves fiber matrix adhesion, thereby considerably increasing the strength of composite, decreasing its water absorption.
and improving its thermal stability. Joseph et al. [44] and Nair et al. [111] used NaOH and benzoyl chloride (C₆H₅COCl) solution for surface treatment of sisal fibers. A hypothetical model of the interface of PS benzoylated sisal fiber composite has been postulated by Nair et al. [111]. It was observed that the thermal stability of treated composites were higher than that of untreated fiber composites. A similar method was also applied by Wang [114] to improve the interfacial adhesion of flax fiber and polyethylene (PE) matrix. The fiber was initially alkaline pretreated in order to activate the hydroxyl groups of the cellulose and lignin in the fiber; then the fiber was suspended in 10% NaOH and benzoyl chloride solution for 15 min. The isolated fibers were then soaked in ethanol for 1 h to remove the benzoyl chloride and finally were washed with water and dried in the oven at 80°C for 24 h.

13.8.2.5 Acrylation and Acrylonitrile Grafting

Acrylation reaction is initiated by free radicals of the cellulose molecule. Cellulose can be treated with high energy radiation to generate radicals together with chain scission [21]. Acrylic acid (CH₂=CHCOOH) can be graft polymerized to modify glass fibers [115, 116]. Sreekala et al. [117, 118] used acrylic acid in natural fiber surface modification. Oil palm fibers were mixed with 10% NaOH for about 30 min and then treated with a solution of acrylic acid at 50°C for 1 h at various concentrations. The fibers were washed with aqueous alcohol solution and dried. The tensile strength of oil palm fiber–PE composites did not increase. Other chemical treatments on oil palm fibers were also investigated, including alkaline, acetylation, peroxide, permanganate, silane and acrylation. Treatments like silane and acrylation led to strong covalent bond formation, and thereby the tensile strength and Young's modulus of treated fibers were improved marginally. However, it was reported by Li et al. [119] that the tensile strength of acrylic acid-treated flax fiber–HDPE composites was improved and the water absorption of composites was decreased.

Acrylonitrile (AN) is also used to modify fibers. The reaction of AN with fiber hydroxyl group occurs in the following manner [45]:

\[
\text{Fiber– OH + CH}_2=\text{CHCN} \rightarrow \text{Fibre – OCH}_2\text{CH}_2\text{CN}
\]

Graft copolymerization of AN on sisal fibers was studied by Mishra et al. [94] using a combination of NaIO₄ and CuSO₄ as initiator in an aqueous medium at temperatures between 50 and 70°C. Reaction medium, treatment time, initiator, AN concentration and even fiber loading influenced the graft effect. It was found that untreated fibers absorbed the most water
and 25% AN-grafted sisal fibers absorbed the least water, suggesting that changes in chemistry of the fiber surface reduced the affinity of fibers to moisture. It was also found that grafting of chemically modified fibers with 5% AN brought a higher increase in tensile strength and Young’s modulus of fibers than grafting with 10 and 25% AN. The explanation for this was that grafting at low concentration of AN may create orderly arrangement of polyacrylonitrile units. Mishra et al. [94] also concluded that optimum graft yield was obtained for treatment duration of 3 h.

Sreekala et al. [118] treated oil palm fiber with AN in 1% H₂SO₄ solution after alkali and KMnO₄ oxidized pretreatment. However, the expected increase in fiber-matrix adhesion and reduction in water sorption on fiber-reinforced phenol formaldehyde (PF) composites after treatment were not observed.

13.8.2.6 Permanganate Treatment

Permanganate is a compound that contains permanganate group MnO₄⁻. Permanganate treatment leads to the formation of cellulose radical through MnO³-ion formation. Then, highly reactive Mn³⁺ ions are responsible for initiating graft copolymerization as shown below [62]:

\[
\text{Cellulose} - \text{H} + \text{KMnO}_4 \rightarrow \text{Cellulose} - \text{H} - \text{O} - \text{Mn} - \text{OK}^+ \\
\text{Cellulose} - \text{H} - \text{O} - \text{Mn} - \text{OK}^+ \rightarrow \text{Cellulose} + \text{H} - \text{O} - \text{Mn} - \text{OK}^+ 
\]

Most permanganate treatments are conducted by using potassium permanganate (KMnO₄) solution (in acetone) in different concentrations with soaking duration from 1 to 3 min after alkaline pretreatment [99, 109, 117, 118, 120]. Paul et al. [109] dipped alkaline-treated sisal fibers in permanganate solution at concentrations of 0.033, 0.0625 and 0.125% in acetone for 1 min. As a result of permanganate treatment, the hydrophilic tendency of the fibers was reduced, and thus the water absorption of fiber-reinforced composite decreased. The hydrophilic tendency of fiber decreased as the KMnO₄ concentrations increased. But at higher KMnO₄ concentrations of 1%, degradation of cellulosic fiber occurred, which resulted in the formation of polar groups between fiber and matrix.
13.8.2.7 Peroxide Treatment

In organic chemistry, peroxide is a specific functional group or a molecule with the functional group ROOR containing the divalent ion O=O. Organic peroxides tend to decompose easily to free radicals of the form RO; RO then reacts with the hydrogen group of the matrix and cellulose fibers. For example, the peroxide initiated free radical reaction between PE matrix and cellulose fibers is shown by the following [99, 109]:

\[
\begin{align*}
\text{RO} - \text{OR} & \rightarrow 2\text{RO} \\
\text{RO} + \text{PE} - \text{H} & \rightarrow \text{ROH} + \text{PE} \\
\text{RO} - \text{Cellulose} - \text{H} & \rightarrow \text{ROH} + \text{Cellulose} \\
\text{PE} + \text{Cellulose} & \rightarrow \text{PE} - \text{Cellulose}
\end{align*}
\]

Benzoyl peroxide (BP) \((\text{C}_6\text{H}_5\text{CO})_2\text{O}_2\) and dicumyl peroxide (DCP) \((\text{C}_6\text{H}_5\text{C(CH}_3)_2\text{O})_2\) are chemicals in the organic peroxide family that are used in natural fiber surface modifications. In peroxide treatment, fibers are coated with BP or DCP in acetone solution for about 30 min after alkali pretreatment [109, 117, 118]. Peroxide solution concentration was 6% [109] and saturated solutions of peroxide in acetone were used [117, 118]. Sreekala et al. [170] observed that high temperature was favored for the decomposition of the peroxide; peroxide-treated oil palm fiber-reinforced phenol formaldehyde (PF) composites could withstand tensile stress at a higher strain level. Joseph and Thomas [99] investigated BP and DCP treatment on short sisal fiber-reinforced PE composites. The tensile strength values of composites increased with the increase in concentration of peroxide up to a certain level (4% for DCP and 6% for BP) and then remained constant. As a result of peroxide treatment, the hydrophilicity of the fibers decreased [109] and the tensile properties increased [99].

13.8.2.8 Isocyanate Treatment

An isocyanate is a compound containing the isocyanate functional group \(-\text{N}=\text{C}=\text{O}\), which is highly susceptible to reaction with the hydroxyl groups of cellulose and lignin in fibers. Isocyanate is reported to work as a coupling agent used in fiber-reinforced composites [99, 109, 110]. The reaction between fiber and isocyanate coupling agent is shown below [62]:

\[
\begin{align*}
\text{R} - \text{N} = \text{C} = + \text{HO} - \text{Fibre} & \quad \text{R} - \text{N} - \text{C} = \text{O} - \text{Fibre}
\end{align*}
\]
where R could be different chemical groups (such as alkyl).

George et al. [121] treated pineapple leaf fiber with polymethylene-polyphenyl-isocyanate (C_{15}H_{10}N_{2}O_{2}) solution at 50°C for 30 min to improve the fiber–matrix interfacial adhesion. Comparing silane and isocyanate-treated wood fiber–PS composites, it was reported that isocyanate treatment was more effective than silane treatment in enhancing the mechanical properties of cellulose fiber PS composites [122]. Sreekala et al. [117] reported that toluene-2, 4-diisocyanate (TDIC)-treated oil palm fiber–PF composites had lower tensile strength and Young’s modulus than permanganate-, peroxide- and alkaline-treated fiber PF composites, but had higher tensile strength and similar Young’s modulus with silane- and acrylic acid-treated fiber PF composites.

13.8.2.9 Other Chemical Treatments

Stearic acid (CH₃(CH₂)₁₆COOH) in ethyl alcohol solution was investigated in fiber treatment by Paul et al. [109] and Zafeiropoulos [123]. It was reported that this treatment removed non-crystalline constituents of the fibers, thus altering the fiber surface topography. Zafeiropoulos [123] also observed that treated flax fibers were more crystalline than the untreated ones and stearation decreased the fiber surface free energy.

Sodium chlorite (NaClO₂) usually is used in bleaching fibers; however, it could delignify lignocellulosics. Studies have been conducted wherein it was used in fiber surface treatment for composites. Mishra et al. [124] dipped untreated sisal fiber, for use in sisal–PS biocomposites, in sodium chlorite solution with a liquor ratio of 25:1 at 75°C for 2 h. Tensile strength of bleached sisal fiber–PS composite was less than other chemically treated fiber composites, which may be due to the fact that delignification of the fiber lowered its tensile strength [124]. But it was reported that flexural strength was better for bleached fiber composite because of lower stiffness and more flexible character of fibers after delignification. After delignification, the polymer replaces the role of lignin in fibers and makes composites more hydrophobic and tougher [124]. Li et al. also reported a similar result on the tensile strength of bleached composites using sodium chlorite on flax fiber–PE composites [119].

It was also reported that triazine (C₃H₃N₃) derivatives (e.g., C₃N₃Cl₃) could form covalent bonds with cellulose fibers. Therefore, these can be used in the modification of vegetable fiber for natural fiber composites to reduce the number of cellulose hydroxyl groups which are available for water uptake [12].
13.9 Naturally Occurring Polymers

The history of man is strongly linked to a wide variety of naturally occurring polymers. For most of this history the fact that these substances were polymers was not known. In many quarters this ignorance persists. The natural polymers fall into four broad groups:

- Polysaccharides – Starch, Cellulose
- Proteins – Gelatin, Caseins, Silk, Wool
- Polyester – Polyhydroxyalkanoates
- Others – Lignin, Shellac, Natural Rubber

It cannot be automatically assumed that natural polymers “are beautiful for environmental degradation.” The rate of degradation and the formation of the ultimate metabolites depend very much on the structural complexity of the material and the environmental conditions selected for the degradation trial.

13.10 Synthesized Biodegradable Polymers

There are many polymers produced from feedstock derived from petrochemical or biological sources that are biodegradable. Many of these have been around for some time either as curiosities or materials of commerce filling very special market niches as, for example, “dissolving” suture material used in the medical field. Others such as certain biopolymers attempted for many years to compete against the standard commodity resins but failed to make significant market advances due to their high price.

The introduction of new materials, unless niche oriented, is generally caught in the volume, price conundrum. High sales volumes are not achievable because of high prices, but in order to reduce price costs must be reduced through the benefits that accrue from high volumes of production.

In more recent times several sizable niche markets have opened for biodegradable plastics, e.g., bags for municipal composting. In addition, the potential value of wastes, such as waste sugar feedstocks, has been recognized. The drive for sustainable development has promoted interest in the development of chemicals derived from the farming of particulars crops among a number of large multinational corporations. As a result the capital resources, marketing expertise and capability in research and development are coming together to lay the foundation for
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a new industry. There are a number of biodegradable synthetic resins such as:

- Polyalkylene esters
- Polylactic acid and its copolymers
- Polyamide esters
- Polyvinyl esters
- Polyvinyl alcohol
- Polyanhydrides

Each of these has its particular properties and potential applications. Polyvinyl alcohol is widely used because of its solubility in water. Polylactic acid is growing in terms of production volume and applications. All of the materials in the list have been found to exhibit degradation promoted by microorganisms, often coupled to chemical and mechanical degradation.

13.11 Applications of Biodegradable Polymers

Biodegradable polymers have been demonstrated to be capable of being processed by most conventional plastic processing techniques. This is not to say that modifications of machinery and adjustment of processing conditions are unnecessary. Products may be formed by film extrusion, injection molding, blow molding, thermoforming, etc. As a result, myriad products are potentially available. The key factor in the marketing of them is a demonstrated “value-in-use” in the application being considered. The current relatively high prices of truly biodegradable, compostable materials will at least for the time being discourage their “frivolous use.”

As previously stated, biodegradable and compostable plastics are not a panacea for the issues surrounding the management of waste. Indeed, they are not a universal substitute for the common resins of commerce. Neither of these sources of raw materials is environmentally caring, and the environmental impact associated with them can only be ascertained by carrying out a life-cycle assessment.

In a similar vein, the use of the products also needs an environmental assessment. Even in a simple application, such as bags for conveying garbage to the landfill and then depositing the bag in the landfill, the determination of whether a conventional plastic bag or a biodegradable bag has a lower impact requires an analysis. A conventional bag in a landfill is essentially inert while a biodegradable bag will over the active life of the landfill decompose into $\text{CO}_2$ and Methane ($\text{CH}_4$), both of which are greenhouse gases.
No one anticipates that biodegradable materials or polymers derived from “renewable resources” will replace over the short term the familiar commodity materials derived from petrochemical sources.

13.12 Preparation of Biodegradable Reinforced Polymer

Among the biodegradable materials, natural starch-based plastics have drawn more and more attention from researchers due to their availability, renewability and low cost [125–127].

During the preparation of biodegradable starch/clay nanocomposites, a plasticizer mixture of urea and ethanolamine has been demonstrated to be a better plasticizer than glycerol for improving the compatibility of starch with clay and enhancing the barrier property of the starch composites [128]; and plasticizer mixture of sorbitol and formamide has also been verified to be able to effectively intercalate clay layers to improve the thermal stability and mechanical property of the starch composite [129]. It has also been reported that the usage of mixture of formamide and water together with glycerol as starch plasticizer can enhance the dispersion and the interfacial affinity in the starch/poly(lactic acid) composites [130]. Moreover, monosaccharide, other amino compounds (such as ethylenebisformamide, N, N-bis(2- hydroxyethyl)formamide, N-(2-hydroxypropyl)formamide, N-(2- hydroxyethyl)-N-methylformamide, formamide mixture, etc.), ionic liquid, and N,N-dimethylacetamide combined with lithium chloride have also been utilized as novel plasticizers for starch. Comparable with the polyol-plasticized starch films in tensile tests, monosaccharide-plasticized starch films were more resistant in moisture permeation, which should be attributed to the denser polymer-plasticizer complex, smaller size of free volume, and less segmental motions of starch chains resulting from the structural compatibility of monosaccharide with starch [131].

13.12.1 Preparation of Starch Composites

Before the preparation of the starch composites (SC), starch and plasticizer of glycerol or polyol mixture were premixed by hand and sealed for 12 h to make plasticizer to swell the starch granule to enhance the molecular interactions between plasticizer and starch. During processing, the pre-mixtures were melt-blended in a record 900 HAAKE roller mixer at 150°C for 10 min with a constant screw rotation speed of 100 rpm, and the torque and melt temperature were monitored. The obtained starch composites
were then hot pressed at 160°C to achieve sample sheets of 1 mm thickness and cut into different shapes for measurements. After that, the samples for testing were placed in tightly sealed polyethylene bags to prevent moisture absorption and reserved for 3 days before testing to make the material equilibrated and stable. The formulation of these starch composites is listed in Table 13.4. Just as shown in Table 13.4, the SC-G series represents the starch composites plasticized by different content of glycerol, and the following number describes the amount of glycerol used. The SC-GS, SC-GX and SC-GM series represents the starch composites plasticized by mixture of glycerol and sorbitol, mixture of glycerol and xylitol and mixture of glycerol and maltitol, respectively, and the following numbers describe the amount of sorbitol, xylitol and maltitol used. In each of the above polyol mixture-plasticized starch composite, the amount of plasticizer is fixed to be half that of starch. In Table 13.4, the component amount is represented by phr, which means parts per hundreds of starch [132].

Table 13.4 The formulation of the starch composites plasticized by polyol mixtures [132].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Starch (phr)</th>
<th>Glycerol (phr)</th>
<th>Sorbitol (phr)</th>
<th>Xylitol (phr)</th>
<th>Maltitol (phr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-G40</td>
<td>100</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-G45</td>
<td>100</td>
<td>45</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SC-G50</td>
<td>100</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SC-G55</td>
<td>100</td>
<td>55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-G60</td>
<td>100</td>
<td>60</td>
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<td></td>
</tr>
<tr>
<td>SC-GS5</td>
<td>100</td>
<td>45</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-GS10</td>
<td>100</td>
<td>40</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-GS15</td>
<td>100</td>
<td>35</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-GS20</td>
<td>100</td>
<td>30</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-GS25</td>
<td>100</td>
<td>25</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-GX20</td>
<td>100</td>
<td>30</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>SC-GM20</td>
<td>100</td>
<td>30</td>
<td></td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>
13.13 Processing Techniques for Natural Fiber Composites

Most biocomposites in current production are based on thermoplastic polymer matrices such as polypropylene and polyethylene, with the standard method of processing involving sheet compounding followed by extrusion. In the compounding process, the polymer is heated to a molten state before the fiber is added as flour, together with any additives required. Once mixing has been completed, the biocomposite can often be extruded directly as the final product or alternatively made into pellets prior to further extrusion of injection molding. A major limitation of this extrusion process, however, is that only relatively short fibers can be successfully utilized, resulting in limited reinforcement [133].

In principle, the production techniques for natural fiber composites can be similar to those for glass fibers. Exceptions to this are techniques used where continuous fibers are used like pultrusion (a yarn has to be made first), or where fibers are chopped, like in spray-up or sheet molding composite (SMC) prepreg preparation. A few examples of techniques are discussed below [134].

13.13.1 Resin Transfer Molding or Vacuum Injection

Resin transfer molding (RTM), or vacuum injection, is a clean, closed mold technique. Dry fibers are put into the mold, then the mold is closed by another mold or just a bagging film, and resin is injected. Either with over-pressure on the injection side or vacuum at the other side the fibers are impregnated. Tailored lay-ups and high fiber volume contents are possible. Therefore, the technique enables the manufacture of very large products with high mechanical properties. A difference compared to glass is the springy character of the natural fibers. To enable proper fiber placement and high fiber volume contents, a preforming step may be required. Preforming is pressing the mats with a small amount of binder (like H₂O) into a more compact shape. Dense mats of flax can be difficult to impregnate. Better resin flow can then be obtained by using the thicker leaf fibers like sisal [134].

13.13.2 Sheet Molding Compound Techniques

An important difference with glass sheet molding compound (SMC) is the production of the prepreg. Normally prepgregs are made by chopping the
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Glass strands and dropping them on a film of resin-filler compound. This preparation will not work for natural fibers since the chopping is very difficult. Other techniques are being developed. An appropriate method to get a layer of fibers with an anisotropic orientation which is loose enough to provide sufficient fiber flow during the molding process depends on the type of fiber and on the way in which the raw material is being supplied. This resembles the vacuum injection, but it is a bit quicker and less sophisticated. After fiber placement, a basket with resin is poured in the middle of the product, a rigid top mold is put on, and at the edge of the set of molds vacuum is applied. Meanwhile, successful replacement of glass fibers by natural fibers has been achieved within the series production of a component of a caravan’s coach. Mechanical properties are comparable while a weight saving of 10 percent is achieved. Although these benefits are small, natural fibers could take the place of glass since the raw material cost is lower [134].

13.13.3 Sandwich Technology

Today, composite laminates in glass polyester are produced in a continuous way up to a width of 3 m and with infinite length. Bonded on two sides of a foam block, they build stiff sandwich panels that are used a lot in trucks, trailers and building construction. They provide thermal insulation and can fulfill a primary structural function. Small-scale prototyping has proved that substitution of glass by natural fibers is feasible. A bit less insulating, but still very well suitable for wall and roof construction, are sandwiches made of natural fiber composite skins and bamboo pillars as the sandwich core. An optimal combination of two different mechanical “tours de force” made by nature, this concept is now under development.

Compared to corrugated iron the “vegetable sandwich” is not only more elegant, it is more durable, it insulates far better, and it uses renewable and local resources. Furthermore, the zinc-coat on the steel pollutes, and when the zinc has gone, rust will appear. Finally, in hot climates, a steel roof gives no insulation, and the heat under such a roof can be unbearable [134].

13.14 Natural Fiber-Reinforced Composites

Natural fibers such as sisal, flax, jute, coir, etc., possess good reinforcing capability with polymers. These fibers are relatively inexpensive, originate from renewable resources, and possess favorable value of specific strength and specific modulus. Natural fiber-reinforced composites come from
the renewable materials and can be mechanically recycled. Some of the recent studies on natural fiber-reinforced composites have been cited in this manuscript.

13.14.1 Banana Fiber-Reinforced Composites

The effect of chemical modifications on the dynamic mechanical properties of banana fiber-reinforced polyester composites was studied by Pothan et al. [135]. A number of silane coupling agents were used to modify the banana fibers. Joseph et al. studied the environmental durability of chemically modified banana fiber-reinforced phenol formaldehyde (PF) composites. They observed that silane, NaOH and acetylation treatments improved the resistance of the banana/PF composites on outdoor exposure and soil burial [136].

Idicula et al. investigated the thermo-physical properties of banana sisal hybrid-reinforced composites as a function of chemical modification. Sisal and banana fiber were subjected to mercerization and polystyrene maleic anhydride (MA) treatments. They observed that chemical modification resulted in an increase of 43% in the thermal conductivity when compared with untreated composites [137].

13.14.2 Flax Fiber-Reinforced Composites

Most of the studies concerning the chemical modification of flax fiber have been reported earlier on by many researchers. Weyenberg et al. [138] investigated the chemical modification of flax fiber by alkali treatment. The study concentrated on optimizing parameters, such as time and concentration of NaOH, to develop a continuous process for the treatment and fabrication of unidirectional flax fiber epoxy composites. The authors observed a specific improvement in the mechanical properties of the resulting material; treatment with 4% NaOH increased the transverse strength of the composites by up to 30%.

Wang et al. [139] investigated the effects of different chemical modifications on the properties of flax fiber-reinforced rotationally molded composites. The chemical modifications carried out were mercerization, benzylation, and peroxide treatment. The modified fibers were then extruded with the polymer matrix to form the composite and an improvement in interfacial adhesion was observed.

Zafeiropoulos et al. [140] investigated the effect of chemical modification on the tensile strength of flax fibers. The authors tried acetylation and stearation and found that the tensile strength of flax fibers did not exhibit
any drastic improvement. The SEM examination of the fractured surfaces revealed that acetylated fibers exhibited a different mode of failure from the other fibers, suggesting that the treatment altered the bulk properties along with the surface properties.

### 13.14.3 Hemp Fiber-Reinforced Composites

Bledzki et al. [141] have studied the influence of chemical treatment on the properties of hemp fiber-reinforced epoxy and PP composites. The effects of different mercerization parameters, such as concentration of alkali (NaOH), temperature, duration time, and tensile stress applied to the fibers on the structure and properties of hemp fibers, were studied and judged via the cellulose I-II lattice conversion. It was observed that the mechanical properties of the fibers can be controlled in a broad range using appropriate parameters during mercerization treatment.

According to Vincent Placet [142], thermoplastic/hemp fiber composites were manufactured using a film stacking process. This method consists of heating and compressing a sandwich of polymer films and fiber mats. Panels of 100 mm by 100 mm were made. Polypropylene films with a thickness of 1 mm were prepared from pellets, using an injection machine (BOY 22M). Two types of fiber mats were prepared from jumbled fibers: mats of randomly scattered fibers and mats of unidirectional fibers. For unidirectional mats, the fibers were manually carded. The composites were molded from a stack of three polymer films interleaved with hemp fiber mats. This stack was placed in a mold on an electromechanical press equipped with a furnace, with which the assembly was heated to 180°C. At this plateau temperature, the stack was compressed at 10 bars for 3 minutes, following which the composite was allowed to cool to room temperature. The pressure was maintained at a constant value until 160°C.

### 13.14.4 Pineapple Fiber-Reinforced Composites

Green composites were fabricated using pineapple leaf fibers and soy-based resin [50]. The addition of polyester amide grafted glycidyl methacrylate (PEA-g-GMA) as compatibilizer was seen to increase the mechanical properties of the composites. Tensile and flexural strengths of composites containing treated fibers were found to be 35 and 50 MPa, respectively, whereas those of composites containing untreated fibers were found to be 30 and 45 MPa, respectively.

Lopattananon et al. [143] investigated the chemical modification of pineapple leaf fibers in natural rubber; NaOH solutions (1, 3, 5, and 7%,
w/v) and benzoyl peroxide (BPO) (1, 3, and 5 wt% of fiber) were used to treat the surface of the fibers. It was found that all surface modifications enhanced adhesion and tensile properties. The treatments with 5% NaOH and 1% BPO provided the best improvement of strength (28 and 57%, respectively) of composites when compared with that of untreated fiber composites.

13.14.5 Sisal Fiber-Reinforced Composites

Mwaikambo and Ansell [144] carried out the alkali treatment of sisal fibers and analyzed the changes with respect to the diameter and internal structure, such as cellulose content, crystallinity index, and micro-fibril angle. Alkalization was found to change the internal structure of sisal fibers which exhibited approximately the same specific stiffness as that of steel. The crystalline nature of the treated fibers was also found to increase due to alkali treatment. Their results indicated that the structure of sisal fiber can be chemically modified to attain properties that will make the fiber useful as a replacement for synthetic fibers.

Martins et al. [145] studied the effect of chemical modifications on the structure and morphology of sisal fibers by NMR spectroscopy. Mercerization, acetylation, and resorcinol/hexamethylenetetramine (R/H) treatments were applied to sisal fibers in order to improve their adhesion in composites materials. The results showed that the fibers/acetylation of fibers prior to the treatment with 20/10 g/L R/H solution for 15 min was the best treatment since the fibers obtained exhibited the biggest effective surface area available for chemical interaction and mechanical interlocking with the matrix.

13.15 Properties of Composites

The mechanical properties of a natural fiber composite depend on many parameters such as fiber strength, modulus, length and orientation, in addition to the fiber matrix interfacial bond strength. Fiber-matrix interface plays an important role in the composite properties. A good interfacial bond is required for effective stress transfer from the matrix to the fiber, whereby maximum utilization of the fiber strength in the composite is achieved, e.g., the mechanical properties of kenaf fiber composites depend on several factors such as orientation of fibers (random or unidirectional), loading and form (fabric or fiber), chemical modification, use of compatibilizer or coupling agent [146]. The crosslinking density has the highest relevance in many properties such as mechanical properties for
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Crosslinked polymers. For example, the mechanical properties increase with the increase of crosslinking as it demands more stress value for rupture [147]. Thus determination of degree of crosslinking has great practical significance. The degree of crosslinking was determined according to the gel fraction content by extracting low molecular content by toluene in a Soxhlet apparatus. It is known that uncured polyfurfuryl alcohol (PFA), which is not crosslinked by chemical bonds, is soluble in toluene while cured PFA is not. The degree of crosslinking was found to be quite high for PFA resin (85%) and for green composites (79–82%).

13.16 Application of Natural Fiber Composite

Natural fiber composites have a very interesting field of applications because of their promising properties. Many automotive components are already produced in natural composites, mainly based on polyester or PP and fibers like flax, hemp or sisal. The use of natural fibers in automobiles has largely been restricted to upholstery applications because of the traditional shortcomings of natural fiber composites, low impact strength and poor moisture resistance. Recent research results show that there is a large potential in improving those two properties. This potential can be found either in pretreatments of the fibers or in improving the chemistry while impregnating the fibers with the matrix material.

Treatment is required to turn just-harvested plants into fibers suitable for composite processing. For example, in the case of flax, the first step is retting. It is a controlled retting process that gets rid of the pectin that connects the fiber bundles with the wood core of the stem. After the retting, hemicellulose and lignin can be removed by hydrothermalysis or alkali reactions. The hemicellulose is responsible for a great deal of the moisture absorption. The lignin is the connecting cement between the individual fiber cells. Although the lignin builds the bundle, in a composite it will be the weakest link. During harvesting, pretreatments and processing, the handling plays an important role. Failure spots on the fibers can be induced, which cause a reduction of the tensile strength.

Composite materials find uses in car, aircraft, railway and truck industries. Polymers have displaced steel and ferric alloys in car construction from 80 percent used in 1965 to 60 percent in 1995. This field of polymers application was pioneered by Henry Ford, who designed the car body entirely in polymer, a car “made of soybean” in 1941. In 1953 a Chevrolet Corvette had many parts made of polyester resins reinforced with different fibers, allowing the weight of the car to be decreased by about 85 kg [148].
Application of natural fibers in the automotive industry may include different types of fillings, reinforcing fiber and in some cases replacement of glass fiber, one of the components of hybrid composites, degradable composite of natural fibers and natural polymers. The great advantage of composites reinforced with fibers is that when the fibers are arranged parallel to the direction of applied forces (unidirectional laminates), the possibility of utilization of anisotropic properties of material for structure arises (crushed fibers, embroidered and 3D woven structures). The properties of this new material can be compared with regular glass fiber or reinforced polymers in normal conditions, for instance, in the automotive industry, road construction, irrigation systems, landfills, furniture industry and also in sport. New nanobinders have been proposed for jute, hemp composites by the Institute for New Materials, Saarbrücken, Germany, resulting in flame-resistant construction elements with a compressive strength of 3.5 MPa by a specific weight of only 0.13 g/cm² [149].

Composition boards, including particleboard (extruded and plate-pressed), and fiber boards, especially medium-density fiberboard (MDF), are quite common in construction, furniture and interior panelling. The most common raw material used is wood, but many countries successfully use other agriculturally based residues like flax and hemp shives, jute stalks, bagasse, reed stalks, cotton stalks, grass-like Miscanthus, vetiver roots, rape straw, oil flax straw, small grain straw, peanut husks, rice husks, grapevine stalks and palm stalks. These cheap raw materials can be valuable in lignocellulose board production from wood particles [150, 151]. Medium-density fiberboards consist of 82 percent fibers from wood or annual plants, 9 percent gluing amino resin, 1 percent paraffin and 8 percent water [152]. There is growing interest in using annual plants to make boards because annual plants are renewed each year, and produce three times more cellulose per year than ring-growth in trees. Residues of annual plants such as rape or canola straw, oil flax straw, small grain straw, reed and reed wastes are useful for production of insulating boards for the building industry, important for houses in earth-globe areas. Hemp also makes excellent insulating boards [153]. Bast fibrous plants are a source of food, fodder, pharmaceutical products and cosmetics. Flax and hemp seeds are perfect raw materials for agriculturally based industries such as the production and processing of food, natural pharmaceuticals, cosmetics, or paint varnishes.

According to Williams [154], a biomaterial is a material used in implants or medical devices, intended to interact with biological systems. Those common types of medical devices include substitute heart valves and artificial hearts, artificial hip and knee joints, dental implants, internal
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and external fracture fixators and skin repair templates, etc. One of the major features of biocomposite materials is that they can be tailor made to meet different application requirements. The most common types of conventional composites are usually composed of epoxy, unsaturated polyester resin, polyurethanes (PU) or phenolic reinforced by glass, carbon or aramid fibers. These composite structures lead to the problem of conventional removal after their end-of-life, as the components are closely interconnected, relatively stable and thus difficult to separate and recycle. A material that can be used for medical applications must possess a lot of specific characteristics, which are different than those for the general domestically used plastic products. The most fundamental requirements are related to biocompatibility, without having any adverse effect to the host tissues. Therefore, those traditional composite structures with non-biocompatible matrix or reinforcement are substituted by bioengineered composites. Table 13.5 summarizes several important factors that need to be considered when selecting a material for biomedical applications.

In the environmental concern, the use of these fibers mixed with biodegradable polymers, like PLA and poly(glycolide) (PGA) can produce biodegradable composites (somehow, they are called “green composites” or “environmentally-friendly plastics”). These composites should possess moderate strength and/or thermal stability, while they must be recyclable after being used [155].

13.17 Environmental Effects

Because of environmental awareness and consciousness throughout the world, there has been increasing interest in the development of natural fibers and their application in various fields. Natural fiber composites are also claimed to offer environmental advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and end-of-life biodegradability of components.

The majority of biocomposites are currently used in the automotive, construction, furniture and packaging industries, where increasing environmental awareness and depletion of fossil fuel resources are providing the drivers for the development of more new renewable products. Whichever application of natural or natural fiber-reinforced plastics will be used when and where depends on the different environmental conditions, which are likely to influence aging and degradation effects. In contrast, such effects are often desirable, as is the case with compostable materials. Natural fibers
Table 13.5 Key factors for the selection of materials for biomedical applications [155].

<table>
<thead>
<tr>
<th>Factors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical/biological characteristics</td>
<td>Physical characteristics</td>
</tr>
<tr>
<td>1st Level material properties</td>
<td>• Chemical composition (bulk and surface)</td>
</tr>
<tr>
<td>2nd Level material properties</td>
<td>• Adhesion</td>
</tr>
<tr>
<td>Specific functional requirements (based on applications)</td>
<td>• Biofunctionality</td>
</tr>
<tr>
<td>• Bioinert</td>
<td>• Coefficient of thermal expansion</td>
</tr>
<tr>
<td>• Bioactive</td>
<td>• Biostability</td>
</tr>
<tr>
<td>Processing &amp; Fabrication</td>
<td>• Reproducibility, quality, sterilizability, packaging, secondary processability</td>
</tr>
<tr>
<td>Medical/surgical procedure, period of application/usage Cost</td>
<td></td>
</tr>
</tbody>
</table>
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are subject to degradation in acids and in alkaline solutions, as well as under UV rays. These effects, however, can be minimized by using suitable modification. Unmodified cellulose-fibers are normally degraded by enzymes after about 6–12 months; this can be altered through suitable treatment so that no significant changes of mechanical properties will be noticed for two years. Within a period of 2.5 years, dry-stored fibers show only little change in their mechanical properties. This is true especially with regard to strength and elongation at break. In this respect, sisal fibers are comparably more stable than abaca and other fiber [21].

Lower temperatures, −70°C, clearly result in lesser strength, but the effect can be minimized by previous drying. Higher temperatures, such as 100–130°C, lead in the case of cotton, to a notable degradation after 80 days. Their strength was thereby reduced to 68%, i.e., 10% of the original value. Depending on the temperature applied, these values are reduced to 41% and 12% for flax-fibers and to 26% and 6%, for ramie-fibers. In composites moisture content results in lower mechanical properties. This effect is greater when using ocean rather than fresh water. With fresh water it is more likely that bacteria and fungi appear on the scene. Against such influences, ramie, jute and kopak fibers are more resistant than other plant fibers [156]. The lower resistance of natural fibers against environmental factors, decisively affects the mechanical properties of the composites [157].

Products made from sustainable biocomposites must satisfy the requirement that no hazardous effects to the environment or to human health will be derived throughout their service life in the intended application. Reinforced biocomposites possess, in general, limited thermal stability at the required temperatures for thermo-mechanical processing, which may contribute to the formation of low molecular weight compounds as a result of the degradation of either the polymeric matrix or the lignocellulosic fibers used as reinforcements. This may lead to the release of undesirable odors during processing and service life, which may hinder the applicability of biocomposites in indoor applications, such as in construction elements or automotive components. The processing temperatures of natural polymers and natural fiber-reinforced composites are normally restricted to 200°C, but even at lower temperatures degradation may occur, leading to volatile compounds formation. The common procedures for the thermo-mechanical processing of biocomposites are similar to those used for synthetic polymers and composites; these include extrusion (including reactive extrusion, foaming, sheet and film forming), compression molding, and injection molding [158]. Other procedures such as film casting could be explored to avoid thermal degradation of biocomposites, especially for biomedical or packaging applications. Detailed knowledge about the thermal
stability and the thermal decomposition mechanisms under temperature and shear conditions is therefore fundamental for material and product development, in order to avoid undesired effects such as odor emission or the release of degradation products into the surrounding media.

Oxidized compounds such as alcohols, aldehydes, ketones, and carboxylic acids together with a wide variety of phenolic compounds have been reported to be produced and emitted from sustainable biocomposites based on a recycled polypropylene (PP) matrix reinforced with natural fibers [159]. Among the identified compounds, phenolic degradation products from the antioxidants incorporated in the thermoplastic matrix could be identified in the non-aged material. Other compounds, such as carboxylic acids, alcohols, and esters, which are believed to derive from the degradation of the lignocellulosic fibers, seem to increase their relative abundance after aging; these compounds may be responsible for the characteristic odor emitted by lignocellulosic composites. Some authors have proposed the introduction of porous absorbents in the composition of biocomposites to decrease the amount of emitted odoros molecules without major reductions in the material's mechanical properties [160]. Other environmental implications may arise, however, from the application of inorganic fillers in biocomposites.

13.18 Work Carried Out in CSIR-NEIST, JORHAT

Medium density particle/fiberboards are wood substitute products used as building material. Various lingo-cellulosic materials are now being utilized for construction purposes. The recent trend is the utilization of agro-industrial wastes like sawdust, rice straw, jute sticks, etc., for making items for use in building construction. Hard boards, particleboards, fiberboards, etc., are known to have been used in one form or another for construction work. Lingo-cellulosic materials are converted to a particular size bonded together with a suitable binder by means of heat and pressure. Boards of different densities are made in a hot press. The laboratory has developed know how for manufacturing medium-density particleboard from different agro waste material like cereal straws, sugarcane bagasse, etc., and forming scraping/dust of low-density wood and other forest wastes like Nol (*Phragmites karka*), Khagra (*Neyraudia reynaudiana*), Ekora (*Erianthus longisetosus*), Ipomoea (*Ipomoea carnea*), Zhau (*Tamarix dioica*), Birina (*Andropogon squarosus*), etc., grasses [161]. These boards are suitable for false ceiling in Assam-type buildings, find extensive use in auditoriums, computer centers, cinemas and theater halls, business premises, as well as display boards in commercial apartments. These boards can
also be used as partition walls, decorative walls, covering, tabletops, flush doors, showroom cabinets, furniture fixtures, blackboards, mirror backing, etc. Properties of composites made with different proportions of UF and PF resins are compared in Table 13.6.

Coir is an important lignocellulosic fiber that can be utilized with waste polyethylene in different ways for making composite board to get desired properties and texture. Such coir fiber is hard and rigid with the properties of high-level moisture absorption, poor wettability and insufficient adhesion with polymer matrix, which lead to debonding with time. In order to get better quality product from coir fiber, some improvement of the coir fiber property with the help of chemical treatment is needed. In the present work, chemical treatment of coir fiber with NaOH, dilute HCl, Acetic acid and Alcohol-benzene solution were used for improvement of fiber property, as well as composite boards prepared from treated fiber and waste polyethylene [162]. The chemical constituents of coir fiber like cellulose, lignin, ash and hot water soluble, alkali soluble were tested before and after the chemical treatment. Lignin content of fiber was reduced from 44.48% to 21.50%, 14.50%, 28.30% and 33.65% after the treatment with HCl, NaOH, Acetic acid and Alcohol benzene respectively. Likewise, hot water soluble reduced from 13.9% to 2.35%, 5.40%, 5.84% and 6.78% in HCl-, NaOH-, Acetic acid- and Alcohol benzene-treated fiber respectively. The composite boards made from different chemically treated fibers were tested and it was found that water absorption and total swelling values were drastically reduced and the mechanical strength properties, i.e., ultimate tensile strength (UTS) and modulus of rupture (MOR), increased. Among the different chemical treatments, 15% NaOH-treated fiber was found more effective in improving the composite board quality. Physical and mechanical properties of board made from different treated coir fibers are summarized in Table 13.7.

Another investigation was carried out to study the coir fibers mixed with different synthetic resin binder to make medium-density particleboard to determine their physical strength properties. A comparison among the synthetic resin binder was carried out [163]. Also the physicochemical properties of coir fiber and alkali (10% NaOH)-treated coir fiber were determined. The treated fiber was used for the board preparation. From the study, it has been concluded that physical strength properties of the board manufactured by solely using phenol formaldehyde (PF) resin was the highest among the other resins used. To reduce the formaldehyde emission effect from the board, other resin binder like polyvinyl alcohol (PVA) or polyvinyl acetate (PVAc) can also be used with PF resin for preparation of medium density particleboard to get the optimum physical strength properties [164]. Table 13.8 revealed the properties of composites made with
Table 13.6 Characteristic properties of particleboards made with different proportions of UF and PF resins.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resin Content UF:PF</th>
<th>Thickness mm</th>
<th>Density g/cm²</th>
<th>Moisture content %</th>
<th>MOR Kg/cm²</th>
<th>Water absorption %</th>
<th>Total volumetric swelling %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100:0</td>
<td>7.1</td>
<td>0.82</td>
<td>8.8</td>
<td>139</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>B</td>
<td>100:0</td>
<td>7.2</td>
<td>0.84</td>
<td>8.6</td>
<td>136</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>100:0</td>
<td>7.1</td>
<td>0.83</td>
<td>8.0</td>
<td>141</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>A</td>
<td>75:25</td>
<td>7.2</td>
<td>0.81</td>
<td>8.3</td>
<td>149</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>B</td>
<td>75:25</td>
<td>7.8</td>
<td>0.86</td>
<td>8.0</td>
<td>153</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>C</td>
<td>75:25</td>
<td>7.5</td>
<td>0.82</td>
<td>8.1</td>
<td>151</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>A</td>
<td>50:50</td>
<td>7.6</td>
<td>0.83</td>
<td>8.0</td>
<td>153</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>50:50</td>
<td>7.2</td>
<td>0.85</td>
<td>7.8</td>
<td>157</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>C</td>
<td>50:50</td>
<td>7.3</td>
<td>0.83</td>
<td>7.6</td>
<td>156</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>A</td>
<td>25:75</td>
<td>7.1</td>
<td>0.84</td>
<td>8.2</td>
<td>158</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>25:75</td>
<td>7.3</td>
<td>0.81</td>
<td>8.0</td>
<td>162</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>C</td>
<td>25:75</td>
<td>7.6</td>
<td>0.83</td>
<td>7.6</td>
<td>159</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>A</td>
<td>0:100</td>
<td>7.4</td>
<td>0.87</td>
<td>7.6</td>
<td>168</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>B</td>
<td>0:100</td>
<td>7.6</td>
<td>0.86</td>
<td>7.4</td>
<td>169</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>C</td>
<td>0:100</td>
<td>7.8</td>
<td>0.84</td>
<td>7.4</td>
<td>173</td>
<td>13</td>
<td>12</td>
</tr>
</tbody>
</table>

*M. malabathricum, B- E. odoratum, C- T. Maxima; Particle size (Y)*
Table 13.7 Properties of boards made from different treated coir fibers.

<table>
<thead>
<tr>
<th>Treated coir fiber and waste plastic composite (2:1) Board</th>
<th>Thickness mm</th>
<th>Density g/cm³</th>
<th>UTS MPa</th>
<th>MOR N/mm²</th>
<th>Water absorption, %</th>
<th>Total swelling due to surface absorption, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOH-treated coir fiber</td>
<td>8.9</td>
<td>0.714</td>
<td>5.243</td>
<td>15.21</td>
<td>5.98</td>
<td>2.24</td>
</tr>
<tr>
<td>Dilute HCL-treated fiber</td>
<td>10.2</td>
<td>0.742</td>
<td>4.155</td>
<td>11.55</td>
<td>7.92</td>
<td>3.48</td>
</tr>
<tr>
<td>Acetic acid-treated fiber</td>
<td>11.1</td>
<td>0.733</td>
<td>5.061</td>
<td>11.77</td>
<td>6.51</td>
<td>2.75</td>
</tr>
<tr>
<td>Alcohol benzene-treated fiber</td>
<td>10.3</td>
<td>0.771</td>
<td>4.984</td>
<td>13.58</td>
<td>7.27</td>
<td>5.82</td>
</tr>
</tbody>
</table>
Table 13.8 Characteristics properties of particleboard made with different proportions of PVA and PVAc.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resin content</th>
<th>Thickness (mm)</th>
<th>Density (g/cm³)</th>
<th>Moisture content (%)</th>
<th>MOR (Kg/cm²)</th>
<th>Water absorption (%)</th>
<th>Total volumetric swelling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100:0</td>
<td>7.2 ± 0.05</td>
<td>0.83 ± 0.005</td>
<td>8.2 ± 0.06</td>
<td>118 ± 4.14</td>
<td>30 ± 1.25</td>
<td>25 ± 1.27</td>
</tr>
<tr>
<td>B</td>
<td>75:25</td>
<td>7.4 ± 0.06</td>
<td>0.81 ± 0.003</td>
<td>8.6 ± 0.03</td>
<td>119 ± 2.13</td>
<td>31 ± 2.15</td>
<td>28 ± 2.54</td>
</tr>
<tr>
<td>C</td>
<td>50:50</td>
<td>7.2 ± 0.03</td>
<td>0.87 ± 0.008</td>
<td>8.4 ± 0.06</td>
<td>120 ± 3.15</td>
<td>36 ± 2.31</td>
<td>24 ± 2.30</td>
</tr>
<tr>
<td>D</td>
<td>25:75</td>
<td>7.0 ± 0.02</td>
<td>0.85 ± 0.008</td>
<td>8.4 ± 0.04</td>
<td>122 ± 3.25</td>
<td>31 ± 2.71</td>
<td>26 ± 2.05</td>
</tr>
<tr>
<td>E</td>
<td>0:100</td>
<td>7.2 ± 0.04</td>
<td>0.83 ± 0.007</td>
<td>8.2 ± 0.04</td>
<td>120 ± 4.05</td>
<td>28 ± 3.35</td>
<td>28 ± 1.73</td>
</tr>
</tbody>
</table>

* Mean Value ± standard deviation; three observations per mean.
different proportions of PVA and PVAc and properties of board made with different proportions of PF and PVAc are summarized in Table 13.9.

Another study was conducted to study the physico-mechanical properties of banana fiber-reinforced polymer composite [165]. Utilization of natural fiber as reinforcing material is the latest trend in polymer science to produce higher strength with lower weight composite materials having a wide range of applications. As a natural fiber, banana fiber has been gaining importance in recent years in the reinforcement arena of polymer composites. Two species of banana, viz., *Musa sapientum* and *Musa paradisica*, available in North East India were selected considering their higher fiber yield and adequate strength properties of the fibers. The chemical compositions, spectroscopic and thermal properties of these fibers were studied in order to study their suitability for commercial exploration. Low density polyethylene (LDPE)-banana fiber-reinforced composites were prepared using hydraulic hot press. Physico-mechanical properties (e.g., tensile strength, flexural strength, elongation at break, Young’s modulus) of the prepared composites were determined. The tensile strengths and flexural strengths of the composites increased while using LDPE that was 10 to 30% of the fiber and then started to gradually decrease. Young moduli of the composites increased with the increase of fiber mass. Water absorption also increased accordingly with the increase of the fiber weight. The elongation at break decreased with increasing fiber quantity. The mechanical strength properties of chemically treated banana fiber-LDPE composites were slightly higher than the mechanically extracted fiber-LDPE composites. Structural analyses of the treated fibers were carried out by FTIR and XRD. These studied revealed that due to the removal of noncellulosic constituents such as hemicelluloses and lignin the crystalline properties of the fibers were increased. All the properties of composite like tensile strength, flexural strength, water absorption capacity, etc., plays a significant role in these polymer composite materials. Table 13.10 and 13.11 represent the properties of composites made from mechanically and chemically extracted banana fiber and LDPE.

Moreover, another study was continuing on preparation of composite material using coir fiber, bamboo pulp fiber, as precursor for the development of novel composite material of SiC for different engineering application [166]. Coir fiber, an agricultural waste material of immense economic importance in Indian subcontinent, was used as a precursor to biomorphic SiC ceramics. Fiberboards made of coir fibers were converted to carbon templates by controlled thermal processing. Plant material precursors were characterised by analysis of molecular composition, by determination of bulk density and by scanning electron microscopy. Carbon templates were
Table 13.9 Characteristics properties of particleboard made with different proportions of PF and PVAc.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resin content</th>
<th>Thickness, mm</th>
<th>Density, g/cm³</th>
<th>Moisture content, %</th>
<th>MOR, Kg/cm²</th>
<th>Water absorption, %</th>
<th>Total volumetric swelling, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100:0</td>
<td>7.2 ± 0.07</td>
<td>0.82 ± 0.003</td>
<td>7.2 ± 0.06</td>
<td>166 ± 2.57</td>
<td>14 ± 2.01</td>
<td>12 ± 1.32</td>
</tr>
<tr>
<td>B</td>
<td>75:25</td>
<td>7.3 ± 0.04</td>
<td>0.83 ± 0.005</td>
<td>7.5 ± 0.03</td>
<td>158 ± 4.21</td>
<td>16 ± 3.12</td>
<td>16 ± 2.15</td>
</tr>
<tr>
<td>C</td>
<td>50:50</td>
<td>7.3 ± 0.05</td>
<td>0.85 ± 0.005</td>
<td>7.6 ± 0.05</td>
<td>141 ± 4.14</td>
<td>20 ± 3.42</td>
<td>19 ± 2.32</td>
</tr>
<tr>
<td>D</td>
<td>25:75</td>
<td>7.6 ± 0.04</td>
<td>0.84 ± 0.006</td>
<td>7.3 ± 0.05</td>
<td>130 ± 2.54</td>
<td>23 ± 5.52</td>
<td>20 ± 3.04</td>
</tr>
<tr>
<td>E</td>
<td>0:100</td>
<td>7.2 ± 0.03</td>
<td>0.83 ± 0.004</td>
<td>8.2 ± 0.02</td>
<td>122 ± 4.19</td>
<td>26 ± 1.02</td>
<td>22 ± 1.52</td>
</tr>
</tbody>
</table>

* Mean Value ± standard deviation; three observations per mean.
Table 13.10 Properties of composites made from mechanically extracted banana fiber and LDPE.

<table>
<thead>
<tr>
<th>Banana Fibre %</th>
<th>LDPE %</th>
<th>Density g/cm²</th>
<th>Tensile strength (MPa)</th>
<th>Flexural strength (MPa)</th>
<th>Elongation at break (mm)</th>
<th>Young’s modulus (MPa)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>10</td>
<td>1.06</td>
<td>9.291</td>
<td>16.76</td>
<td>5.291</td>
<td>170.81</td>
<td>23.89</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>0.99</td>
<td>9.487</td>
<td>18.54</td>
<td>5.785</td>
<td>164.87</td>
<td>21.62</td>
</tr>
<tr>
<td>70</td>
<td>30</td>
<td>1.02</td>
<td>10.854</td>
<td>20.31</td>
<td>6.085</td>
<td>163.06</td>
<td>20.37</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>1.00</td>
<td>9.840</td>
<td>18.43</td>
<td>6.396</td>
<td>159.58</td>
<td>20.01</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>0.98</td>
<td>9.056</td>
<td>17.34</td>
<td>6.805</td>
<td>155.39</td>
<td>18.63</td>
</tr>
</tbody>
</table>

Table 13.11 Properties of composites made from chemically extracted banana fiber and LDPE.

<table>
<thead>
<tr>
<th>Banana Fibre %</th>
<th>LDPE %</th>
<th>Density g/cm²</th>
<th>Tensile strength (MPa)</th>
<th>Flexural strength (MPa)</th>
<th>Elongation at break (mm)</th>
<th>Young’s modulus (MPa)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>10</td>
<td>1.06</td>
<td>12.951</td>
<td>19.36</td>
<td>4.249</td>
<td>176.52</td>
<td>21.61</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>0.99</td>
<td>14.817</td>
<td>20.42</td>
<td>5.253</td>
<td>171.61</td>
<td>18.32</td>
</tr>
<tr>
<td>70</td>
<td>30</td>
<td>1.02</td>
<td>15.844</td>
<td>24.38</td>
<td>7.468</td>
<td>167.86</td>
<td>16.54</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>1.00</td>
<td>13.560</td>
<td>21.64</td>
<td>7.534</td>
<td>162.54</td>
<td>16.51</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>0.98</td>
<td>12.576</td>
<td>18.49</td>
<td>7.624</td>
<td>161.57</td>
<td>15.34</td>
</tr>
</tbody>
</table>
characterized by measurement of dimensional shrinkages, mass loss and bulk density, and by scanning electron microscopy and XRD. The carbon templates were further subjected to infiltration with liquid Si at 1550°C under vacuum, when spontaneous infiltration and reaction yielded composite ceramics preserving the morphology of native coir fiber derived precursors on macro- and microscale. The resulting material had a density of 2.59 g/cm³ and, on a microstructural scale, contained SiC and Si in addition to carbon (trace) and porosity (2 vol%). The end ceramics offered room temperature flexural strength of 116 MPa and elastic modulus of 167 GPa. Fractographic examination indicated brittle failure. The biomorphic SiC material derived from coir fiberboard precursor is likely to be suitable for use in advanced engineering applications as structural ceramics (Figure 13.1).

13.19 Conclusion

Natural fiber composites present immense opportunities to play an important role as alternate materials, especially as wood substitutes. Fiber-reinforced composite materials encompass a wide range of material classes from reinforced glasses, plastics, and rubbers through to more recently developed metals and ceramics. They have special relevance to developing countries in view of their low cost, energy savings and applications as substitute materials. Problems related to natural fibers such as inconsistency in the products performance due to the basic nature of variability in the fibers’ origin, nonavailability in the molding forms of reinforcements (roving, long fiber strands, prepeg, chopped strand mats, etc.), use of fiber in a partially prepared state, poor fiber-matrix interface, etc., need to be improved for industrial exploitation. Applications development of
natural fiber composites as alternate building materials must be thoroughly researched for their durability and cost-effectiveness in order to obtain consistent product performance under use conditions. Whilst there is thus ample opportunity for fiber-reinforced composites to enter new markets and find new applications, it is essential that the benefits in terms of the environment and cost savings continue to be highlighted, emphasising the strong commercial case for these materials. One of the biggest challenges of fiber-reinforced composites is also one of its greatest potential benefits: even though, to-date, fiber-reinforced composites are not as cost-effective as their synthetic equivalents, the price difference shows signs of continuing to decrease such that eventually they will not only be the more environmentally responsible choice, but also more economical. While it should not be claimed that fiber-reinforced composites are currently more “green” than traditional building materials (such as wood, steel, and concrete) in all applications, life cycle analyses have shown that they compare favorably to synthetic composites, using only around 20–40% as much energy. Finally, the development of a worldwide infrastructure-based natural composite industry has the potential to assist in providing poverty alleviation, higher employment, and cost-effective housing in many different countries. Promoting fiber-reinforced composite materials through widespread training and education will also be required if the industry is to establish sustainable commercial viability. Future research in the field of natural fiber composites for infrastructure applications would be most beneficial if aimed at one of the highlighted challenge areas, particularly at continuing to improve mechanical properties, moisture resistance, and durability. Finally, of course, enlightened investment in research and development will be essential to maintain a constant flow of new products and ideas.

References

Recent Development of Fiber Reinforced Composite Materials

Recent Development of Fiber Reinforced Composite Materials

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