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Tribology of natural fiber polymer composites

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Preface

Fiber reinforced polymer (FRP) composites which have been established as the one of the most promising modern materials to replace conventional metals and alloys in numerous structural and tribological applications have gained a great deal of attention in the recent years. FRP materials developed using thermoplastic and thermosets as matrices, natural and synthetic fibers as reinforcements and organic and inorganic materials as fillers have tremendous potential owing to their high strength-to-weight ratio, tailoring potential and resistance to wear, corrosion and impact. Synthetic fibers such as glass, carbon, aramid, etc. have been used largely with both thermosets (epoxy, polyester, phenolics, vinylester) and thermoplastics (polyetheretherketone, polyethylenes, polyamides, polyimides, polypropylenes, polycarbonates, etc.) to develop FRP materials. Natural fiber reinforced composites developed using plant fibers obtained from plants such as sisal, cotton, sunhemp, jute, hemp, flax, banana, coir, etc. have attracted the attention of the manufacturers because of their high strength, low cost and biodegradability. This book focusses on the science and technology of natural fiber polymer composites vis-à-vis recent developments and advances in the field. The main thrust is on explaining the behavior of these composites while keeping specific application areas in mind. The book particularly covers the potential use of these composites in structural and tribological applications. It consists of seven chapters dealing with the availability and processing of natural fiber composites and their structural, thermal, mechanical and tribological properties. Details of the chemical composition of natural plant fibers are given in the Appendix at the end of the book which is intended to serve as a quick reference for readers.

The first chapter introduces various types of natural fibers, composites based on them and their applications in various fields. Natural fibers, extracted from plants (leaves, roots, stems, fruits, seeds, etc.) are non-carcinogenic, lightweight, strong, biodegradable and economically viable. By virtue of their high performance properties, such as high modulus and tensile strength, they are poised to replace expensive synthetic fiber reinforcements, such as glass, carbon, aramid, organic and mineral fillers in fiber reinforced polymer composites. Plant fibers, which have a long history of conventional and traditional use to make baskets, clothing, sacks, ropes, rugs, etc., have made headway in developing FRP materials for tribological and structural applications. For instance, plant fibers such as kenaf, hemp, flax, jute and sisal are making their way into the interiors and upholstery of cars. Natural fiber composites of thermoplastics and thermosets have been developed to make door panels, seat backs, headliners, package trays, dashboards, and trunk liners in passenger cars. This has been a direct consequence of the strict environmental legislation that bans the use of glass fibers in cars and forces manufacturers to replace existing material with biodegradable components. Natural fibers are biodegradable and, when they are reinforced in biodegradable polymers, the disposal of products based on such biocomposites becomes easy.

Since the book is focused on the tribological characterization and applications of natural fiber based polymer composites, a brief introduction to the subject of tribology is taken up in Chapter 2. This will immensely benefit readers who are interested in natural fibers and composites but are not very familiar with the concepts of tribology. The chapter includes the essentials and basic principles of friction and wear characterization of materials.

Chapters 3, 4, 5, 6 and 7 discuss the progress which has been made in the development, characterization and property evaluation of various polymer composites based on natural fiber reinforcements in the form of sisal, jute, cotton, bamboo and wood, respectively. Amongst the plant fibers available worldwide, these are the ones for which tribological characterization has been carried out and which have been identified as potential substitutes as reinforcements in tribo-composites. Emphasis has been placed on the tribological characterization of the natural fiber polymer composites and their structure-property correlation.

The authors feel that this book will be specifically useful for industry, researchers, academicians and students who are associated with research and development in the field of tribology involving natural fibers and their composites. A strong need was felt for such a book because the data available from different sources are scattered. Moreover, no book is available dealing with the tribological behavior of such composites and their structure–property correlation.

Every effort has been made to include as many references as possible. However, some references may have been inadvertently left out, and it will be appreciated if this is brought to the attention of the authors.

Authors

List of abbreviations

AFRP	aramid fiber reinforced plastic
AN	acrylonitrile
BP	benzoyl peroxide
CCA	chromated copper arsenate
CF	carbon fiber
CFRP	carbon fiber reinforced plastic
CMC	ceramic matrix composite
CMT	compression moulding technique
DCP	dicumyl peroxide
DSC	differential scanning calorimetry
DTA	differential thermal analysis
DTG	derivative thermogravimetry
EDA	ethylenediamine
ELV	end-of-life of vehicles
FM	flexural modulus
FRP	fiber reinforced polymer
FTIR	Fourier transform infrared
FWHM	full width at half maximum
GF	glass fiber
GFRP	glass fiber reinforced plastic
HDPE	high density polyethylene
HM-CFRP	high modulus carbon fibre reinforced plastic
HS-CFRP	high strength carbon fibre reinforced plastic
IPN	interpenetrating network
iPP	isotactic polypropylene
LAOW	low amplitude oscillating wear
LDPE	low density polyethylene
LLDPE	linear LDPE
MAH	maleic anhydride
MAPE	maleic anhydride grafted polyethylene
MAPP	maleic anhydride grafted PP
MDF	medium density fiber

MDI/PMDI	polymeric diphenylmethane diisocyanate
MDI	methylene diphenyl diisocyanate
MDPE	medium density polyethylene
MEMS	micro-electro mechanical systems
MF	melamine-formaldehyde
MF	microfiber
MMC	metal matrix composite
MOE	modulus of elasticity
MOR	modulus of rupture
NFRP	natural fibre reinforced plastics
PA	phthalic anhydride
PAI	polyamideimide
PCL	polycaprolactone
PE	polyethylene
PEEK	polyetheretherketone
PEI	polyetherimide
PET	polyethyleneterephthalate
PF	phenol-formaldehyde
PHBV	polyhydroxybutyrate-valerate
PI	polyimide
PMC	polymer matrix composite
PP	polypropylene
PPE	poly(phenylene ether)
PPS	polyphenylene sulphide
PS	polystyrene
PTFE	polytetrafluoroethylene
PVA	poly(vinyl alcohol)
PVC	polyvinylchloride
RH	relative humidity
RMT	roller mill technique
RTM	resin transfer moulding
SEM	scanning electron microscope
SFRP	sisal fiber reinforced plastic
SFRP	short fiber reinforced polymer
TG	thermogravimetriy
TGA	thermogravimetric analyses
TM	tensile modulus
TS	tensile strength
UCS	unconfined compressive strength
UD	unidrectional
UF	urea-formaldehyde
UFS	ultimate flexural strength
UHMWPE	ultra high molecular weight polyethylene

UTS	ultimate tensile strength
WAXD	wide angle x-ray diffraction
WF	wood flour
WPC	wood–plastic composite
WPG	weight percent gain
XLPE	crosslinked polyethylene

Contents

1
Natural fibers and their composites

Abstract: This chapter gives an introduction to the types of vegetable fibers that can be extracted from different parts of plants and to their sources. These fibers, extracted from plants such as sisal, cotton, jute, bamboo, wood, etc., are popularly known as natural (plant) fibers. They are biodegradable and, following surface treatments, they develop mechanical properties close to those of synthetic fibers. By virtue of this, they form an important class of fibrous reinforcements for fiber reinforced polymer composites. These composites, in turn, enable the development of tribological components having excellent wear, friction and lubrication properties which find numerous applications in industry, particularly in the automotive sector.

Key words: vegetable fibers: sisal, cotton, jute, bamboo, wood, flax, coir, banana; fiber surface treatment; natural fiber reinforced polymer composites.

1.1 Introduction

The oft-repeated maxim that *there is sufficient for everybody's need but not for their greed* appears to be literally true for the natural resources available in abundance across the world. Had there been an optimum utilization of these resources, the threat to the ecological system together with other environment-related concerns would not have reached such alarming proportions. Today, with the fast pace of industrialization and large-scale housing construction in urban areas spreading at an ever faster rate, these natural resources are depleted and forest cover is shrinking. There is an urgent need to maintain a balance between growth of human settlement and exploitation of natural resources, in particular the depletion of forests. The harmony between human settlement and natural vegetation, flora and fauna is a law of nature; the long history of human existence has been a witness to the stark reality that whenever this harmony is disturbed it has given rise to problems of dangerous proportions.

Conservation of metals is one such major issue. Metals are extracted from naturally occurring minerals and ores, found in the Earth's crust, through long, tedious and expensive metallurgical processes. Continuous exploitation of these natural resources has become detrimental to the existence of large reserves. Consequently, concerted efforts are being focused on developing materials that can be a suitable alternative, if not a perfect substitute, for metals and alloys. From time immemorial, metals have been an integral part of human life, ranging from their use in household items to their large-scale applications as building material in the construction and transport industries, aircraft structures, ship building, and the defence and automobile industries. The replacement of metals would have been a distant dream but for the rapid progress in the development of materials such as glass, polymers, ceramics, synthetic fibers and numerous organic and inorganic substances which has proved to be a turning point. All these materials have unique property profiles and possess outstanding characteristics. Even more amazing is the fact that when combined together to form composites, they offer a plethora of useful properties. The shortcomings of one ingredient are compensated by other ingredients. For instance, fiber reinforced polymer composites filled with inorganic fillers have found large-scale applications in almost every field of engineering (Table 1.1).[1] Composites, defined as multiphase systems that consist of at least two different groups of materials, which are chemically and physically distinct and separated by interfaces, have generated a great deal of interest. Their impact on socio-economic structures has been so immense that composite technology has become an active area of research and development across the world. No sector has remained untouched by the benefits of composites. From household items, toys, and sports equipments to the construction industry and aircraft structures, composites have occupied every possible inch.

Composites consist of one or more discontinuous phases embedded in a continuous phase. The discontinuous and continuous phases are termed *reinforcement* and *matrix*, respectively. The type and reinforcement geometry provide strength to the matrix, and the resultant composite develops properties such as high specific strength, stiffness, and hardness, which are much more than the individual components. For this reason, composites are often termed *tailored* materials because judicious choice of matrix, reinforcing elements and processing techniques allows properties to be achieved as per the requirement. Nowadays, the field has grown so much that a range of inorganic and organic fibers/fabrics, chemically coated fiber/fabrics, matrices (polymeric, ceramic), fillers and a host of processing techniques are available that have rendered possible the realization of any type of composite. You name it and you can find it on the market.[2]

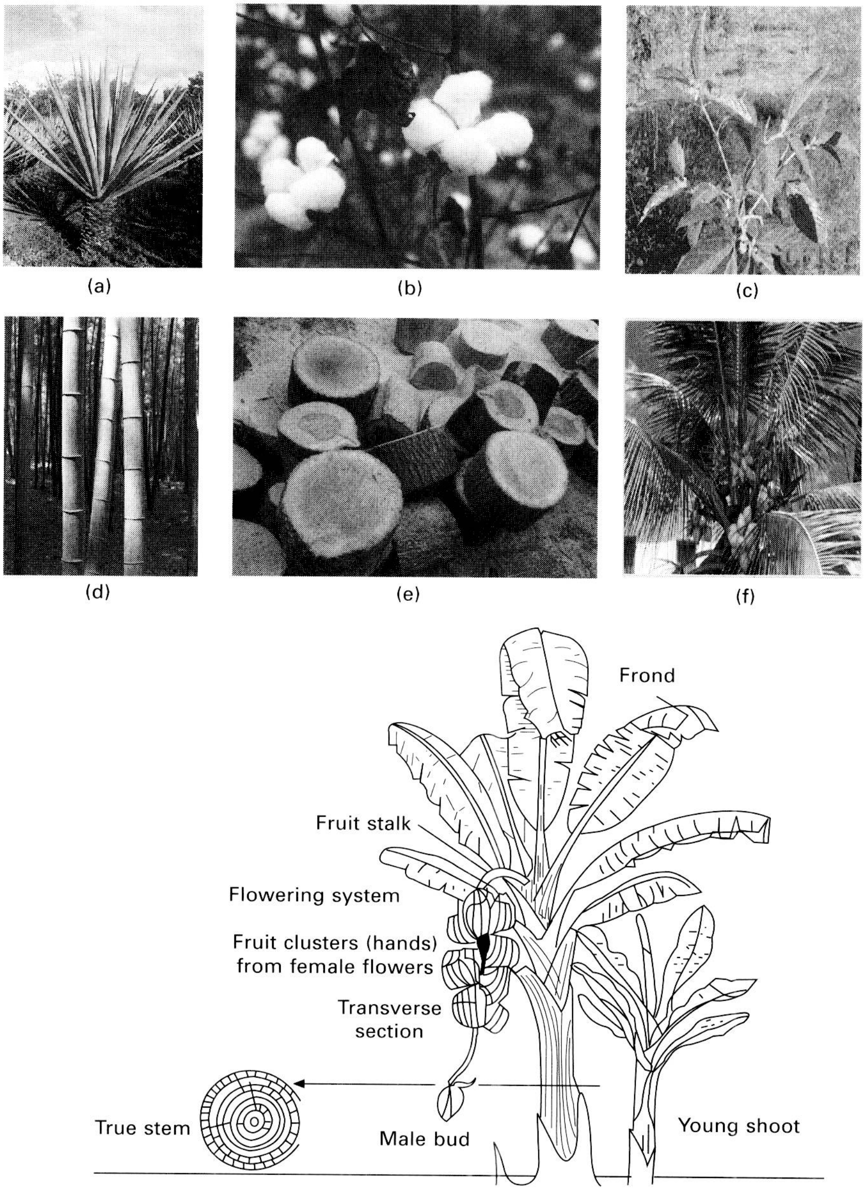
As fast as the field of composites has grown, the problems related to them have caught up even faster, one of these being disposal. This is because they contain toxic ingredients and are difficult to recycle. They neither degrade

Table 1.1 Applications of composites in different areas of engineering[1]

Field	Composites	Applications
Mechanical engineering	MMCs, CMC, PMCs	Turbines, pump blades, gears, bearings, seals, machine components, cutting tools, tool bits
Automobile engineering	PMCs, MMCs	Aircraft components, brakes, tyres,
Civil engineering	PMCs	Conveyors, radomes, building materials, panels, cabinets, overhead tanks, storage tanks
Medical engineering	PMCs, CMCs	Biomedical applications, orthopaedics, prosthetics, joint prostheses, hip and joint replacements, dentistry
Aerospace engineeering	Carbon–carbon composites, PMCs, MMCs	Seals, bearings, brakes
Electrical engineering	PMCs, CMCs	Semiconductors, piezoelectric transducers, bushes, electrodes, turbocharger rotors
Miscellaneous	PMCs, MMCs, CMCs	Agricultural and mining equipment, sports equipment, boats, magnetic tape recording, magnetic optical data storage

nor decompose on their own and pose a threat to the surrounding ecological system. Due to this issue of environmental pollution, there is an increasing demand to develop composites that are biodegradable. Fibers are an important and integral part of the composite industry. Various inorganic (glass) and organic (carbon, graphite, aramid, polymer) fibers can be used to develop lightweight, high strength, high modulus polymer composites. Apart from these synthetic fibers, plant-based fibers, now known as natural fibers, are also used to reinforce polymers.

A great deal of research is being focused on extracting fibers from plants and modifying them artificially so that they become compatible with the polymeric matrices. Common plant fibers, also known as lignocellulosic fibers, are obtained from plants like sisal, jute, cotton, banana, hemp, ramie, flax, linen, bamboo, wood, coir, etc., some of which are shown in Fig. 1.1. The main advantages of these fibers are that they are biodegradable, economical and available in abundance, and offer properties comparable with those of synthetic fibers. Another advantage is that they provide employment to thousands of people living in the rural areas where the extraction of fibers has grown into a fully-fledged industry. For instance, the coastal states of



1.1 Sources of plant fibers; (a) sisal; (b) cotton; (c) jute; (d) bamboo; (e) wood; (f) coir; (g) banana.

India like Kerala, where naturally occurring coconut plantations are abundant, have become major suppliers of coir fibers (Fig. 1.2). When these lightweight, non-carcinogenic plant fibers are reinforced in polymeric matrices or biodegradable polymers, their utility is much increased. Natural fiber reinforced

1.2 Landscape showing coconut plantation in the coastal state of Kerala.

polymer composites have found large-scale applications in the automotive industry and as building material in low cost housing, as will be discussed in the subsequent sections.

1.2 Sources of natural fibers

Natural fibers are generally classified in the literature as being derived from plant, animal or mineral sources according to their origin.[3] Plant fibers are composed of cellulose. Common examples include cotton, linen, jute, flax, ramie, sisal and hemp. These fibers are extracted from the fruits, seeds, leaves, stem and skin of plants. Hence they are categorized as seed fiber (collected from seeds or seed cases, e.g. cotton and kapok), leaf fiber (collected from leaves, e.g. sisal and agave), bast fiber or skin fiber (collected from the skin or bast surrounding the stem, e.g. jute, kenaf, hemp, ramie, rattan, soyabean, vine and banana fibers), fruit fiber (collected from the fruit of the plant, e.g. coconut, coir fiber) and stalk fiber (stalks of the plant, e.g. straws of wheat, rice, barley and other crops including bamboo, grass and tree wood). The most widely used natural fibers are cotton, flax and hemp, although sisal, jute, kenaf and coir are equally popular.

Fibers obtained from animals are composed of proteins. Common examples include silk, wool, mohair and alpaca. These fibers are obtained from hairy mammals such as sheep (wool), goat (alpaca, cashmere), horse, etc. Silk