PHYSICAL, MECHANICAL AND ABRASIVE WEAR BEHAVIOUR OF JUTE FIBER REINFORCED POLYMER COMPOSITES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

In

MECHANICAL ENGINEERING

By

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(Roll No: 511ME103)

Department of Mechanical Engineering
National Institute of Technology, Rourkela (India)

JULY 2014

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Under the Supervision of
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JULY 2014

Dedicated to

My Beloved Parents

Department of Mechanical Engineering
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C E RT I F I C A T E

This is to certify that the thesis entitled "***Physical, Mechanical and Abrasive Wear Behaviour of Jute Fiber Reinforced Polymer Composites***", submitted by ***Vivek Mishra*** (Roll No: 511ME103) in partial fulfilment of the requirements for the award of **Doctor of Philosophy in Mechanical Engineering** to the National Institute of Technology, Rourkela is an authentic record of research work carried out by him under my supervision and guidance.

To the best of my knowledge, the work incorporated in this thesis has not been submitted elsewhere for the award of any degree.

Place: Rourkela
Date:

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ABSTRACT

Now-a-days, abrasive wear of engineering and agricultural machine components caused by the abrasive particles is a major industrial problem. Therefore, a full understanding of the effects of all system variables on the abrasive wear rates is necessary in order to undertake appropriate steps in the design of the machinery and the choice of materials to reduce/control wear. The need for the use of newer materials to combat wear situations has resulted in the emergence of polymer based system. Polymers and their composites form a very important class of tribo-engineering materials and are invariably used in mechanical components where wear performance in non-lubricated condition is a key parameter for the material. The advantages of these materials are light weight, excellent strength to weight ratios, resistance to corrosion, non-toxicity, easy to fabricate, design flexibility, self-lubricating properties, better coefficient of friction, and wear resistance. The present research work is undertaken to study the physical, mechanical and three body abrasive wear behaviour of jute fiber reinforced polymer composites. Three different forms of jute fiber (short jute fiber, bidirectional jute fiber and needle punched nonwoven jute fiber) are considered for the present research work. Attempts have been made to explore the possible use of needle punched nonwoven jute fibers as reinforcement for polymer composites. The design of experiments approach using Taguchi methodology is employed for the parametric analysis of abrasive wear process. The study reveals that abrasive wear performance of needle punched nonwoven jute based composites is better than that of the short and bidirectional jute fiber reinforced composites. The morphology of abraded surfaces is examined by using scanning electron microscopy (SEM) and possible wear mechanisms are discussed. Finally, the ranking of the composite materials under study is done by using AHP-TOPSIS method based on their physical, mechanical and abrasive wear attributes.

acknowledgement

It gives me immense pleasure to express my deep sense of gratitude to my supervisor **Prof. Sandhyarani Biswas** for her invaluable guidance, motivation, constant inspiration and above all for her ever co-operating attitude that enabled me in bringing up this thesis in the present form.

I am grateful to **Prof. Sunil Kumar Sarangi**, Director, National Institute of Technology, Rourkela who has been a constant source of inspiration for me. I am equally grateful to **Prof. Siba Sankar Mahapatra**, Head of the Department of Mechanical Engineering for his help and cooperation. I also appreciate the encouragement from faculty members of the Mechanical Engineering Department of National Institute of Technology, Rourkela.

I would like to record my sincere thanks to **Prof. P. K. Ray**, **Prof. D. Sarkar**, **Prof. A. Satapathy** and **Prof. A. Sahoo**, learned members of my doctoral scrutiny committee for being helpful and generous during the entire course of this work.

I am also thankful to my friends and roommates, offering me advice, and supporting me through this entire process. Special thanks to my NIT Rourkela friends: **Alok Kumar Jha**, **Alok Agarwal**, **Gaurav Gupta**, **Abhijeet Ganguly**, **Saurabh Sharma**, **Saurabh Chandrakar**, **Abhishek Sharma**, **Vaneshwar Sahu** and **Panchanand Jha**.

I greatly appreciate and convey my heartfelt thanks to **Prabina Kumar Patnaik**, **Priyadarshi Tapas Ranjan Swain**, **Prity Aniva Xess** and **Siva Bhaskara Rao Devireddy** scholars associated with our department and all my well-wishers for their support and co-operation that is difficult to express in words.

My very special thanks go to all my family members. Their love, affection and patience made this work possible and the blessings and encouragement of my beloved parents greatly helped me in carrying out this research work. I am also extremely thankful to my relatives for their kind support.

Finally, but most importantly, I thank Almighty God, my Lord for giving me the will power and strength to make it this far when I didn't see a light.

Place: Rourkela **Vivek Mishra**
Date:

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The development of mankind is defined in terms of advances in materials i.e. the stone age, the bronze age, and the iron age. The present era of material belongs to the composite materials because of its lighter weight, higher strength, corrosion resistance, ease to shape and durability. The composites are not new to the mankind; it has a history of more than 3000 years. In ancient Egypt, people used to build walls from the bricks made of mud with straw as reinforcing component [1]. Another important application of composites can be seen around 1200 AD from Mongols. Mongolians invented a bow made up of composites. Using a combination of animal glue, bone and wood, bows were pressed and wrapped with birch bark [2]. The word ‘composites’ derived from the Latin word compositus, which means ‘put together’ signifying something made by putting together different parts or materials [3]. In general, composites are materials which consist of two or more physically distinct and mechanically separable components, existing in two or more phases. The mechanical properties of composites are superior to those of its individual constituents, and in some cases may be unique for specific properties [4]. Usually, composites have two phases i.e. continuous and discontinuous. The discontinuous phase is usually stronger and harder than the continuous phase and is called the reinforcement, and continuous phase is termed as the matrix. Composites can be classified in two ways i.e. based on the reinforcement used (particle reinforced and fiber reinforced) and based on the matrix used (i.e. metal matrix, polymer matrix and ceramic matrix). Composite materials have a wide range of applications. They possess applications in buildings and public works (chimneys, housing cells, door panel, windows, partitions, swimming pools, furniture and bathrooms); electrical and electronics (insulation for electrical construction, armor, boxes, covers, cable tracks, radomes, antennas, tops of television towers, and wind mills); general mechanical components (gears, bearings, housing, casing, jack body, robot arms, flywheels, weaving machine rods, pipes, components of drawing table, compressed gas bottles, tubes for offshore platforms and pneumatics for radial frames); rail transports (front of power units, wagons, door, seat, interior panels and ventilation housing); road transports (body components, complete body, wheel, shields, radiator grills, transmission shaft, suspension spring, chassis, suspension arms, casing, cabin, seats, highway tankers and isothermal trucks); marine transports (hovercrafts, rescue crafts, patrol boats, trawlers, anti-mine ships, racing boats, pleasure boats and canoes); space transport (nozzles, rocket boosters, reservoirs and shields for atmosphere reentrance); air transports (all composite passenger aircrafts and gliders, helicopter blades, propellers, transmission shafts and aircraft brake discs); cable transports (telepherique cabins and telecabins); sports and recreation (poles used in jumping, tennis and squash rackets, fishing poles, bicycle frames, roller skates, skies, sails, javelins, surf boards, bows and arrows, protection helmets, golf clubs and oars) etc. [5].

From a very long time composites have been used to solve the technological problems, but only in 1960s with the introduction of polymer based composites, it starts getting the attention of industries. Since then, it has become a common engineering material. The growth in its usage also came about because of increased awareness in terms of product performance and increased competition in the world market for lightweight components [6]. For the past few decades, fiber reinforced polymer (FRP) composites acquired an important space in the field of composite materials. FRP composites have been widely used in various applications, i.e. automotive, aerospace, marine, defence, and sports goods because of their high specific strength and stiffness. These materials provide design flexibility, high durability, excellent corrosion resistance and lightweight which make them attractive material in these applications [7, 8]. The fiber which acts as reinforcing agent in the reinforced plastics may be either synthetic or natural. Various type of synthetic (or man-made) fibers have been developed such as aramid, Kevlar, glass, polyetheretherketone (PEEK), nylon, rayon, acrylic, olefin, polyester, vinyl etc. On the other hand, some of the known natural fibers are cotton, wool, silk, hemp, linen, ramie, coconut, pinewood, jute, pineapple, mohair, angora, kapok, angora, sisal, kenaf, flax, wood fiber, banana, bamboo etc. [9].

The growing ecological concern and governmental rules lead to rise in the demand of the natural fibers as a substitute of synthetic fibers [10 -12]. The natural fibers such as hemp, sisal, jute, flax and bamboo are renewable and biodegradable in nature and possess high technical qualities such as good modulus and specific strength, low density and cost, and reduced dermal and respiratory irritation [13]. The mechanical properties of natural fibers, particularly hemp, sisal, flax, and jute are relatively good, and may compete with glass fiber in terms of specific strength and modulus [14]. Interestingly, numerous types of natural fibers which are abundantly available have proved to be effective and good reinforcement in the thermoplastic and thermoset matrices. Among all the natural fibers, jute is more promising as it is relatively inexpensive and commercially available in various forms [15]. Jute fiber has many inherent advantages like luster, low extensibility, high tensile strength, moderate fire and heat resistance and long staple lengths [16, 17]. Traditionally, jute is used in packaging fabrics, saking, mats, manufacturing hessian, carpet backing, bags, ropes, twines and tarpaulins. Jute fibers are also used in wide range of products like decorative fabrics, salwarkamizes, chic-saris, soft luggage’s, greeting cards, molded door panels, footwear and other innumerable useful consumer products [17]. However, the major breakthrough came when the pulp and paper, automobile, and furniture industries started to use jute for the fabrication composite materials [18]. Generally, India, Bangladesh, China and Thailand are the leading jute producer in the world. Thus, the use of jute fiber as reinforcement in composite materials could create employment opportunities in urban and rural sector of these countries.

Jute fiber can be used as reinforcement in polymer composites in various forms such as short jute fiber, woven jute fiber, unidirectional jute fiber etc. Another form of jute fiber is needle-punched nonwoven fiber mat. In polymer reinforced composites, the use of needle-punched nonwoven mats is beneficial as they offer good inter-laminar shear and compression properties. The numerous connected pores in needle-punched structure led to easy flow of the resin material and interlinked mechanism with fibers takes place. The needle-punched nonwoven mats have a three-dimensional fiber reinforcing structure formed due to the entanglement or interlocking of the fibers. The applications of needle-punched nonwoven mats ranges from blankets to high performance geotextiles [19].

Tribology is defined as the science and technology of interacting surfaces in relative motion and of related subjects and practices [20]. The word ‘tribology’ is derived from the Greek word ‘tribos’ meaning rubbing or sliding. FRP composites form an important class of tribo-material because of its relative low density, high loading capacity, high specific strength and corrosion resistance [21]. FRP composites are used for producing a number of mechanical components like seals, clutches, gears, cams, wheels, brakes and bearings. Most of these are exposed to tribological loading environments [22]. Many studies have consistently concluded that the cost of wear and friction put a severe burden on industrialized countries. The cost of friction and wear may appear too small to an average engineer, but when the same costs are summed for an entire country a huge loss of resources becomes apparent [23]. Wear is defined as damage to a solid surface, generally involving progressive loss of material, caused by relative motion between that surface and a contacting substance or substances [24]. It is a response of material to the external stimulus and can be mechanical or chemical in nature. Wear is not an intrinsic material property and is affected by many factors, i.e., material properties, surface roughness, contact geometry, contact force, environment (temperature, lubrication) and time [25]. Various wear types have been recognized, e.g. adhesive, abrasive, erosive, fretting, corrosion and oxidation. Wear of solid is generally considered as the mechanical process. However, corrosion, oxidation and other chemical processes are exemptions of this rule. Among all the wear types, abrasive wear is one of the major problem encountered by the industries which is about 50% of total wear problem faced, and it also contributes almost 63% of all cost associated with the wear in industrial components [26,27]. Generally, abrasive wear occurs when hard asperities on one surface move across a softer surface under load, penetrate and remove material from the softer surface, leaving grooves [28]. Abrasive wear conditions are encountered in numerous applications such as gears and vanes; bearings in steel mills subjected to heat; pumps handling industrial fluids; chute liners abraded by coal, coke, and mineral ores; food processors, etc. [29].

The terminology 'abrasive wear' does not exactly describe the involved wear mechanism. There are, actually, quite often several different mechanisms of wear acting in concert, all of which have distinct features [23]. In general, the abrasive wear process involves four different mechanisms i.e. microcutting, microploughing, microcracking and microfatigue. Abrasive wear in the cutting form occurs when an abrasive tip with large attack angle plow a grove over the material surface and the material removes in the form of a ribbon-shaped or discontinuous debris particle similar to that created in the metal cutting operation (Figure 1.1). In the plowing process, material is displaced from a groove to the edges without the removal of material (Figure 1.2) [30].

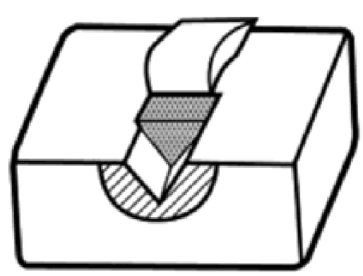

Figure 1.1 Microcutting [31]

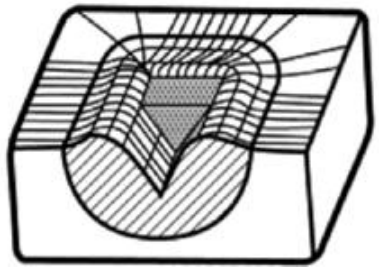

Figure 1.2 Microploughing [31]

In brittle material, an additional mode of abrasive wear occurs i.e. microcracking or microfracture. This kind of wear takes place when force applied by the abrasive grain surpass the materials fracture toughness [32]. Figure 1.3 represents a schematic diagram of microcracking mechanism.

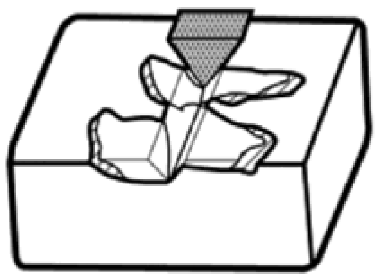

Figure 1.3 Microcracking [31]

Wear due to microfatigue occurs when a ductile material is abraded by a blunt asperity/particle and the worn surface is continually loaded and unloaded. The schematic diagram of microfatigue mechanism is shown in Figure 1.4.

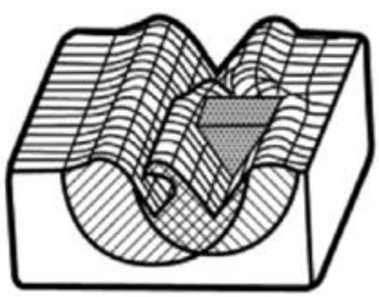

Figure 1.4 Microfatigue [31]

In general, there are two modes of abrasive wear, known as two-body and three-body abrasive wear. The primary meaning of two-body or three-body concept is to describe whether the abrasive particles are bound (two-body) or free to roll or slide (three-body) [33]. When there are only two bodies in relative motion and one is relatively harder, such abrasive damage is termed as two-body abrasion. In Figure 1.5 (a), the two-body abrasion wear situation is shown in which the harder rough surface of abrasive grit is sliding over the softer surface. This situation arises in mechanical processes such as cutting, grinding and machining. In three-body abrasive wear, the hard abrasive particles act as interfacial third body elements between the two moving primary bodies and are accountable for wear on either or both of the surfaces, mainly depending on their hardness [34]. The three-body abrasive wear situation is represented in Figure 1.5 (b), in which abrasive particle is free to slide as well as roll in between the two surfaces. This occurs, for example, in abrasive free polishing and lapping.

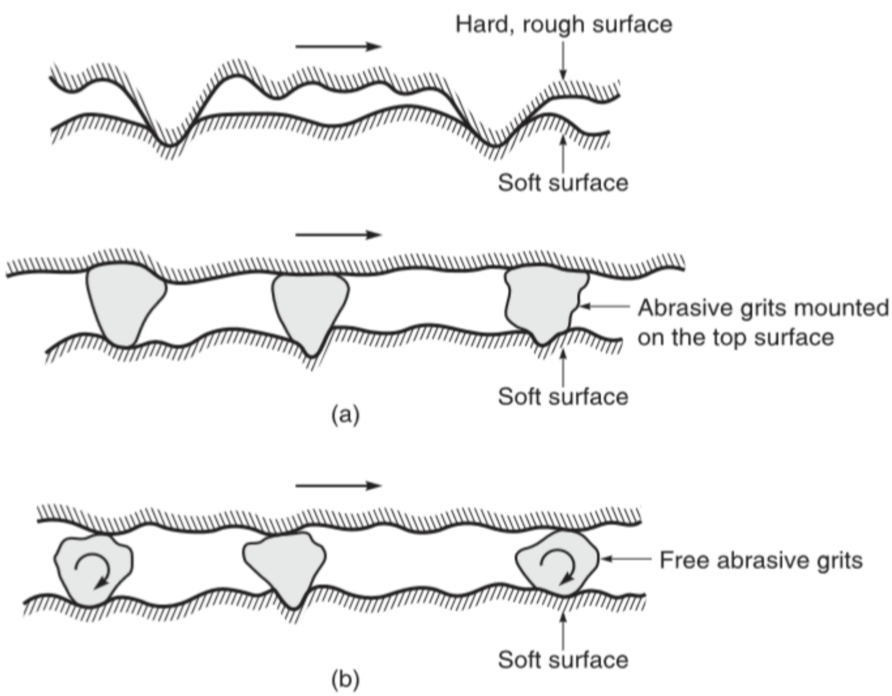

Figure 1.5 Schematics of (a) two-body abrasive wear and (b) three-body abrasive wear [23]

Most of the abrasive wear problem in industrial and agricultural equipment is associated with three-body abrasive wear, whereas two-body abrasive wear occurs particularly in material removal operations [35]. Wear due to three-body abrasion is often of considerable practical importance, but appears to have received much less attention than two-body abrasive wear [36]. Although many studies have focused attention on the sliding wear behaviour of polymeric composites, the data related to three-body abrasive wear study of polymer composites is limited [37].

Design of experiments (DOE) or Experimental design is a statistical technique used to study the multiple factors or variables simultaneously. DOE is an effective tool for maximizing the amount of information gained from a study while minimizing the amount of data to be collected [38]. It provides information about the interaction of factors and the way the entire system works, something not obtainable through testing single factor at a time while keeping the other factors constant. DOE also depicts how interconnected factors respond over a wide range of values, without needing the testing of all possible values directly [39]. It has wide applications particularly in the field of engineering and science for the purpose of process optimization and development, process management and validation tests [40]. DOE has been successfully adopted by many industries which include automotive, medical devices, semiconductor, chemical products, etc. [41]. By applying this technique, scientists, engineers, and researchers can significantly reduce the time required for any experimental analysis. Three-body abrasion is a complex wear phenomenon in which a number of control factors collectively determine the performance output (i.e. the specific wear rate) and there is huge scope in it for implementation of appropriate statistical techniques for optimization of process. But unfortunately, such studies have not been adequately reported so far. The present research work addresses to this aspect by adopting a statistical approach called Taguchi experimental design to optimize the process parameters to minimize wear rate of the jute fiber reinforced polymer composites.

For designing and developing any structural component, material selection is one of the most challenging issues. The success of any component depends on the better performance and low cost of material used. Thus, it becomes a real challenge for the designers to optimally select material from the vast range of available materials that satisfy the complex design problems. Recently, multi-criteria decision-making (MCDM) approach is used as an effective tool for material selection of complex design problems [42]. The MCDM process involves creating alternatives, forming the required criteria and assessing the alternative materials using a set of criteria weights. The outcome of these steps is a ranked list of alternative solutions [43]. Depending upon the complexity of the situation in engineering decision making problems, various MCDM techniques like weighted product model (WPM), the analytic hierarchy process (AHP), revised AHP, weighted sum model (WSM), elimination and choice translating reality (ELECTRE) and technique for order preference by similarity to ideal solution (TOPSIS) can be used [44]. Among various MCDM approaches, integrated AHP and TOPSIS method offers a number of benefits. Firstly, it is a reliable and systematic method as it is capable of capturing an expert's view when complex MCDM problems are considered. Secondly, it considers the pair-wise comparisons, hierarchical structure and consistency checks in the assessment process. Its calculations are much faster than other mathematical methods such as analytic network process (ANP), data envelopment analysis (DEA), intelligent and fuzzy logic based methods. Finally, the integrated AHP and TOPSIS method is very suitable and flexible for numerous decision making conditions [45]. Therefore, an attempt has been made to obtain the best alternative from the set of composite materials under the present study using integrated approach of AHP and TOPSIS.

The novelty of the current research work is to develop low cost eco-friendly polymer composite materials for wear resistance applications using jute fibers. For the first time, the effect of three different types of jute fibers (short, bidirectional and needle-punched nonwoven) on the physical, mechanical and three-body abrasive behavior of polymer composites have been investigated and the selection of best material among many alternatives based on MCDM approach is presented. The research findings can help to understand the effect of different parameters like fiber loading, fiber types, abrasive size, normal load, sliding velocity etc. on the three-body abrasive wear behavior of composites. The specific objectives of this work are clearly outlined in the next chapter.

1.2 Thesis Outline

The rest of the thesis is structured as follows:

Chapter 2. Includes a literature review to provide a basic knowledge of the main subjects presented in this thesis. It presents the research works carried out by various investigators specifically on jute fiber reinforced polymer composites.

Chapter 3. Provides information of the raw materials used, fabrication technique, test procedures, and characterization of the composites under study and also a description of the Taguchi experimental design and Integrated AHP and TOPSIS method.

Chapter 4. Presents the test results of physical, mechanical and three-body abrasive wear behaviour of the composites under study.

Chapter 5. Presents the ranking of composites under study using AHP-TOPSIS method.

Chapter 6. Provides conclusions drawn from the experimental study and scope of future research.

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CHAPTER 2

LITERATURE REVIEW

A review of available literature is done to put forward the background information on the issues to be considered in this thesis and to highlight the importance of the present study. The review is focused on the various aspects of the polymer composites with a special reference to jute fiber and its composites. This chapter contains review of existing research reports:

- On Natural Fiber and Natural Fiber Reinforced Composites
- On Jute Fiber and Jute Fiber Reinforced Composites
- On Abrasive Wear Behaviour of Composites
- On Taguchi Method
- On MCDM Approach

Section 2.1 provides general information about the natural fibers along with the literature related to the natural fiber reinforced composites. The section 2.2 provides the information about the various forms of jute and a brief review on the jute fiber based composites. In section 2.3, review related to the abrasive wear behaviour of the composites is provided. Section 2.4 provides a review on the past work related to the Taguchi method. Section 2.5 gives a review on the various methods used for MCDM problems. Based on the literature survey, the knowledge gap is presented at the end of the chapter. Subsequently the objectives of the present research work are also outlined.

2.1 On Natural Fibers and Natural Fiber Reinforced Composites

Increased ecological awareness and consciousness all over globe has developed the increasing interest in natural fibers and its application in different fields [46]. Now-a-days, in various fields, natural fibers are considered as a potential alternative to the synthetic fibers. They are extracted from the substances that are available naturally [47]. Natural fibers can be divided into three groups based on their origin, i.e. vegetable/plant fibers (flax, hemp, sisal, etc.), animal/protein fibers (hair, wool, silk, chitin, etc.) and mineral fibers (asbestos, wollastonite etc.). Figure 2.1 shows the classification of the natural fibers based on its origin.

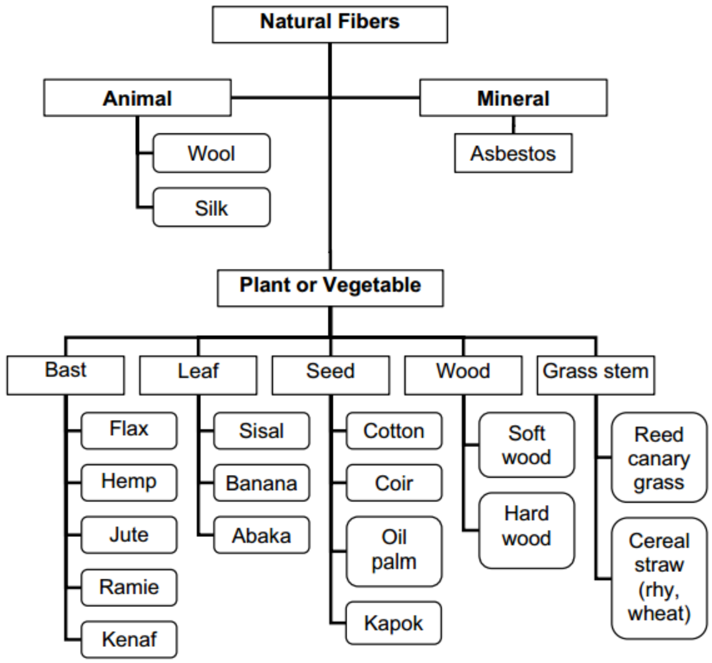

Figure 2.1 Classification of natural fibers [48]

The chemical structure of natural fiber or plant fiber comprises of cellulose, hemicellulose, lignin, pectin and extraneous materials. Characterization of plant fiber can be done based on its cellular structure. Each cell of fiber comprises of crystalline cellulose regions (microfibrils) which are interconnected via hemicellulose and lignin fragments. A natural fiber cell has one thin primary wall and three thick secondary walls (Figure 2.2) [49]. The primary wall is the first layer deposited during cell growth surrounding a secondary wall. The secondary wall consists of three layers and the thick middle layer controls the mechanical properties of the fiber [50]. It is observed that the higher fiber strength takes place when the microfibrils are arranged more parallel to the fiber axis [51]. Cellulose is the major framework component of the fiber and provides the strength, stiffness and structural stability of the fiber [52]. Hemicellulose comprises a group of polysachrides compiled of a combination of five and six carbon ring sugars. It is hydrophilic in nature, soluble in alkali and easily hydrolyzed in acids [50]. It occurs mainly in the primary cell wall and have branched polymers carbon sugars with varied chemical structure [52]. Lignin is an amorphous, cross-linked polymer network comprising of an irregular array of variously bonded hydroxy- and methoxy- substituted phenylpropane units. It is less polar than cellulose and acts as a chemical adhesive within and between fibers [53]. Hemicellulose and lignin contributes to the characteristic properties of fiber. Toughness depends on the lignin and hemicellulose content of the plant fiber. It decreases with the decrease in the amount of lignin and/or hemicellulose, while at the same time the strength and stiffness of the fiber increases up to a limit [54]. Pectins form a group of highly heterogeneous and branched polysaccharides that are rich in D-galacturonic acid residues. The hemicelluloses, pectin polysaccharides and aromatic polymer lignin, interact with the cellulose fibrils, forming a rigid structure strengthening the plant cell wall [55].

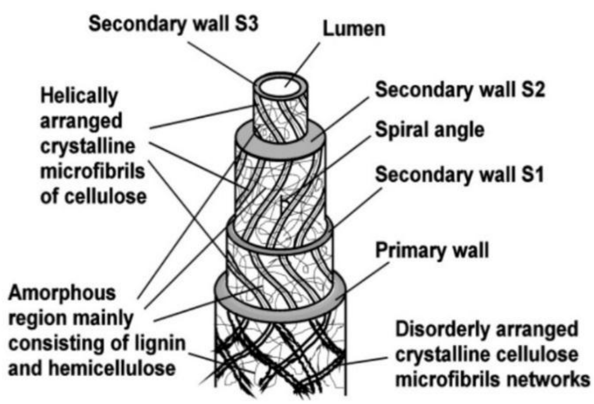

Figure 2.2 Structure of natural fiber [49]

Natural fibers as reinforcement in composite materials have recently attracted the attention of researchers because of their several advantages such as low density, low cost and high specific strength [56]. Natural fiber composites are eco-friendly and bio-degradable in nature and due to this the government and private organizations invest millions of dollars in the research and development of natural fiber based composites as a variable option to the synthetic composites [57]. The energy consumption during the processing of the natural fiber based composites is less compared to the synthetic fiber reinforced composites. They also reduce the dermal and respiratory irritation during handling [58]. It is also known that natural fibers are non-uniform with irregular cross sections, which make their structures quite unique and much different from man-made fibers such as glass fibers, carbon fibers etc.

A great deal of work has been done on the use of natural fibers in polymer composites by various researchers. Summerscales et al. [59] carried out a review on the bast fiber and their composites and reported that the natural fibers which are currently attracting most interest are kenaf, jute, hemp and flax. Holbery and Houston [60] reported the potential of natural fiber based composites in automotive applications. Ku et al. [56] done a thorough study on the tensile properties of natural fiber reinforced polymer composites. The review reveals that the tensile properties of the natural fiber based composites are largely influenced by the interfacial bonding between the fiber and the matrix. Mukherjee and Kao [61] studied the effects of processing methods, fiber orientation, fiber length, fiber volume fraction, and fiber surface treatment on the fiber/matrix interfacial bonding and mechanical behaviour of various natural fiber reinforced poly (lactic acid) (PLA) composites. Saheb and Jog [62] presented the work carried out by various researchers on natural fiber composites with a special reference to the type of matrix, fibers, fiber treatments and fiber matrix interface. Chauhan et al. [63] presented the findings of various researchers on the basis of physical, chemical, thermal and mechanical properties of the natural fiber composites.

Wirawan et al. [64] reviewed the mechanical properties of the natural fiber reinforced PVC composites and concluded that natural fibers gives positive result to the stiffness of the composites while reducing the density. Satyanarayana et al. [65]

studied the performance of natural fiber reinforced composites subjected to indoor and outdoor weathering condition using both destructive and non-destructive testing techniques. Begum and Islam [66] reported that the natural fiber reinforced composites can attain equivalent mechanical strength as that of the glass fiber composites on using higher volume fraction of natural fibers than glass fibers during the preparation of composites. They also reported that the natural fiber reinforced polymer composites have already been proven alternate to synthetic fiber reinforced composites in applications like transportation, automotive, packaging and construction industries. Verma et al. [67] reported that various natural fiber composites attain the mechanical properties of glass fiber composites and are already used in various industries like furniture industries. Pathania and Singh [68] emphasized on the work carried out by various researchers on the electrical properties (i.e. volume resistivity, dielectric loss factor, dielectric dissipation factor and dielectric constant) of the natural fiber composites and suggested that the systematic and determined research will lead to a better future of these composites in electrical applications such as circuit boards, connectors, terminals, switches etc. Joseph et al. [69] have done a survey on the sisal fiber reinforced composites with reference to the structure and properties of sisal fibers, fabrication methods and physical and mechanical behaviour of the sisal composites. Mehjoub et al. [70] gathered the findings on mechanical properties of oil palm empty fruit bunch fiber reinforced composites in terms of flexural and tensile properties. Akil et al. [71] presented an overview on the development made in the field of kenaf fiber composites considering the mechanical properties, thermal properties and processing techniques. Shahzad [72] analysed the findings on hemp fiber reinforced with thermoset, thermoplastic and biodegradable matrices and reported that these composites exhibit good mechanical properties. They also reported that the hemp fiber has properties comparable to glass fiber. Khalil et al. [73] provided a highlight of the work carried out by the researchers using bamboo fiber as reinforcement.

Hassan et al. [74] studied the work carried out by researchers on the oil palm empty fruit bunch (EFB) fiber-reinforced polymer composites and stressed on the mechanical and water absorption behaviour of these composites. Jawaid et al. [75] reported that the addition of jute fiber in the oil palm composites increases the storage modulus whereas the damping factor moves towards the high temperature region. Jawaid et al. [76] investigated the chemical resistance, void content and tensile properties of oil palm/jute fiber reinforced hybrid composites.

2.2 On Jute Fiber and Jute Fiber Reinforced Composites

2.2.1 Jute Fiber

Jute is multicelled in structure [77]. Jute fiber is generally derived from the steam of a jute plant. It is an annual plant that grows to 2.5-4.5 m and flourishes in monsoon climates [78]. Jute is a lingo-cellulosic fiber because its major chemical constituents are lignin and cellulose. The thermal and electrical conductivity, biological degradation, proneness to mildew and moths, ability to protect from heat, cold and radiation, reaction to sun and light, etc. are determined by cellular constitution and morphology [79]. The chemical composition of the jute fiber has been reported by many researchers [50, 51, 80, 81]. Among different natural fibers, jute fibers are easily obtainable in fiber and fabric forms with good thermal and mechanical properties [82]. The inborn properties of jute fiber such as low density, high tensile modulus and low elongation at break and its specific stiffness and strength comparable to those of glass fiber draws the attention of the world [83-85]. Over hundreds of years it has been used in the applications of ropes, beds, bags etc. High quality and new uses of this fiber can create more job opportunity in the rural sector [86]. Jute has also got applications in the automobile industry and packing materials. Unlike cotton and most of the food crops, jute does not require any pesticides and fertilizer and hence is a “pure green” agro-product. Riverflats, depressions and saline-alkali soils are very much suitable for the jute plantation [87]. Jute is mostly grown in countries like India, Bangladesh, China, Nepal and

Thailand. About 95% of the global production of jute fibers is produced by these countries [86]. Islam and Alauddin [88] reported a comparative study among the major jute producing nations. It has been found that India is one of the largest jute producing nations over the past two decades. In India, jute industry is one of the most labour-intensive industries which provide direct employment to about 2.3 lakhs industrial workers and source of income to another 1.4 lakh people in the tertiary sector and allied activities [89].

2.2.2 Jute in Various Forms

Raw Jute: Jute is a long, soft and shiny fiber obtained from the bark of jute plant. Commercially the smallest unit of raw jute is known as reed. Depending upon the grade, the length of the reed varies from 1-4.5 m. The reed diameter is usually 6-20 microns [90]. Figure 2.3 shows the raw jute fiber. Raw jute can be processed to different forms like yarn or mats. Raw jute is principally used in the manufacturing of hessian, sacking cloths, cords, ropes, bags, handicrafts and miscellaneous fabrics [91].

Short Jute Fiber: Jute in the form of short fiber is shown in Figure 2.4. Composites made from short fiber are used widely in non-load bearing applications to obtain complex geometry in aerospace and automobile industry [92, 93].

Figure 2.3 Raw jute fiber

Figure 2.4 Short jute fiber

They have also got applications in general purpose and specialty products ranging from hoses, diaphragms, belts and seals to tyres [94]. The utilization of short jute fiber as reinforcement in polymer composites has already been reported by many researchers [95-99].

Woven Jute Fiber Mat: Woven mat reinforced composites are attaining popularity due to its balanced properties in mat plane as well as their ease of handling during fabrication. The woven configuration of the mat leads to a synergetic effect on the improvement of the wear resistance of the composites [100]. Woven mat composites belong to a class of two dimensional textile composites where the warp and weft fiber tows are woven into each other to form a layer. The laminated composite obtained from the woven mat has good properties in mutually orthogonal directions as well as better out of plane impact resistance than the multidirectional laminate [101]. Woven mat composites have found wide range of applications in aerospace, automobile and defence industries [102]. Figure 2.5 shows a typical example of woven jute fiber mat. A great deal of work has been done on the woven jute fiber reinforced polymer composites by many researchers [83, 103-107].

Figure 2.5 Woven jute fiber mat

Figure 2.6 Needle-punched nonwoven jute fiber mat

Needle-punched Nonwoven Jute Fiber: Another form of jute is needle-punched nonwoven fiber mat as shown in Figure 2.6. In polymer reinforced composites, the use of needle-punched nonwoven mats is beneficial as these materials improve the toughness and strength with light weight [108]. Additionally, these nonwoven have an important quality that offers excellent z-directional properties that minimizes the delamination problem [109]. The entanglement or interlocking of fibers in needle-punched nonwoven mats results in a three dimensional fiber reinforcing structure. Nonwoven mat is widely used as geotextile, filtration, medical goods, aerospace and military applications [110]. These materials have been discovered for various industrial and technical applications including abrasive composite materials [109]. In search of diversified use of jute fiber, successful efforts have been made to use this natural and eco-friendly technical fiber in the field of geotextile, floor covering and filtration [111]. The research on the different needle-punched nonwoven fiber based polymer composites has already been done by few researchers [112, 113]. However, the potential utilization of needle-punched nonwoven jute fiber as reinforcement in polymer composites is hardly been reported.

2.2.3 Jute Fiber Reinforced Polymer Composites

Over the last few decades, there has been renewed interest in the use of natural fibers to replace synthetic fibers in composite applications. Among various natural fibers, jute fiber is a promising reinforcement for use in composites on account of its low cost, easy availability, renewability, much lower energy requirement for processing, high specific properties and no health risk. A great deal of work has been published regarding the reinforcing potential of jute fiber on polymer composites. Properties of FRP composites are determined by many factors such as properties of the fibers, orientation of the fibers, concentration of the fibers, properties of the matrix, fiber-matrix interface strength etc. Increasing the volume content of reinforcements can increase the strength and stiffness of a composite to a point. If the volume content of reinforcements is too high there will not be enough matrix to keep them separate, and they can become tangled. Similarly, the arrangement or orientation of the fibers relative to one another within the matrix can affect the performance of a composite. There are many factors to be considered when designing with composite materials. In order to obtain the favored material properties for a particular application, it is important to know how the material performance changes with the different factors. To this end, the effect of jute fiber on various properties of polymer composites is discussed below:

On Mechanical Properties

Many materials during its service life are subjected to different loads or forces. Thus, it is very important to understand the mechanical behaviour of materials so that the product made from it will not result in any failure during its life cycle. An adequate knowledge of mechanical properties of material helps in selection of its suitable applications. For example lighter and stronger materials are required for vehicles such as bicycles, automobiles, or aerospace applications. Tensile, flexural, inter-laminar shear strength, impact strength and hardness are the important mechanical properties of the FRP composites.

In structural design applications, tensile properties are considered as one of the important material property. The tensile strength and modulus of composite is more sensitive to matrix and fiber properties [114]. The tensile strength of composites mainly depends on the strength and modulus of fibers, the strength and chemical stability of the matrix and the effectiveness of the bonding strength between the matrix and fibers in transferring stress across the interface [15]. Tensile properties of highly viscous thermoplastic or rubber materials are governed by many factors, such as entrapped air during mixing (wetting problems), dispersion problem (agglomerate formation) and increase of stress concentration points at fiber ends [115]. In general, the tensile properties are significantly improved by reinforcement of fibers in polymer matrix as fibers have much higher stiffness and strength values than that of the matrices [56]. A great deal of work has been done on the tensile behaviour of jute fiber reinforced polymer composites. It was reported that the tensile strength of unreinforced polyester resin improved with incorporation of jute and jute-glass fabric [106]. Albuquerque et al. [84] evaluated the effect of fiber surface wettability, alkali treatment and different ageing conditions on the tensile properties of longitudinally oriented jute roving reinforced polyester composites as a function of fiber content. It was found that the tensile properties of longitudinal composites increased with fiber content. Das et al. [116] reported that the tensile strength of the biocomposite films (5, 10 and 15 wt.% filler loaded) increased by 51%, 130% and 197%, respectively in comparison to the unreinforced one. This improvement in the tensile strength was due to very fine nature of jute micro/nanofibrils (JNF) and also due to effective stress transfer at the interface between the matrix and JNF. Doan et al. [117] studied the effect of coupling agent (maleic anhydride grafted polypropylene) on the tensile behaviour of short jute fiber reinforced polypropylene composites. It was found that the tensile strength of jute/PP composites increased in humid ageing conditions, which was attributed to both improved polymer-matrix and interfacial adhesion strength. Gowda et al. [15] evaluated the tensile behaviour of jute fabric reinforced polyester composites in both longitudinal and transverse direction. It was found that the tensile strength and modulus of composites obtained in longitudinal direction were almost five times the strength and modulus of polyester resin and twice that for the transverse laminate. The differences in ultimate stress between the same laminate specimens are due to the highly non-uniform and inconsistent nature of the jute fibers. Hong et al. [118] investigated the tensile properties of jute-polypropylene composites in order to detect the reinforcement effects of the untreated and silanized jute fibers. Jawaid et al. [76] fabricated tri layer hybrid composites based on chopped mat of oil palm EFB and jute fibers with two different stacking sequences i.e. EFB/Jute/EFB and Jute/EFB/Jute. It was found that the tensile properties were slightly higher for the composites having jute as skin and oil palm EFB as core material. Jawaid et al. [119] reported that the incorporation of jute woven fiber in pure EFB composite enhances the tensile property of hybrid composites. Khan et al. [85] studied the tensile behaviour of jute-polycarbonate composites with 13 %, 23 %, 26 %, 32 %, 35 % and 42 % jute content. It was found that as the fiber content raised the tensile strength of the composites increased up to 32% jute content, but further increase in the jute content lead to decrease in the strength values. Liu et al. [120] evaluated the effect of surface modification on the tensile properties of jute poly (butylene succinate) (PBS) biocomposites. It was found that the tensile strength and modulus increased gradually from 0 wt. % to 20 wt. % of fiber and at 30 wt. % there is a drop in tensile properties. The decreased tensile strength at 30 wt.% fiber loading may be due to the presence of so many fiber ends in the composites that cause crack initiation and hence potential composite failure as well as nonuniform stress transfer due to grouping of the fibers within the matrix. Mohanty et al. [121] studied the effect of jute fiber content on the tensile behaviour of jute fabrics-polyester amide composites. Jute content was varied from 20 to 53 wt. % to determine its effect on the tensile properties. It was reported that the tensile strength of composite increased from 20 wt. % to 32 wt. % fiber loading and afterward with further increase of jute content properties tend towards lower values. Mohanty et al. [122] reported that the tensile strength of jute-Biopol composites was enhanced by more than 50% relative to pure Biopol sheets. In another study, Mohanty et al. [123] investigated the effect of fiber loading on the tensile strength of untreated jute fiber reinforced high density polyethylene (HDPE) composite. It was observed that the tensile strength of the composite increased with increase in fiber loading from 0 to 30 wt. %, above which there was a significant decline in the strength. An increase in tensile strength of the composite was observed with the increase in concentration of maleic anhydride grafted polyethylene (MAPE) up to 1 %. Plackett et al. [124] studied the tensile behaviour of jute fiber reinforced L-polylactide composites. It was found that the tensile strength and stiffness of the composites was almost doubled when jute fiber reinforcement was used on 40 wt. % basis.

Rahman et al. [125] investigated the tensile behaviour of the raw and oxidized jute fiber reinforced polypropylene (PP) composites and urotropine post-treated composites at different fiber loading. It was observed that the tensile strength of the raw jute fiber reinforced composites decreases with increase in fiber loading which may be due to the increase in the weak interfacial area between the fiber and matrix. In order to increase the compatibility of jute fiber with PP, raw fiber was oxidized and manufactured composites were post-treated with urotropine. The result indicates that the tensile strength of the composites with 20 wt. % fiber loaded post-treated composite is increased when compared to the PP matrix itself. Seki [126] studied the effect of siloxane treatment on the tensile properties of jute-thermoset composites. It was found that the siloxane treatment on the alkalized jute fabrics results in improved tensile properties of both jute epoxy and jute-polyester composites. Stocchi et al. [127] studied the effect of treatment on the tensile behaviour of woven jute fabric/vinyl ester composites at two different times of treatment. It was found that composites with 4 h alkali treated mats under biaxial stress exhibit significant improvement in the stiffness compared to composites with 24 h alkali treated mats under biaxial stress and untreated mats. Tao et al. [128] investigated the tensile properties of natural fiber/PLA composites with short jute and ramie as reinforcement. The fiber loading of jute-PLA and ramie-PLA composites were varied from 10-50 %. It was found that the tensile strength of composites increased up to 30 % fiber content and after that it decreased. Vilaseca et al. [129] reported that the increase in fiber loading results in increased tensile properties of untreated jute fiber reinforced starch polymer composites. The alkali treatment of jute fiber results in enhanced tensile properties of composites. Ishiaku et al. [130] investigated the effect of weld line on the tensile properties of short-fiber reinforced jute/poly butylene succinate biodegradable composites. The weld lines are formed on fabrication of polymer composites by injection moulding process which often involves the use of multiple gates. Khan and Hinrichsen [131] studied the influence of coupling agents on mechanical properties of jute fiber reinforced polypropylene composites. 2- hydroxy ethylmethylacrylate (HEMA) and 2-ethylhexylacrylate (EHA) were used as coupling agents. It was found that composites prepared with EHA treated fiber exhibit superior tensile properties than untreated and HEMA treated fiber composites. Khondker et al. [132] studied the tensile behaviour of unidirectional jute/polypropylene composites fabricated by film stacking method. The experimental investigation revealed that the tensile strength and modulus of PP resin increased by approximately 285 % and 388 % respectively, due to 50 wt.% reinforcement by natural jute yarns. Additional enhancements of about 14% and 10% in strength and modulus, respectively were achieved when treated yarns were used. Mantry et al. [133] investigated the tensile behaviour of both unfilled and SiC particles filled jute epoxy composites. It was found that the tensile strength of unfilled jute epoxy composite increased with increase in fiber loading. On the other hand the strength of particle filled jute composites decreased with the increase in the particle content. Yang et al. [97] studied the effect of fiber content and hot water immersion on tensile properties of injection moulded jute/polypropylene composites. Firstly, the tensile strength of composite increased with increase in fiber loading but latter it decreased after 30 wt.% of fiber. Aging has the significant effect on the tensile strength and modulus of composite as it decreased with higher fiber content. It was found that after 300 h of hot water immersion, the strength even showed low value than that of neat polypropylene.

Flexural strength is a combination of the compressive and tensile strengths, which is also another important mechanical property. In flexural testing, different mechanisms, like tension, compression and shearing takes place simultaneously [134]. As FRP composites has found increasing application in the aerospace, automobile, aviation and marine industries, they are susceptible to such loading conditions and catastrophic failure of the components may occur due to increase in the external load. Thus, it is necessary to understand the flexural behaviour of the composites. Several authors have studied the flexural behaviour of jute fiber based polymer composites. Ahmed et al. [106] reported an increase in flexural properties of jute-glass polyester composites with the increase in fiber content from 0 to 40 wt.% of the fiber . But, no further improvement in the flexural properties was observed with the increase in fiber weight to 60 %. The arrangement of glass fiber plies at extreme and jute fiber plies in middle of jute-glass polyester composite results in considerable improvement of flexural strength. Analysis of the effect of fiber surface wettability, alkali treatment and different ageing conditions on the flexural properties of longitudinally oriented jute roving reinforced polyester composites as a function of fiber content was done [84]. It was observed that the flexural property of longitudinal composites increases with fiber content. Gassan and Gutowski [135] studied the effect of corona discharge and UV treatment on the flexural properties of jute-fiber epoxy composites. An increase in the composites flexural strength of about 30% was achieved at the optimum treatment conditions. Gassan and Bledzki [136] studied the effectiveness of MAH-PP copolymers (graft copolymer of PP and maleic anhydride) as coupling agents in jute-polypropylene composites. It was found that the flexural strength of the composites increased with fiber loading, and has greater value for composites with MAH-PP treated fibers than that of unmodified fibers. Gowda et al. [15] investigated the flexural properties of jute fabric reinforced polyester composites. The average ultimate flexural strength and modulus of the composites were found to be 92.5 MPa and 5.1 GPa respectively, and the corresponding values for polyester resin was 48 MPa and 2.2 GPa. Hossain et al. [137] studied the flexural behaviour of surface modified jute fiber reinforced biopol nanophased green composites. Untreated jute, treated jute, treated jute with 2%, 3% and 4% nanoclay reinforced composites were fabricated. The treated jute fiber reinforced composites without nanoclay exhibit 9 % and 12 % increase in flexural modulus and flexural strength, respectively when compared to untreated jute fiber reinforced composites. According to Jawaid et al. [119], the layering sequence has a significant effect on the flexural properties of hybrid composites. Woven jute (Jw), chopped jute and oil palm EFB were used to reinforce on epoxy resin. Comparison of flexural properties of EFB/Jw/EFB, Jw/EFB/Jw, EFB/Jute/EFB and Jute/EFB/Jute hybrid composite was done. It was found that Jw/EFB/Jw hybrid composite exhibit superior flexural properties than other hybrid composites. Kafi et al. [138] observed the influence of manufacturing process on the flexural behaviour of woven jute polyester composites. Methyl ethyl ketone peroxide (MEKP) was used as curing agent. It was concluded that the fiber volume fraction and fiber/matrix interfacial strength has a greater influence in improving the flexural performance of composites rather than the degree of cure. Khan et al. [139] investigated the effect of fiber content on the bending properties of the jute-polycarbonate composites and reported that the bending modulus of the composites increases with the increase in fiber content up to 35 %. But it was also found that the modulus decreased unexpectedly at 42 %. It was suggested that this result may be due the presence of void content. An increase in the bending strength was observed up to 32 % jute content, after that it decreases. Liu et al. [120] observed an increase in flexural strength and modulus of surface modified jute poly (butylene succinate) biocomposites from 0 to 20 wt. % fiber, but a decrease in properties was observed at 30 wt. % of fiber content. The flexural modulus, as well as tensile modulus, is very sensitive to the matrix properties and fiber-matrix interfacial bonding, so surface modification has more effects on flexural or tensile modulus than on strength. Mohanty et al. [121] reported the increase in the flexural strength of the jute-polyester amide composites for fiber loading from 20 to 32 wt. % but with further increase in fiber loading, decrease in flexural strength was observed. In another study, Mohanty et al. [122] observed the enhancement of bending strength of jute-Biopol composites prepared from chemically treated jute fabrics. Rahman et al. [125] reported that the flexural strength of the raw and oxidized jute fiber reinforced polypropylene composite and urotropine post-treated composites increases with increase in fiber loading up to 30 wt. %, however a decrement in the strength was also observed from 30 wt. % to 35 wt. % fiber loaded composites. The post-treated composites yielded higher flexural strength and modulus compared to the raw and oxidized ones. Siloxane treatment has significant effect on the properties of jute epoxy and jute-polyester composites and these composites exhibit higher flexural properties compared to polymer composites containing alkalized jute fabric [126]. Tao et al. [128] reported an increase in flexural strength of short jute/PLA composites up to 30 % fiber content. The increased flexural strength of the composite compared with the neat PLA matrix may be due to the addition of fiber and an efficient stress transfer between PLA and natural fiber. Vilaseca et al. [129] found significant improvement in the flexural properties of jute reinforced starch polymer composites with alkali treatment as well as increase in fiber loading. Ishiaku et al. [130] evaluated the influence of weld line on the flexural properties of short-fiber reinforced jute/poly butylene succinate biodegradable composites. The study revealed that both bending strength and modulus increased with the incorporation of jute fibers. Khan and Hinrichsen [131] examined the effect of coupling agents (i.e. EHA and HEMA) on bending properties of jute reinforced polypropylene composites. It was found that the coupling agent has significant effect on bending properties. The coupling agent improved the bending properties of composites and has higher strength and modulus compared to untreated fiber composites and neat polypropylene resin. Khondker et al. [132] reported that the maximum bending stress and modulus of jute/PP composites comprising untreated yarns were nearly 190% and 460% higher than those of the virgin PP resin. And the bending properties were enriched by further 11% and 23%, respectively, due to coating treatments on the yarn surface. Mohanty et al. [140] observed an improvement of 79 % in bending strength of cross-wounded jute/Biopolcomposites when compared to composites resulting from once and twice winding of yarns. Ray et al. [141] studied the effect of fiber loading and alkali treatment time on flexural behaviour of jute/vinylester composites. It was found that the treatment time of 4 h was optimal to get maximum strength of the vinylester composites reinforced with jute fibers treated with 5 % alkali solution at 30°C. Satapathy et al. [133] reported an increasing trend of flexural strength with the increase in fiber loading of jute epoxy composites. However, a decreasing trend in case of particulate filled jute epoxy composites was found with the increase in filler content.

Impact strength signifies the ability of the material to absorb impact energy. In order to cope up with the problem of high fuel cost, automobile and aeronautical industries require light weight and fracture resistance composites with high impact strength. The composites also have applications in the area of sports, buildings and musical instruments where the impact strength of the material is of primary concern. Fibers play a key role in the impact resistance of the composites as they interact with the crack formation in the matrix and act as stress transferring medium [142]. Many researchers have reported about the impact properties of jute fiber reinforced composites. Albuquerque et al. [84] reported the effect of fiber surface wettability, alkali treatment and different ageing conditions on the impact strength of longitudinally oriented jute roving reinforced polyester composites. It was found that the impact strength increased linearly with the fiber loading. Gowda et al. [15] reported the average impact energy unit area of jute-polyester composites and polyester resin specimens were 29 Kj/m^2 and 1.76 Kj/m^2, respectively. An attempt has been made by Jawaid et al. [143] to investigate the impact characteristics of oil palm EFB and jute fiber reinforced hybrid composites. The results indicated that the impact strength of pure EFB composites is higher than the hybrid composites. The hybrid composite with EFB/Jute/EFB sequence has better impact strength than Jute/EFB/Jute hybrid composites. Mohanty et al. [122] studied the influence of chemical modification on the impact strength of jute-Biopol composites. It was observed that the reinforcement of Biopol with untreated jute also improves the strength of the resulting composite quite significantly. According to Mohanty et al. [123], the impact strength of untreated jute HDPE composite increased linearly with the increase in fiber loading from 0 to 30 wt.%. However, pronounced decrease in impact strength of the composites was reported, as the fiber loading was increased from 30 wt.% to 45wt.%. Improvement in the impact strength of the composite (30 wt. % fiber loading) was observed with the incorporation on MAPE treated fibers in relative to the untreated jute fiber reinforced composites. The composites prepared at 1% MAPE concentration showed significant enhancement in impact strength with an increase of 67%, with respect to the untreated composite at 30 wt.% fiber loading. Plackett et al. [124] studied the impact behaviour of PLA/jute composites and observed no statistical difference in mean impact resistance between the PLA processed at 190 °C and the PLA/jute composite processed at 200 °C. Rahman et al. [125] investigated the variation of the impact strength with fiber loading for both raw and oxidized jute composites and urotropine post-treated composites. It was found that the impact strength increased with increase in fiber loading. But, at higher fiber loading (i.e. from 30 wt.% to 35 wt.%) there was a decrease in impact strength of the composites. At higher fiber loading, the probability of fiber agglomeration increases which results in regions of stress concentration requiring less energy for crack propagation. Rana et al. [144] reported the increase in impact strength of short jute fiber reinforced polypropylene composites with the addition of impact modifiers. It was also found that the notched and un-notched Izod impact strength of composite increased with increase in fiber loading. The experimental investigation carried out by Tao et al. [128] on impact strength of short jute/ PLA composites indicated a slight improvement in properties upto 30 % fiber content in comparison to neat PLA matrix. Vilaseca et al. [129] observed a small enhancement in the impact strength of jute reinforced starch polymer composites after the alkali treatment of fibers. Lima et al. [145] evaluated the impact strength of recycled polyethylene (PE) composites reinforced with used or new jute fabric. The incorporation of both new and used jute fabric considerably increased the impact energy of composites, with greater values related with the new jute fabric. However, the composites with 30 % weight fraction of fiber exhibit highest impact strength in all the cases. Experimental investigation carried out by Mohanty et al. [140] reported that the impact strength of cross-wounded jute/ Biopol composites improved by 166% compared to composites obtained from once and twice winding of yarns. Shubhra et al. [146] found jute/polypropylene composites gained 186 % increase in impact strength over that of the polypropylene composites.

Inter-laminar shear strength (ILSS) may be defined as the resistance of a laminated composite to internal forces that tend to induce relative motion parallel to, and between, the laminas [147]. ILSS is a matrix dominated property [148]. The ILSS of composites mainly depends on the resin strength and composite void content [149]. Under service conditions, the performance of laminated composites largely depends upon its ILSS. ILSS is often used as a key measure in judging the soundness of fiber matrix interface [150]. The ILSS of jute-glass hybrid composites increased by 9.4 % and 21.1 % with the addition of glass fiber as extreme plies by 20 % and 40 % of the total fiber weight, respectively. However, further increase in glass fiber lead to decrease in ILSS. ILSS depends mainly on the matrix properties and fiber matrix interfacial strength rather than the fiber properties [106]. Gowda et al. [15] investigated the ILSS of the jute-polyester composites. The average ILSS of the composites was 10 MPa. Seki et al. [126] found that oligomeric siloxane treated alkalized jute epoxy composites exhibit better ILSS compared to jute epoxy, jute-polyester, alkalized jute epoxy, alkalized jute polyester and oligomeric siloxane treated alkalized jute polyester composites. An attempt has been made by the Sever et al. [151] to improve the mechanical properties of jute/HDPE composites by oxygen plasma treatment of jute fibers. Low frequency (LF) and radio frequency (RF) plasma system was used for the study. Experimental results showed that the ILSS values of composites increased with increasing plasma power in RF plasma system. Also, in LF plasma system, ILSS value exhibited a tendency to increase at 30 and 60 W plasma powers. But, further increase in plasma power to 90 W results in decreased ILSS value of jute/HDPE composites. Satapathy et al. [152] found an increase in ILSS of SiC particle filled jute epoxy composites with the increase in SiC filler content.

Hardness is defined as the resistance of material to permanent deformation such as indentation or scratch. Traditionally, hardness tests were used for metals to correlate their mechanical properties and wear resistance. However, hardness measurements are also used for polymer and composites in order to inspect the relationship between tribological performance and elastic/plastic properties of their near-surface area [153]. A great deal of work has been done by researchers on the hardness of jute fiber reinforced polymer composites. Gowda et al. [15] studied the hardness of jute-polyester composites and found that the Barcol hardness value of composites lie in the range of 15-25 against 27-30 for polyester resin. This variation in the hardness value was due to the difference in the hardness between matrix and filler material. It was concluded that the addition of jute in the resin reduces the hardness of the binding material. Rahman et al. [125] found that the average hardness of composite increased with the fiber loading, oxidation of jute fiber and urotropine post-treatment. It was due to the increase of stiffness and decrease of flexibility of the corresponding composites. The post-treated jute fiber composites exhibit much higher hardness on comparing with the raw and oxidized ones. It was due to both stronger interfacial bonding between the fiber and matrix and dispersion of fiber into the matrix with minimization of voids. Shubhra et al. [146] studied the hardness of jute fiber reinforced polypropylene composites and observed that the incorporation of jute fibers inside polypropylene did not reduce the hardness of composite but had almost similar properties. Satapathy et al. [152] measured the hardness of unfilled and SiC particle filled jute epoxy composites. It was found that the hardness increased with the increase in fiber loading. Similarly, the incorporation of particles in the jute fiber composites results in improved hardness.

Thermal Properties

Materials working outside room temperatures are exposed to thermal loads that may arise from various sources and the temperature change not only affects the mechanical behaviour but also changes all material properties. Thus, material selection decision for components that are exposed to sub-ambient/elevated temperatures, temperature gradients and/or temperature changes requires the better understanding of the thermal response of materials [154]. Doan et al. [155] analyzed the thermal stability of jute fiber, polypropylene (PP) and jute/PP composites by thermal gravimetry (TG) and derivative thermal gravimetry (DTG). The composites were found more thermal stable than that of either the fiber or the neat PP in both air and nitrogen due to the fiber-matrix interaction. It was found that the modification of matrix by 2 wt.% MAHgPP improvers the thermal resistance of the jute/PP composites. This improvement might be due to the stronger interaction between the fiber and matrix caused by the formation of the covalent bond at the interface. The overall thermal resistance of composites was also found to increase with fiber content due to the lower thermal stability of PP compared to jute fiber in air. Khan et al. [139] carried out dynamic mechanical analysis of polycarbonate (PC), untreated polycarbonate jute (PCJ) composites and polycarbonate jute HEMA (PCJH) treated composites. It was found that the initial storage modulus of PCJH at 30°C improved enormously by 101 and 77% when compared with PC and PCJ, respectively. The tan δ values of PCJ and PCJH composites were 3.7 and 6 times lower than those of PC, respectively. Kumar et al. [156] done the thermal gravimetric analysis of three types of composites prepared from ethylene–propylene (EP) copolymer with (i) 3% NaOH treated jute fiber (J1C), (ii) 17.5% NaOH treated jute fiber (J2C) and (iii) commercial microcrystalline cellulose (MC) powder. The derivative thermogram of the samples showed the thermal stability of the fiber reinforced composites was higher than the neat polymer due to the heat deflection property of the fibers. However, the jute fiber reinforced composites (i.e. J1C and J2C) were found to be more thermal stable than commercial cellulose composites and this may be attributed to the existence of aromatic ring based lignin.

Mohanty et al. [123] investigated the dynamic mechanical behaviour of MAPE treated jute reinforced HDPE composites. The dynamic mechanical analysis data indicated an increase in storage modulus of the treated composites, approximately 191.2% increase in flexural modulus and 21% in storage modulus was observed with 1% MAPE treated composites. DTG and TGA thermograms showed an increase in the thermal stability of HDPE matrix with fiber reinforcement and MAPE treatment. Ray et al. [157] considered loss modulus peak of the vinylester resin as the Tg of the system, which was observed at 101.2 °C. The addition of jute fiber in the matrix limited the mobility of the polymer molecules at the interface and increased the Tg of the composites by approximately 28°C. The loss modulus at Tg increased significantly in the jute/vinylester composites (823-928 MPa) compared to the vinylester resin (298.7 MPa). A decrease in Tg of 8 h treated fiber composites (125.1 °C) was observed when compared to untreated composites (128.3°C). The tan values were found less in the composites compared to the resin as composites has less matrix by volume to dissipate the vibrational energy. Tao et al. [128] studied the thermal behaviour of jute fiber/PLA composites. The DMA results indicated that the storage moduli of the PLA/jute composites increase with respect to the plain matrix. Sinha and Rout [158] reported that the alkali treatment of jute fiber results in increased thermal stability of the jute/unsaturated polyester (UPE) composites. Fardausy et al. [159] reported that the TG, DTG and DTA curves of jute/PVC composites are the average of fiber and of PVC. The degradation of jute/PVC composites happened in two stages. The thermal stability of PVC-jute fiber composites was observed higher than that of jute fiber but lower than that of PVC film. Sreepathi et al. [160] measured the thermal conductivity of the jute fiber reinforced polyester composites. They concluded that thermal conductivity of unidirectional jute composites in fiber direction (longitudinal) is marginally higher than thermal conductivity of woven jute fabric composites in normal to the fabric (transverse) direction. Acha et al. [83] tried to improve the compatibility of the polar fibers (jute) and non-polar matrix (polypropylene) with two alternatives by chemical modification of fibers and also by the addition of compatibilizers. Dynamic mechanical tests confirmed that the interphase between the matrix and fiber was modified by the addition of coupling agents, and also by using chemically treated fibers. This study also revealed that the polymer reinforcement effect obtained using woven fabrics is much better than the one that can be attained using short fibers. Mir et al. [161] carried out thermo-mechanical tests on woven jute mat reinforced epoxy composites in the two principle directions i.e. warp and weft. The test results indicated that the thermal coefficient of expansion in warp direction is 48% larger compared to the weft direction.

Wear Properties

Tribology focuses on wear, friction and lubrication of interacting surfaces in relative motion. It is a field of science which applies an operational analysis of problem of great economic importance such as wear, maintenance and reliability of technical equipment ranging from household application to aircraft [162]. Polymer and its composites are finding increasing usage for various industrial applications in sliding/rolling components where their self-lubricating properties are exploited to avoid the need for grease or oil lubrication with its attendant problems of contamination [163]. Wear is directly related to reliability or life of the system, and hence, it should be controlled in order to achieve the desired life and performance of the system [164]. The definition of wear has been proposed as ‘progressive loss of substance from the operating surface of a body as a result of relative motion at the surface’ [27]. Wear of polymers as an undesirable phenomenon depends on many factors that includes sliding speed, applied load, sliding distance, temperature, mechanical, chemical and thermal properties, has been categorized into mild and sever wear [165]. A lot of research has been made on the wear behaviour of jute fiber reinforced polymer composites. Dwivedi and Chand [166] studied the impact of fiber orientation on the friction and sliding wear performance of jute fiber reinforced polyester composites. Different fiber orientation in the composite namely LL, LT and TT with respect to sliding direction were taken for wear study. The maximum wear resistance was observed in case of TT sample and minimum in case of LL sample. The coefficient of friction was highest for TT sample and lowest for LT sample. Micro-cracking, micro-pitting and debonding were responsible wear mechanisms under sliding wear mode in jute-polyester composites. Chand and Dwivedi [167] investigated two body abrasive wear behaviour of chopped jute-polypropylene composites to understand the effect of coupling agent i.e. maleic anhydride-grafted-polypropylene (MA-g-PP) on composites during abrasion. It was found that coupling agent results in improved wear resistance compared to untreated composites (UT). The MA-g-PP melt-mixed jute fiber reinforced PP composites offered better wear resistance than the MA-g-PP solution-treated jute fiber reinforced PP composites. From the study it was also observed that wear volume increased with increase in sliding distance for all the composites. Experimental investigation also revealed that wear rate increased with increase of normal load.

Mantry et al. [133] studied the erosion response of the jute epoxy composites reinforced with SiC particles as a function of impingement angle. It was observed that for all the unfilled jute epoxy composites the peaks of erosion rates were located at an impingement angle of 60° and also the erosion rate was found increased with the increase in fiber content. However, in case of SiC filled composites peak erosion occurs at 75°. It was also revealed that the erosion wear resistance of composites improved due to the presence of SiC particles and this enhancement depends on the content of the filler. Ahmed et al. [168] investigated the wear behaviour of jute/epoxy composites filled with ceramic filler like SiC and Al_2O_3. Dry sliding wear tests were carried out for different velocities (3 m/s, 4.5 m/s and 6 m/s) by applying normal loads of 30 N, 40 N and 50 N, using pin-on-disk apparatus. It was found that the addition of filler on composites enhances its wear resistance. The Al_2O_3 filled composites exhibited better wear resistance than SiC filled composites. Wear loss and friction coefficient of all the prepared composites increased with the increase in normal load at all sliding velocities and vice-versa. Goriparthi et al. [169] carried out research work to improve the adhesion of jute fiber with PLA. For this purpose surface modification of jute fiber was done by alkali, permanganate, peroxide and silane treatments. It was found that the weight loss increased with increase in sliding distance which was due to progressive material removal with distance. The surface modification of fibers results in significant effect on composite properties, and it was found that composite with surface modified fibers exhibit better wear resistance than the untreated one. Out of the different modification process silane treated fiber composites shows highest wear resistance due to strong interfacial adhesion. Patel et al. [170] reported that layering sequence has significant effect on the erosive strength of the composites. They found that a composite with two glass layers between jute layers at extreme ends gives the lowest erosive wear value. El-Sayed et al. [171] studied the wear behaviour of linen fiber-polyester composite (LF-PC) and jute fiber-polyester composite (JF-PC). A considerable improvement in the friction coefficient with increase in volume fraction (up to 15 %) was observed when composites with linen or jute fibers were used as reinforcement in the longitudinal and transverse direction. Moreover, friction coefficient was found to be increased for fiber orientation in normal direction in case of linen as well jute fiber composites. The longitudinal and transverse orientation of fibers in JF-PC and LF-PC system exhibit lower wear rate than matrix material and normal orientation fibers offer its lowest wear rate at 15 % volume fraction.

2.3 On Abrasive Wear Behaviour of Composites

Wear may occur in various forms i.e. adhesion, abrasion, erosion, fretting, fatigue, corrosion and oxidation. It was assessed that the total wear of machine element can be recognized as 80-90 % in the form of abrasion and 8 % as in the form of fatigue wear [172]. The abrasive wear of materials takes place when a hard rough surface slides over the other surface [173]. As per the ASTM International, abrasive wear is defined as the loss of material due to hard particles that are forced against and move along a solid surface [174]. Generally, two-body abrasion and three-body abrasion are the two modes of abrasive wear. A great deal of work has been done on the abrasive wear behaviour of polymer composites. Khan et al. [175] performed the abrasive wear study of chemically treated coir fiber filled epoxy composites. The estimation of wear characteristics was done by considering two parameters i.e. sliding velocity and normal load using a pin-on-disc wear testing equipment. They reported a decrease in abrasion rate of the composites compared to the pure matrix material. Mishra and Acharya [176] studied the abrasive properties of the bagasse fiber composites in three different orientations namely, normal orientation (NO), parallel orientation (PO) and anti-parallel orientation (APO) using a two-body abrasion wear tester. It was reported that the composites tested in normal orientation exhibits the least or minimum wear rate than anti-parallel and parallel orientation composites. Raju et al. [177] studied the two-body abrasive wear behaviour of alumina filled glass reinforced epoxy composites. They reported that the alumina filled glass epoxy composites had offered an excellent wear resistance. Raju et al. [178] examined the abrasion behaviour of SiO_2 filled glass fabric reinforced epoxy composites and found a very low volume loss in case of composites with 10 wt.% filler. The experimental results showed that the wear volume loss decreases with increase in filler loading and increases with increase in abrading distance. Mohan et al. [179] found less abrasive wear of matrix in the SiC filled glass fabric composites. They reported that the SiC filler facilitates lower damage to the fiber and acts as a barrier during wear to prevent large scale fragmentation. Hashmi et al. [180] determined the abrasive wear behaviour of liquid crystalline polymer (LCP) fibers and glass fibers reinforced hybrid composites using a two-body abrasion tester under different applied loads. They concluded that the incorporation of LCP fiber results in improved wear performance of glass fiber reinforced linear-low-density-polyethylene (LLDPE) composites. El-Tayeb [181] investigated the abrasive wear properties of polyester composites reinforced with chopped strand mat of glass fiber (CSM-GRP), chopped untreated sugarcane fiber (C-SCRP) and unidirectional sugarcane fiber (UM-SCRP) in two different orientations. Sudheer et al. [182] performed the two-body abrasive wear test to understand the effect of the addition of MoS_2 (10 wt.%) particles on the wear behaviour of epoxy with/without glass fiber mat reinforcement. They noticed a significant reduction in specific wear rate and wear loss after the incorporation of MoS_2 filler that allowed less wear of matrix during abrasion which in turn facilitated lower fiber damage. Chairman et al. [183] evaluated the two-body abrasive wear performance of the Titanium Carbide (TiC) filled glass fabric-epoxy composites. They reported highest wear resistance of glass epoxy composite that contained 2wt. % TiC in particulate form. Harsha and Tiwari [184] studied the abrasive wear performance of the polyaryletherketone composites under different load and sliding distance conditions using a pin-on-disc machine. Chand and Dwivedi [167] analyzed the two-body abrasive wear behaviour of chopped jute polypropylene composites to understand the effect of coupling agent (MA-g-PP) on composites during abrasion. Dwivedi et al. [185] studied the abrasive wear behaviour of polyester composites filled with bamboo powder. It was found that the weight loss of the polyester composite decreases with the increase in sliding distance. Suresha and Kumar [186] investigated the abrasive wear properties of glass/carbon fabric reinforced vinyl ester composites. The specific wear rate of the composites was decreased with abrading distance. The specific wear rate also decreased with decrease in abrasive particle size. The vinyl ester composites reinforced with glass fabric exhibited higher specific wear rate compared to carbon fabric reinforcement. Suresha and Kumar [187] studied the two-body wear behaviour of clay and clay along with short carbon fiber filled polyamide66/polypropylene (PA66/PP) nanocomposites. The reinforcement of clay in the PA66/PP blend was found to be detrimental to the abrasive wear resistance. The clay plus short carbon fiber filled PA66/PP blend exhibited better abrasive wear performance than the clay filled PA66/PP nanocomposites. Chand and Fahim [188] determined the effect of irradiation on the abrasive wear behaviour of glass-vinylester composites. The vinylester matrix based composites exhibited improved wear resistant properties when exposed to laser beams and gamma-irradiation. Rao et al. [189] performed the abrasive wear analysis on coir fiber reinforced epoxy composites. The study revealed that the treated fiber composites exhibited better wear resistance than the untreated ones. It was also found that the abrasive wear rate decreased with increased amount of fiber in the composites. Deo and Acharya [190] studied the effect of fiber content on the abrasive wear performance of Lantana Camara fiber reinforced composites subjected to sliding velocity of 0.314 m/s and normal load of 5, 10, 15, 20 and 25 N. The optimum wear reduction was obtained in case of composites with 40 wt.% fiber content. Chairman and Babu [191] studied the multipass two-body abrasive wear behaviour of glass and basalt fabric reinforced composites. The basalt fabric reinforced composites exhibited lower specific wear rate values at different normal load conditions in comparison to glass fabric reinforced composites. Majhi et al. [192] compared the abrasive wear behaviour of untreated and treated rice husk reinforced composites. They concluded that the modified rice husk composites exhibited better abrasive properties than the untreated composites. Mohanty et al. [193] reported that the addition of date palm leaf fibers on the matrix material results in significant improvement of abrasive wear resistance of composites up to an optimum fiber content and then decreases on further increase in fiber content.

Though the three-body abrasive wear is slower than the two-body abrasive wear, but it has considerable practical importance as most of the abrasive wear problem in industrial and agricultural equipment is connected with the three-body abrasion. Therefore, researchers are trying to understand the three-body abrasive wear phenomenon of the materials. Chand et al. [194] studied the abrasive wear behaviour of short E-glass fiber reinforced polyester composites with and without filler. According to the investigation, high weight fraction of glass fibers in composites improves the abrasive wear resistance. Patnaik et al. [195] studied the effect of different filler type (Al_2O_3, SiC and pine bark dust) on the wear behaviour of glass-epoxy composites. The experimental results concluded that the wear of composite is significantly influenced by the filler types. Mohan et al. [196] investigated the effect of synthetic (graphite, silicon carbide) and natural fillers (filler jatropha oil cake) on abrasive wear behaviour of glass epoxy hybrid composites. Harsha et al. [197] studied the effect of reinforcement fibers, solid lubricants, mass of abrasives and load in three-body abrasive wear situations on various polyaryletherketone (PAEK) matrixes. The effect of abrading distance and applied load on abrasive wear behaviour of short glass fiber reinforced polyurethane composite was investigated by Suresha et al. [35]. It was concluded from the study that the wear volume tends to increase linearly with increasing abrading distance and strongly depends on the applied load. Investigation by Agarwal et al. [198] on the wear behaviour of bidirectional and short kevlar epoxy composites revealed that the wear rate increases with increase in normal load whereas, with the increase in sliding velocity the specific wear rate decreases for both the cases. Stachowiak and Stachowiak [199] reported that the wear caused by abrasive grits depends on their shape, size, toughness, hardness, contact pressures they exert on the counter-surface, sliding velocity, etc. Suresha et al. [200] studied the abrasive wear behaviour of woven E-glass fabric reinforced/graphite-filled epoxy composites and found that with the increase in abrading distance as well as load, the wear volume loss of neat epoxy, glass-epoxy, and graphite filled glass-epoxy composites increases. Yousif and El-Tayeb [201] investigated the abrasive wear behaviour of chopped strand mat glass fibers reinforced polyester (CGRP) composites under high stress in three principal orientations of the fibers, i.e. N-O, P-O, and AP-O. Experimental investigation revealed that CGRP composites having P-O of fibers exhibited better wear characteristics. Harsha and Nagesh [202] used artificial neural network to predict the weight loss of different polyaryletherketones and its composites in three-body abrasive wear condition. Yousif et al. [203] examined the three-body abrasive wear response of the betelnut fibers reinforced epoxy composites. Suresha et al. [204] studied the three-body abrasive wear behaviour of organo-modified montmorillonite-filled epoxy nanocomposites with different filler loading. It was reported that 5 wt.% organo-modified montmorillonite-filled epoxy nanocomposite showed enhanced abrasive wear resistance as compared to that of the other organo-modified montmorillonite-filled epoxy nanocomposites and neat epoxy. Kumaresan et al. [205] reported that the wear volume loss of SiC filled bidirectional carbon fiber reinforced epoxy composites increases with the increase in abrading distance. The specific wear rate of the SiC filled hybrid composites decreased with increasing abrading distance/ load and it also depends on the filler loading. Some authors also used woven carbon fabric with graphite [100] and fly ash cenospheres [206] to understand the three-body abrasive wear behaviour of the composites. Ranganatha et al. [207] investigated the three-body abrasive wear behaviour of Al_2O_3 filled polymer composites in which carbon fiber strands were added for reinforcement. Siddhartha and Gupta [208] studied the abrasive wear properties of the bidirectional and chopped E-glass fiber reinforced composites. It was concluded that the chopped glass fiber reinforced composites were performed better than bidirectional glass fiber reinforced composites under abrasive wear conditions. Attempts had been made by the authors to enhance the three-body abrasive wear resistance of the woven E glass fiber reinforced composites using fillers like SiC [209], graphite [210], and alumina [210]. Syed et al. [211] examined the three-body abrasive wear behaviour of coleus spent filled unsaturated polyester/polymethyl methacrylate semi interpenetrating polymer network composites. It was concluded that in the early stage specific wear rate value was very large and as the abrading distance increased, it decreased gradually and reached a steady state.

2.4 On Taguchi Method

The need of optimization is to obtain the best result. By altering the input parameters, the optimization process seeks for improved output so that the performance of a system can be enhanced. In general, optimization techniques can be categorized into global and local techniques. Simulated Annealing (SA), Genetic Alogorithm (GA), Particle Swarm Optimization (PSO) and Taguchi's method are considered as global optimization methods whereas gradient-based technique as local optimization method [212]. In the field of composites, various optimization techniques are widely used for enhancing the performance of materials properties. A great deal of work has been done in the optimization of composite manufacturing by various researchers [213-220]. Wang et al. [213] applied Kriging models in multi-objective optimization of composite manufacturing processes. A data envelopment analysis was also carried out, based on the data obtained from the Kriging model to optimize the resin transfer molding (RTM) process. Baran et al. [214] performed the optimization of the thermosetting pultrusion process in preparation of composite rod using hybrid and mixed integergenetic algorithms. Tumtum et al. [215] used multiple objectives for the optimization of the pultrusion process based on a thermo-chemical simulation. The thermo-chemical simulation of the pultrution process was integrated with evolution multi-objective optimization algorithm to concurrently minimize the pulling speed total energy consumption. Gupta et al. [216] used bi-level multi-objective evolutionary algorithms for optimizing composites manufacturing processes. Govindaraju et al. [217] worked on the optimization of process parameters for the preparation of wool based polypropylene composites with respect to mechanical properties. Compression moulding based fabrication technique was considered for this study. Yan et al. [218] carried out the optimization of fabrication process of hemp/polypropylene composites. It was stated that the optimization of the fabrication process, specifically the compounding process is an effective method to attain the optimal properties of the composites. Lam et al. [219] worked on the development, implementation, and validation of a numerical procedure for arriving at an optimum amalgamation of die-heater temperatures and pull-speed for making a uniformly cured composite pultrudate. Gupta et al. [220] utilized a surrogate model based evolutionary game-theoretic methodology for optimizing non-isothermal compression resin transfer moulding processes.

Similarly, many researchers [221-224] also applied optimization techniques in the machining processes. Arunkumar and Prabaharan [221] worked on the optimization of cutting parameters in machining of polyphenylene sulphide composites. Jenarthanan and Jeyapaul [222] carried out the optimization of machining parameters on milling of glass fiber reinforced polymer composites by desirability function analysis. Palanikumar et al. [223] discussed the application of the optimization method to optimize the machining parameters involved in turning operation of glass fiber reinforced polymer composites. Babu et al. [224] used the optimization technique to find out the preferred optimum cutting parameters for minimized appearance of delamination and also for maximum residual tensile strength in drilled unidirectional hemp fiber reinforced composites. Investigators [225-228] also studied the optimization of process parameters for enhancing the performance of composite materials. Hussain et al. [225] applied genetic algorithm to optimize the process parameters of surface roughness in turning of glass fiber reinforced composites. Maheswaran and Renald [226] investigated the wear behaviour of Al6061-Al_2O_3-graphite hybrid composites by means of artificial neural network. Sathiyamurthy et al. [227] predicted and optimized the mechanical properties of particles filled coir polyester composites using RSM and ANN algorithms. Xu and You [228] worked on minimizing the thermal residual stresses in ceramic matrix composites using iterative mapreduce guided particle swarm optimization algorithm.

Among various optimization techniques, DOE based on Taguchi methodology is suitable for optimizing various process variables. DOE techniques enables designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. A full factorial design will identify all possible combinations for a given set of factors. Since most industrial experiments usually involve a significant number of factors, a full factorial design results in a large number of experiments. To reduce the number of experiments to a practical level, only a small set from all the possibilities is selected. The method of selecting a limited number of experiments which produces the most information is known as a partial fraction experiment. Although this method is well known, there are no general guidelines for its application or the analysis of the results obtained by performing the experiments. Taguchi has envisaged a new method of conducting the design of experiments which are based on well-defined guidelines. This method uses a special set of arrays called orthogonal arrays. These standard arrays stipulate the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter.

Taguchi experimental design is used in various fields like agriculture sciences, environment sciences, engineering, management and business, chemistry, physics, statistics and medicine [229]. Some researchers used Taguchi experimental design method for the optimization of process parameters involved in mechanical behaviour, fabrication and machining processes [230-236]. Authors applied experimental design to investigate the effects of concentrations and types of chemical foaming agent, wood flour content and HDPE melt flow index on density, mechanical properties and morphological structure of HDPE/wood flour composite foams [230]. Fei et al. [231] done a review on the practical applications of Taguchi method for optimization of processing parameters for plastic injection moulding process. Esmizadeh et al. [232] used Taguchi method for reducing cost and improving properties of PVC/acrylonitrile butadiene rubber (NBR)/organoclay nanocomposites. Sailesh and Shanjeevi [233] predicted the optimal process parameter setting for maximum hardness value of the bamboo/banana/glass fiber reinforced hybrid composites using Taguchi method. Vankantia and Gantab [234] worked on the optimization of process parameters such as feed, cutting speed, chisel edge width and point angle in drilling operation of glass fiber reinforced polymer composites. They reported Taguchi method is very useful in choosing optimum values of various parameters that would not only minimize the torque and thrust force but also decrease the delimitation and enhance the quality of the drilled hole. Uysal et al. [235] utilized the Taguchi method and Analysis of Variance (ANOVA) to obtain the optimal cutting parameter and to examine the effects of parameters on the wear of tool. Mehat and Kamaruddin [236] used Taguchi methodology to analyze the effect of injection molding parameters on the mechanical behaviour of recycled plastic parts.

Several researchers performed Taguchi analysis to obtain the optimal parameter setting for the erosive response of the polymeric materials [237-240]. Rout et al. [237] adopted Taguchi methodology to examine the erosive wear response of the graphite filled glass polyester hybrid composites. Patnaik et al. [238] performed the Taguchi analysis for the parametric optimization of erosive wear behaviour of alumina filled glass/polyester hybrid composites. It was found that the control factors like alumina percentage, impingement angle, erodent size and impact velocity in the order of priority had major considerable effect to minimize the erosion rate. Patnaik et al. [239] used Taguchi experimental design to investigate the erosive wear behaviour of the glass polyester composites filled with SiC particles at different operating conditions. The velocity of impact, SiC percentage, stand-off distance, impingement angle and erodent size were taken as the control factor for the study. Kaundal et al. [240] used the Taguchi experimental design to study the erosion behaviour of SiC particle filled short glass polyester. Researchers also utilized the design of experiment method to determine the effective parameters in sliding wear of the polymer composites. Rout and Sathapathy [241] conducted the dry sliding wear experiments as per the Taguchi experimental design. It was reported that the factors like sliding velocity, filler content and normal load had significant effect on the specific wear rate. Padhi and Sathapathy [242] analyzed the sliding wear behaviour of blast furnace slag filled composites using Taguchi approach and obtained the optimal parameter settings for the minimum wear rate. It was found that the sliding velocity had larger effect on the wear rate. Basavarajappa et al. [243] successfully analyzed the sliding wear behaviour of the composites using Taguchi method with load, filler content, sliding speed and sliding distance as the control factors. Anjum et al. [244] carried out Taguchi experimental analysis and reported that sliding distance is the major factor followed by the applied load, sliding velocity and SiO_2 content in the wear loss of glass epoxy composites filled with SiO_2. Mahapatra and Chaturvedi [245] studied the abrasive wear behaviour of short bagasse fiber reinforced composites by Taguchi methodology and reported that the fiber length play a major role in the wear phenomenon of the composites. Rao et al. [246] selected filler content, normal load and sliding distance as the control factors for the study of abrasive wear behaviour of the graphite filled carbon fiber reinforced composites using Taguchi experimental design. They found that the normal load has the significant influence on the abrasive wear performance of the composites. Raju et al. [247] utilized the Taguchi experimental design approach to analyze wear behaviour of silicon carbide filled glass-fabric reinforced epoxy composites. Agrawal et al. [198] investigated the three-body abrasive wear behaviour of Kevlar fiber reinforced epoxy composites using Taguchi design. Abrasive size, sliding velocity, sliding distance, normal load and fiber loading were selected as the control factors for the study.

2.5 On MCDM Approach

Basically, MCDM is a branch of operations research that deals with decision problems containing finite number of alternatives and decision criteria [44]. MCDM can be defined as the collection of procedures for the comparison, ranking and selecting several alternatives having various attributes [248]. There are numerous techniques such as WPM, AHP, revised AHP, WSM, ELECTRE, TOPSIS and some hybrid techniques like integrated AHP-TOPSIS method; that can be used to solve the MCDM problems. Several MCDM methods have been applied to a number of applications by many researchers. Alanazi et al. [249] used WSM for a mathematical model and proposed that the mathematical model can be utilized by the education and training providers, financers, doctors, and politicians. Santosa et al. [250] implemented the WSM to develop recommender system for tourism destination. They reported that WSM method is a good technique to find which criteria gives the most effective factor in finding the tourism destination. Qiu [251] employed WSM method to help farmers in selecting the best farming system from a finite set of alternative farming systems. Olejnik [252] presented a problem of computer network design for a small enterprise and reported a greater advantage of WSM and WPM method as they allow generating one synthetic global quality index that take into account many quality indices specified by the designer, along with weights associated with them. Baral [253] applied WPM method in decision making processes related to agriculture farm. They implemented the fuzzy model on agricultural farm for optimal allocation of various crops by considering maximization of net benefit, production and utilization of labour. Ermatita et al. [254] reported that the modelling with ELECTRE method can help in decision making to identify gene mutations that can cause cancer. Rouyendegh and Erkan

[255] applied fuzzy ELECTRE method for academic staff selection process. Hatami-Marbini et al. [256] used the fuzzy group ELECTRE method for safety and health assessment in hazardous waste recycling facilities. Mazumder [257] implemented the ELECTRE method for decision making in manufacturing environment. They used this method for selection of material, robot, flexible manufacturing system, rapid prototyping process, material handling equipment and automated inspection device.

Smith et al. [258] utilized the AHP method in selection of the bridge material for several states. Sapuan et al. [259] applied AHP method to determine the most suitable natural fiber composites for automotive dashboard panel and found that the kenaf polypropylene composites with 60% is most suitable for this application. Hambali et al. [260] selected six polymeric composites material for the automotive bumper beam and ranked them on the basis of different criteria using AHP method. It was reported that the glass epoxy composite is the most suitable material for automotive bumper beam. Rohith et al. [261] ranked different material for the solar flat plate collector using AHP and found high density polyethylene as the best alternative. Mansor et al. [262] tried to find the best alternative thermoplastic material for the hybrid natural/glass fiber composites. Low density polyethylene matrix was reported as the best material for the hybrid composite preparation. Kaoser et al. [263] used VIKOR along with AHP method for the selection of material for electroplating process. The AHP method was used to determine the weight criteria. Kumar et al. [264] applied TOPSIS to the decision making unit that comprised of chemical and morphological characteristics of three Eucalyptus and Leucaena varieties to evaluate and rank these raw materials according to the preference for pulping and papermaking. Maity and Chakraborty [265] reported synthetic polycrystal diamond as the best alternative material for the preparation of grinding wheel using fuzzy TOPSIS method. Singh and Kumar [266] used TOPSIS methodology for ranking the material to prepare the bicycle chain in Indian scenario and found AISI 1038 as the best material. Khorshidi and Hassani [267] had done a comparative study between the preference selection index (PSI) and TOPSIS methods for material selection to attain a desirable combination of workability and strength in Al/SiC composite. Both these methods ranked Al-5% SiC composite as the best alternative. Dehury [268] applied TOPSIS method to rank jute/glass hybrid composites by considering physical, mechanical and water absorption behaviour as ranking criteria. Lin et al. [269] used AHP-TOPSIS integrated approach in customer driven product design process. The AHP method was used to evaluate the relative overall importance of the customer needs and design characteristics. The competitive benchmarking was performed by utilizing the TOPSIS methodology. Önder and Dag [270] proposed a supplier selection analysis model considering both AHP and TOPSIS method. In that study, AHP and TOPSIS method were combined for supplier selection in a cable company. Eight criteria namely quality, availability, origin, cost, cost of conveyance, delivery requirements, quality certificates and reliability of supplier were detected for procurement of the electrolytic copper cathode. Özgürler et al. [271] utilized the combined AHP-TOPSIS method to solve the robot section problem for a flexible manufacturing system. Tavana and Hatami-Marbini [272] used a group AHP-TOPSIS framework for human spaceflight mission planning at NASA. Abd et al. [273] applied AHP-TOPSIS approach to solve the scheduling rule selection problem in robotic flexible assembly cell. Rao and Davim [274] presented a logical procedure for the material selection for given engineering design problem using combined AHP-TOPSIS method. Chakladar and Chakraborty [275] had simultaneously employed TOPSIS and AHP methods to select the most suitable non-traditional machining process for a given machining application. Mansor et al. [276] applied AHP-TOPSIS approach to rank the hybrid natural fiber composites materials used for automotive parking brake lever component.

2.6 The Knowledge Gap in Earlier Investigations

The extensive literature survey presented above reveals the following knowledge gap in the research reported so far:

1. The jute fiber based products has many low end applications such as in housing, packing, furniture and transportation, but its potential use in tribological application where synthetic fibers are widely used is less.
2. Although, a great deal of work has been done on the different modes of wear of jute epoxy composites, however study on abrasive wear behaviour specifically on three-body abrasive wear behaviour of jute epoxy composites is rare.
3. Although a number of research efforts have been devoted to the short and woven jute fiber based polymer composites, however the study on needle-punched nonwoven jute fiber composites is hardly been reported in the literature.
4. Studies carried out worldwide on abrasive wear behaviour of jute epoxy composites have largely been experimental and the use of statistical techniques in analyzing wear characteristics specifically three-body abrasive wear behaviour of jute epoxy composites is rare. Taguchi method, being a simple, efficient and systematic approach to optimize designs for performance, quality and cost, is used in many engineering applications. However, its implementation in parametric appraisal of three-body abrasive wear process of jute epoxy composites is hardly been reported.
5. AHP-TOPSIS method is an efficient tool for solving many MCDM problems. However, it is hardly been used for selection of composite materials for abrasive wear applications.

2.7 Objectives of the Present Work

The knowledge gap in the existing literature summarized above has helped to set the objectives of this research work which are outlined as follows:

1. Fabrication of a series of epoxy based composites reinforced with needle-punched nonwoven, bidirectional and short jute fiber.

2. To study the physical and mechanical properties of composites such as density, hardness, tensile strength, tensile modulus, flexural strength, flexural modulus, impact strength and inter-laminar shear strength.
3. To study the three-body abrasive wear behaviour of the composites.
4. To study the effect of fiber loading on the mechanical and wear behaviour of the composites.
5. Optimization and prediction of the effect of control factors on the abrasive wear behaviour of composites using Taguchi experimental design and Analysis of variance (ANOVA).
6. To study the surface morphology of the abraded composites using SEM.
7. Ranking of composites using AHP-TOPSIS method on the basis of mechanical properties and abrasive wear attributes.

Chapter Summary

This chapter has provided

- An in-depth review of the previous investigations on various aspects of polymer composites reported by the researchers.
- The knowledge gap in past research.
- The objective of the present work.

The next chapter refers to the materials and methods used for the fabrication of the composites, the experimental planning, Taguchi method and AHP-TOPSIS methodology.

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CHAPTER 3

MATERIALS AND METHODS

This chapter presents the materials and methods used for the fabrication of composites under study. It presents the details of the physical, mechanical and three- body abrasive wear tests of the composite materials. The methodology based on Taguchi experimental design and AHP-TOPSIS technique of MCDM problems is presented in this part of the thesis.

3.1 Materials

3.1.1 Matrix Material

In composite materials, the constituent which is continuous and present in greater quantity is called matrix. The main functions of the matrix are to hold or bind the fiber together, distribute the load evenly between the fibers and protect the fiber from the mechanical and environmental damage. The matrix material can be metallic, polymeric or can even be ceramic. The most commonly used matrix material is polymer. It has advantages like low cost, good chemical and corrosion resistance, low specific gravity, high specific properties, easy processability, manufacturing flexibility and chemical stability [277, 278]. There are two major classes of polymers used as matrix materials such as thermoplastic and thermoset. Thermoplastic are in general, ductile and tougher than thermoset materials. They are reversible and can be reshaped by application of heat and pressure. Thermoplastic molecules do not cross-link and therefore they are flexible and reformable. The most common materials used in thermoplastic composites are nylons, acrylic, polyethylene, polystyrene etc. Thermoset are materials that undergo a curing process through part fabrication and once cured cannot be re-melted or reformed. Thermoset matrix possesses distinct advantages over the thermoplastics such as higher operating temperature, creep resistance and good affinity to heterogeneous materials [279]. Compared to thermoplastic composites, the initial low viscosity of thermoset polymers enables the higher concentration of both fillers and fibers to be incorporated in it while still holding good dispersion of filler and fiber wet-out [280]. The most common resin materials used in thermoset composites are epoxy, phenolics, vinyl ester, polyester and polyimides. Epoxy resins are unique among all the thermoset resins due to several factors. The distinct properties of epoxy such as high corrosion and chemical resistance, outstanding adhesion to various substrate, good thermal and mechanical properties, good electrical insulating properties, low shrinkage upon cure, and the ability to processed under a variety of conditions make it suitable matrix material for the fiber reinforced composite materials [281]. Epoxy resin has been used for the fabrication of polymer composites by several authors [7, 23, 282]. Due to the above mentioned advantages, epoxy (LY 556) chemically belongs to the 'epoxide' family, is selected as the matrix material for this study. The epoxy resin (density 1.15 gm/cc) and the corresponding hardener HY-951 were supplied by Ciba Geigy India Ltd.

3.1.2 Fiber Material

In composites, the discontinuous phase is usually harder and stronger than the continuous phase and is called the reinforcement. In polymer composites, the reinforcing phase can either be fibrous or non-fibrous (particulates) in nature. In FRP composites, fiber acts as a reinforcing agent. Fibers are the load carrying members which provide strength, stiffness, thermal stability and other structural properties in FRP [283]. If the fibers are derived from the natural resources like plants or some other living species, they are called natural fibers. Natural fibers as reinforcement in composite materials have recently attracted the attention of researchers because of their several advantages. The advantages of natural fibers over synthetic fibers are low cost, low density, comparable specific properties, bio-degradability, renewability, recyclability and less health risk [56]. A great deal of work has been done on various types of natural fibers for polymer composites. Among various natural fibers, jute is more promising to be used as reinforcement in polymer composites as it is relatively inexpensive and commercially available in various forms. Jute fibers have high impact strength in addition to having moderate tensile strength and flexural properties compared to other natural fibers like sisal, coir, pineapple and banana. Due to the above mentioned advantages, jute fiber in three different forms i.e. needle-punched nonwoven, bidirectional and short jute fiber supplied by local supplier are selected as reinforcing material in the present research work. The nonwoven fabrics are sheet or web of directional or randomly oriented fiber which are bonded by cohesion, friction or adhesion. Needle-punching technique involves an array of the barbed needles which are pushed or penetrated through the nonwoven web to form fiber entanglements and 3D fiber orientation [284]. Some fibers are hold by barbs and their orientation is changed as they transfer into the vertical plane of the ensuing fabric [113]. The needle-punching of the fibrous web leads to the formation of a coherent and self-locking material [285]. Needle-punched nonwoven composites offer good compressive, shear and inter-laminar properties [286]. Bidirectional woven fabrics are prepared from fibers crimped as they pass under and over one another. They offer higher strength in the 0° and 90° directions, and allow one laminate to be used for faster fabrication of composite [287]. During fabrication of composites these fabrics are easy to handle and process. The use of short fibers as reinforcement in composites is getting commercial importance, particularly in low load secondary structure applications. Short fiber reinforced composites offer better stiffness, heat distortion temperature and strength in comparison to the base polymer [93]. These fibers provide a less-expensive alternative for the reinforcement in composites and can be used in applications where average mechanical properties are required.

3.2 Composite Fabrication

Needle-punched nonwoven, bidirectional and short jute fibers were reinforced separately in epoxy resin to prepare the fiber reinforced epoxy composites. The composite panels were fabricated by conventional hand lay-up process followed by light compression moulding technique with five different fiber loading (0 wt.%, 12 wt.%, 24 wt.%, 36 wt.% and 48 wt.%). The details and designation of the prepared composites is presented in Table 3.1. This fabrication process is done on a stainless steel mould of dimension 210 × 210 × 40 mm^3. Silicon spray is used as a releasing agent for the easy removal of cured composite panels from the mould.

Table 3.1 Detailed designation and composition of composites

Composites	Composition
NJFE-1/ BJFE-1/SJFE-1	Epoxy (100 wt.%)
NJFE-2	Epoxy (88 wt.%) + needle-punched nonwoven jute fiber (12 wt.%)
NJFE-3	Epoxy (76 wt.%) + needle-punched nonwoven jute fiber (24 wt.%)
NJFE-4	Epoxy (64 wt.%) + needle-punched nonwoven jute fiber (36 wt.%)
NJFE-5	Epoxy (52 wt.%) + needle-punched nonwoven jute fiber (48 wt.%)
BJFE-2	Epoxy (88 wt.%) + bidirectional jute fiber (12 wt.%)
BJFE-3	Epoxy (76 wt.%) + bidirectional jute fiber (24 wt.%)
BJFE-4	Epoxy (64 wt.%) + bidirectional jute fiber (36 wt.%)
BJFE-5	Epoxy (52 wt.%) + bidirectional jute fiber (48 wt.%)
SJFE-2	Epoxy (88 wt.%) + short jute fibers (12 wt.%)
SJFE-3	Epoxy (76 wt.%) + short jute fibers (24 wt.%)
SJFE-4	Epoxy (64 wt.%) + short jute fibers (36 wt.%)
SJFE-5	Epoxy (52 wt.%) + short jute fibers (48 wt.%)

A load of 50 kg is applied over the mould for 24 h during the curing process of composites. Then the cast of composites is removed from the mould and post curing is also done for the next 24 h. Samples of proper dimension were cut by a diamond cutter for the physical, mechanical and abrasive wear testing.

3.3 Testing of Physical and Mechanical Properties

3.3.1 Density

The physical properties of a composite material system can be as important as mechanical properties in assessing suitability for a particular application. Density plays a key role for designing an engineering component or deciding the application of a material particularly where weight is an important factor. Thus, it is necessary to determine the density of the composites fabricated for this study. The theoretical density (ρ_{ct}) of composites in terms of weight fraction is obtained using the relation given by Agarwal and Broutman [288].

$$\rho_{ct} = \frac{1}{\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}} \tag{3.1}$$

where, W and ρ designates the weight fraction and density, respectively. The suffix f, m and ct represent the fiber, matrix and the composite materials, respectively.

The actual density (ρ_{ac}) of the composites is determined by simple water immersion technique. By using the theoretical and experimental density of composites, the volume fraction of voids (V_v) in the composites is determined using the following equation:

$$V_v = \frac{\rho_{ct} - \rho_c}{\rho_{ct}} \tag{3.2}$$

3.3.2 Hardness

Hardness is a measure of material's resistance to permanent deformation or damage [289]. Hardness is generally taken as one of the most important factors that govern the wear resistance of materials. In the present study, a Rockwell hardness tester is used to measure the hardness of the composite samples as per ASTM D785 test standards. During the test a minor load of 10 kg followed by a major load of 100 kg were applied over the smooth surfaces of the samples. The hardness measurement is done by measuring the depth of indentation made by a diamond indenter.

3.3.3 Tensile Strength

The tensile strength of the composites is measured using a computerized universal testing machine Instron 1195 in accordance with the ASTM D 3039-76 standards at a cross head speed of 10 mm/min. Figures 3.1 and 3.2 shows the universal testing machine Instron 1195 and loading arrangement for tensile test, respectively.

Figure 3.1 Universal testing machine, Instron 1195

3.3.4 Flexural and ILSS

The three point bend test is carried out to obtain the flexural properties of all the composite samples using the same universal testing machine Instron 1195. The tests were performed as per the ASTM D 2344-84 standards with the cross-head speed of 10 mm/min. Figure 3.3 shows the loading arrangement for the flexural test.

Figure 3.2 Loading arrangement for tensile test

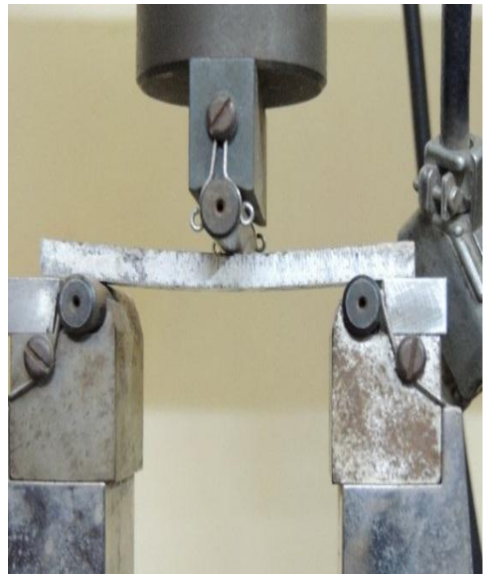

Figure 3.3 Loading arrangement for flexural test

The flexural strength (*FS*) of composite specimen is determined using the Equation 3.3.

$$FS = \frac{3PL}{2bt^2} \tag{3.3}$$

where, *P* is the load applied. *L* is the span length of the sample; *b* and *t* are the width and thickness of the sample, respectively.

The ILSS of the composites were evaluated by short beam shear test. The ILSS values were calculated using Equation 3.4:

$$ILSS = \frac{3P}{4bt} \tag{3.4}$$

3.3.5 Impact Strength

Izod impact tests were performed on a Tinius Olsen pendulum impact tester (IT 504), as shown in Figure 3.4. Samples with dimension of 60 x 15 mm^2 were tested in accordance with the ASTM D256 standards. The sample is impacted by a pendulum with a velocity of 3.46 m/s when dropped from a height of 609.6 mm. The tester calculates and displays the impact energy absorbed by the samples.

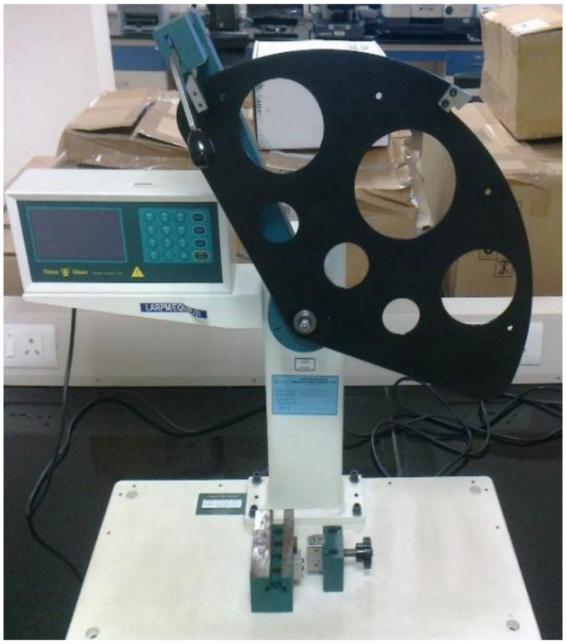

Figure 3.4 Izod impact testing machine

3.4 Scanning Electron Microscopy

Microstructures of the abraded composite samples were examined using a scanning electron microscope (model JEOL JSM-6480LV), as shown in Figure 3.5. Before taking micrographs, a thin film of platinum was vacuum-evaporated onto the surface of the samples in order to enhance the conductivity of the samples. The composite samples were mounted on stubs with silver paste.

Figure 3.5 Scanning electron microscope setup

3.5 Abrasive Wear Testing

The three-body abrasive wear tests is performed on dry sand rubber/wheel abrasion tester as per ASTM G 65 test standards. The schematic diagram of the abrasive wear test rig and its setup is shown in Figures 3.6 (a) and (b), respectively. The setup for test is capable of creating a three-body abrasive wear environment for analyzing the wear properties of the prepared composites. The apparatus consists of sample holder, nozzle, abrasive hopper, rubber wheel, particle collecting bag, steel disk, and an arrangement for the application of load. Dry silica sand of particle size 100μm, 200μm, 300μm, 400μm and 500μm were used as abrasives for the present study.

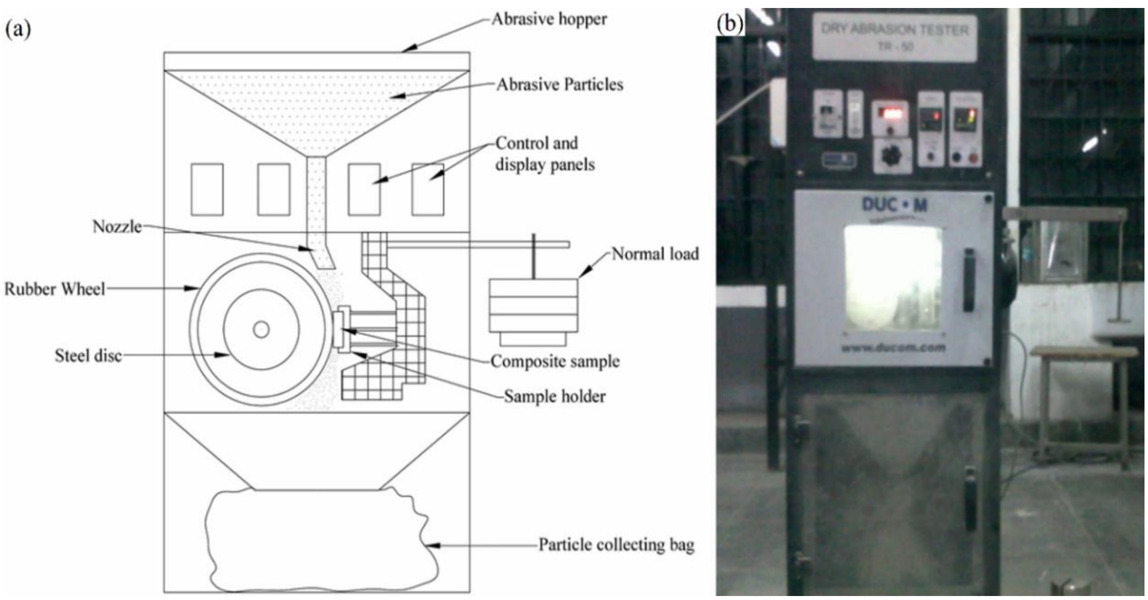

Figure 3.6 (a) Schematic diagram of abrasive wear test rig, and (b) Dry sand rubber/wheel abrasion test setup

The abrasive particles of particular size were stored in abrasive hopper. Samples to be tested are placed in sample holder. The test sample is pressed against rubber wheel at a specified load by means of lever arm. The abrasive particles were fed between the contacting surface of the rubber wheel and test sample. The rubber wheel is allowed to rotate. The abrasive wear occurs as the abrasive particles slides and rolls in between the rotating wheel and sample. For each test run the samples were cleaned in acetone, dried and weighted before and after the test using a precision electronic balance to an accuracy of ± 0.1 mg. The specific wear rate and friction coefficient values were determined by considering factors like abrasive particle size, sliding velocity, sliding distance, normal load and fiber loading. The specific wear rate of the sample is calculated using Equation 3.5.

$$W_s = \frac{\Delta M}{\rho L F} \tag{3.5}$$

where, ΔM is the mass loss of the sample during the test, ρ is the density of the sample used, L is the sliding distance and F is the load applied on the sample.

Figures 3.7 (a), (b) and (c) shows the abraded samples of needle-punched nonwoven jute epoxy composites, bidirectional jute epoxy composites and short jute epoxy composites, respectively.

(a) (b) (c)

Figure 3.7 Photographic image of the abraded (a) needle-punched nonwoven jute epoxy composites, (b) bidirectional jute epoxy composites and (c) short jute epoxy composites

3.6 Taguchi Method

Taguchi method developed in 1950s by Dr. Genichi Taguchi is largely been used by engineers and scientists in order to improve product quality and process performance. This method is a combination of statistical and mathematical techniques used in an empirical study. It is an efficient and powerful tool for the optimization of process parameters. Taguchi method gives a systematic approach for performing experimentation to find out optimum experimental setting of selected design parameters. This method reduces the time and cost involved in any experimental investigation by minimizing the number of experimental runs required to satisfy the design objectives. The two major tools used in Taguchi method are signal-to-noise (*S/N*) ratio and orthogonal arrays [290]. Experiments based on Taguchi methods were performed as per the specifically designed orthogonal array in which control factors or process parameters were taken as input parameters [291]. The experimental result analysis uses *S/N* ratio to aid in the determination of the best process or product design [292]. An important step in design of experiments is the selection of control factors. From the literature review it has been found that parameters like fiber loading, sliding velocity, sliding distance, normal load and abrasive size etc. effects the wear behaviour of polymer composites [293-296]. In this work, the influence of five factors were studied using L_{25} (5^5) orthogonal design. The operating conditions under which abrasive wear tests were performed are shown in Table 3.2. Five factors i.e., sliding velocity (A), fiber loading (B), normal load (C), sliding distance (D) and abrasive size (E), each at five levels are considered in this study.

Table 3.2 Levels of the variables used in the experiment

Control factors	Levels					Units
	I	II	III	IV	V	
Sliding velocity (A)	48	72	96	120	144	cm/s
Fiber loading (B)	0	12	24	36	48	wt.%
Normal load (C)	10	20	30	40	50	N
Sliding distance (D)	50	60	70	80	90	m
Abrasive size (E)	100	200	300	400	500	µm

Table 3.3 shows the Taguchi (L_{25}) orthogonal array, based on which the tests were performed at room temperature. In Table 3.3, each column stands for a test parameter and a row provides a test condition which is the combination of

parameter levels. A full factorial experiment with five parameters with five levels requires $5^5 = 3125$ runs, whereas it reduces to 25 runs only, on using the Taguchi orthogonal array. The experimental results or outputs obtained from the tests were converted into *S/N* ratio. The *S/N* ratios serve as the objective functions for optimization, and help in analysis of data and optimum results prediction [297].

Table 3.3 Experimental design using L_{25} orthogonal array

Expt. No.	Sliding velocity (cm/s)	Fiber loading (wt.%)	Normal load (N)	Sliding distance (m)	Abrasive size (μm)
1	48	0	10	50	100
2	48	12	20	60	200
3	48	24	30	70	300
4	48	36	40	80	400
5	48	48	50	90	500
6	72	0	20	70	400
7	72	12	30	80	500
8	72	24	40	90	100
9	72	36	50	50	200
10	72	48	10	60	300
11	96	0	30	90	200
12	96	12	40	50	300
13	96	24	50	60	400
14	96	36	10	70	500
15	96	48	20	80	100
16	120	0	40	60	500
17	120	12	50	70	100
18	120	24	10	80	200
19	120	36	20	90	300
20	120	48	30	50	400
21	144	0	50	80	300
22	144	12	10	90	400
23	144	24	20	50	500
24	144	36	30	60	100
25	144	48	40	70	200

In the analysis of *S/N* ratio there are three type of quality characteristics i.e. smaller the better, larger the better and nominal the best. These characteristics can be calculated using the expression shown in equations.

Smaller is better : $$\frac{S}{N} = -10 log \frac{1}{n}(\Sigma y^2) \quad (3.6)$$

Larger is better : $$\frac{S}{N} = 10 log (\Sigma \frac{\bar{Y}}{S^2}) \quad (3.7)$$

Nominal is best : $$\frac{S}{N} = -10 log \frac{1}{n}(\Sigma \frac{1}{y^2}) \quad (3.8)$$

where n denotes the number of observations, y denotes the observed data, $\bar{Y}$ is the mean and S indicates the variance.

The *S/N* ratio for specific wear rate and coefficient of friction comes under 'smaller is better' characteristic, which can be calculated as logarithmic transformation of the loss function by using Equation (3.6).

3.7 AHP-TOPSIS Method

Material selection plays a very important role in designing any product or component. Each material has its own properties like hardness, density, strength, wear resistance, corrosion resistance etc. It is the responsibility of a design engineer to select an appropriate material which has best or ideal properties to serve the required purpose. For any design engineer it is very complex situation to decide or select the material with optimum property from a pool of available materials [298]. Therefore, now-a-days various tools based on MCDM process are used effectively to cope up such complexity in material selection decisions. In the present work, an integrated or combined AHP-TOPSIS method is used to rank the fabricated composites materials as it offers a number of benefits. The ranking is done based on physical, mechanical and wear properties of composite materials such as density, hardness, tensile strength, tensile modulus, flexural strength, flexural modulus, impact strength and specific wear rate.

The material ranking process is totally divided in two stages. Firstly, the AHP method was applied to determine the weightage of the selected criteria. In the second stage, TOPSIS method is used for estimating the materials ranking. The criteria weightages obtained from AHP method is used latter in the ranking process to get the overall score of the composite materials used in this study.

The steps for the weighting and ranking process using the combined AHP-TOPSIS method are mentioned below [261,270,276, 299,300]:

Stage A: AHP method (for weighting criteria)

Step 1: A three level hierarchical structure is created for the weighting purpose, as shown in Figure 3.8. In the first level, goal of the study is defined which is to rank the composites materials for wear resistant applications. In the second level, the criteria for the study are represented. The criteria considered are physical property (density), mechanical properties (hardness, tensile strength, tensile modulus, flexural strength, flexural modulus and impact strength) and abrasive wear property (W_s (n) and W_s (v) i.e. mean of the specific wear rate at different normal load and sliding velocity, respectively). The third level of hierarchy contains the alternatives i.e. different set of materials which are ranked to get the best alternative. The alternatives considered are epoxy, NJFE-2, NJFE-3, NJFE-4, NJFE-5, BJFE-2, BJFE-3, BJFE-4, BJFE-5, SJFE-2, SJFE-3, SJFE-4 and SJFE-5.

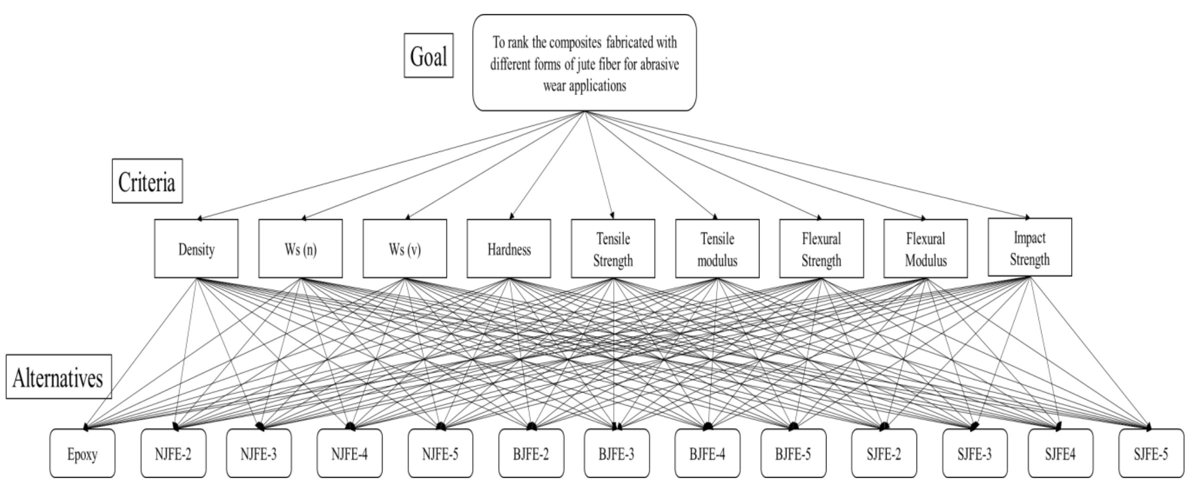

Figure 3.8 Hierarchical structure for the material selection

Step 2: To determine the criteria weights, a pair-wise comparison matrix (matrix A (Equation (3.9)) is prepared. Pair-wise comparison decisions are done on the basis of predefined rating value presented in Table 3.4 for each criterion with respect to the goal. The number of pair-wise comparison assessments depends on the number of criteria involved in the hierarchical structure, and is determined using the *n (n-1)* rule where *n* represents the number of criteria.

Table 3.4 Pair-wise comparison scale

Intensity	Definition
1	Equal importance
3	Moderate importance
5	High importance
7	Very high importance
9	Extreme importance
2, 4,6,8	Intermediate values
Reciprocals	Reciprocal for comparison

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1j} \\ a_{21} & 1 & a_{23} & \cdots & a_{2j} \\ a_{31} & a_{32} & \ddots & \cdots & a_{3j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & a_{i3} & \cdots & a_{ij} \end{bmatrix} \tag{3.9}$$

Step 3: The total sum ($\sum_i C_{ij}$) for each column of the pair-wise comparison matrix is determined.

Step 4: Each cell is standardized using $X_{ij} = \frac{C_{ij}}{\sum_i C_{ij}}$

Step 5: The row sum $R_i = \sum_j X_{ij}$ of the standardized pair-wise comparison matrix is calculated. Thereafter, the weight of the criteria are determined using $W_i = \frac{R_i}{n}$ where, n is the number of criteria.

Step 6: The priority vector is calculated using $V_i = A.W_i$, for *i*=1, 2, 3,........, n.

Step 7: The eigenvector $\lambda_i = \frac{V_i}{W_i}$ is calculated, and the principal eigenvalue $\lambda_{\max}$ (by averaging eigenvector values) are determined.

Step 8: Consistency Index (*CI*) is calculated using the Equation (3.10)

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{3.10}$$

Step 9: Consistency Ratio (*CR*) is obtained by Equation (3.11). The value of random inconsistency index (*RI*) depends on *n*. *RI* values corresponding with n between 1-10 are presented in Table 3.5.

$$CR = \frac{CI}{RI} \tag{3.11}$$

The *CR* value should be less than 10% to be acceptable, in some cases up to 20% may be tolerated [261,300,301].

Table 3.5 Random inconsistency indices (*RI*) for *n* = 10 [299]

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.149

Stage B: TOPSIS method (for ranking of alternatives)

Step 1: Firstly, the overall TOPSIS decision matrix (*DM*) is created based on the following equation

$$DM = \begin{matrix} & C_1 & C_2 & C_3 & \cdots & C_n \\ A_1 & Y_{11} & Y_{12} & Y_{13} & \cdots & Y_{1n} \\ A_2 & Y_{21} & Y_{22} & Y_{23} & \cdots & Y_{2n} \\ A_3 & Y_{31} & Y_{32} & Y_{33} & \cdots & Y_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & Y_{m1} & Y_{m2} & Y_{m3} & \cdots & Y_{mn} \end{matrix} \tag{3.12}$$

The terms C_1, C_2, C_3 …, C_n denotes the criteria, whereas A_1, A_2, A_3 …, A_n represents the potential alternatives that are considered. Y_{ij} is the rating of alternative A_i with respect to criteria C_j where w_j is the weight of criteria C_j [276].

Step 2: The normalized decision matrix is determined and the normalized value n_{ij} is calculated using the expression,

$$n_{ij} = \frac{Y_{ij}}{\sqrt{\sum_{i=1}^{m} Y_{ij}^2}} \qquad i = 1, 2, 3,\ldots m;\ j = 1, 2, 3,\ldots n. \tag{3.13}$$

Step 3: The weighted normalized decision matrix is calculated using equation

$$V = N_D.W_{n\times n} = \begin{bmatrix} V_{1i} & \cdots & V_{1j} & \cdots & V_{1n} \\ \vdots & & \vdots & & \vdots \\ V_{mi} & \cdots & V_{mj} & \cdots & V_{mn} \end{bmatrix} \tag{3.14}$$

where w_j is the weight of the i^{th} criteria or attribute, and $\sum_{j=1}^{n} w_j = 1$

Step 4: Positive ideal and negative ideal solutions are determined using Equations (3.15) and (3.16), respectively

$$A^{+} = \{(^{\max}{}_i v_{ij}; i \in I)(^{\min}{}_i v_{ij}; i \in J)\} \tag{3.15}$$

$$A^{-} = \{(^{\min}{}_i v_{ij}; i \in I)(^{\max}{}_i v_{ij}; i \in J)\} \tag{3.16}$$

where I is related with beneficial attribute, and J is related with non-beneficial attributes.

Step 5: The separation measures (or separation distance) are determined using following equations

$$d_i^{+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{+})^2} \tag{3.17}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad (3.18)$$

Step 6: The relative closeness of the i^{th} alternative to ideal solution is calculated using the following equation:

$$RC_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (3.19)$$

$$0 \le RC_i \le 1$$

On comparing the RC_i values, the ranking of alternatives are done. The alternatives with higher closeness value means higher rank.

Chapter Summary

This chapter has provided:

- Details of the materials used along with fabrication process.
- The various testing methods used for examining the physical, mechanical and abrasive wear behaviour of composites.
- Details related to Taguchi and AHP-TOPSIS methodology used for optimization of process parameters and ranking of materials, respectively.

The next chapter refers to the results and discussion of the physical, mechanical and wear behaviour of composites.

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CHAPTER 4

RESULTS AND DISCUSSION: PHYSICAL, MECHANICAL AND WEAR BEHAVIOUR OF COMPOSITES

This chapter presents the physical, mechanical and three-body abrasive wear behaviour of the jute fiber reinforced epoxy composites. The effect of fiber loading and different forms of jute on various properties of composites is discussed. The effects of sliding velocity and normal load on the three-body abrasive wear response of the composites are also presented. The results of this chapter are divided into three parts. Part-1 represents the physical, mechanical and three-body abrasive wear behaviour of needle-punched nonwoven jute fiber reinforced epoxy composites, Part-2 represents the physical, mechanical and three-body abrasive wear behaviour of bidirectional jute fiber reinforced epoxy composites and Part-3 represents the physical, mechanical and three-body abrasive wear behaviour of short jute fiber reinforced epoxy composites.

4.1 Part 1: Needle-Punched Nonwoven Jute Fiber Reinforced Epoxy Composites

This part of the chapter presents the physical, mechanical and three-body abrasive wear behaviour of needle-punched jute fiber reinforced epoxy composites.

4.1.1 Physical and Mechanical Properties of Composites

4.1.1.1 Density

The theoretical density, experimental density and the corresponding void fraction of the composites is presented in Table 4.1. It is to be noted that the values of theoretical density are not equal to the experimental density of the prepared composites. This difference in the theoretical and experimental density of the composites is the measure of voids or pores present in it. The presence of voids in composites significantly affects its mechanical properties directly or indirectly. It is observed from the Table 4.1 that the addition of fiber in the epoxy resin led to rise in void fraction of the composites. The natural fibers consist of lumens in its cellular structure which acts as void. It means such fiber carries these voids naturally. Thus, it may be the reason of increase in void content with the increase in fiber loading [302]. Similar trend is also observed by previous researchers [303, 304].

Table 4.1 Comparison between experimental and theoretical density of needle-punched nonwoven jute epoxy composites

Composites	Theoretical Density (ρ_{ct}) g/cm^3	Experimental Density (ρ_{ex}) g/cm^3	Void Fraction (%)
NJFE -1	1.150	1.147	0.261
NJFE -2	1.157	1.120	3.198
NJFE -3	1.162	1.124	3.270
NJFE -4	1.167	1.123	3.770
NJFE -5	1.172	1.126	3.925

4.1.1.2 Hardness

The measured hardness value of the composites with different fiber loading is shown in Figure 4.1. The test result shows that with increase in fiber loading, the hardness of the composites increases. The increase in hardness may be due to brittle

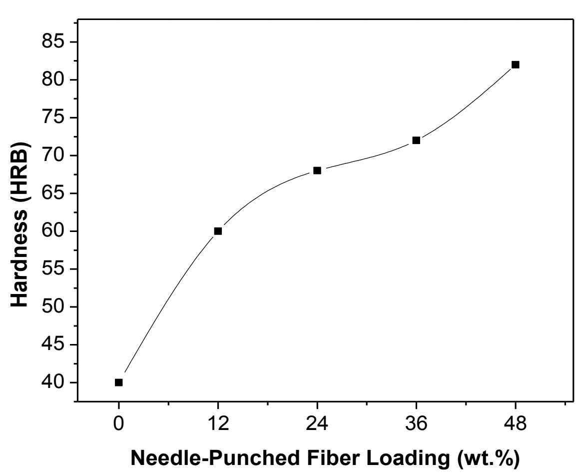

Figure 4.1 Effect of needle-punched jute fiber loading on hardness of composites

nature of lignocellulosic fiber [305]. Similar observation of improvement in the hardness of composites with the inclusion of viscose fiber based Needle-punched nonwovens in the epoxy matrix has been reported by researchers [108]. The composite with 48 wt.% fiber loading exhibit maximum hardness of 82 HRB among all set of composites under the study.

4.1.1.3 Tensile Properties

The variation of the tensile strength and modulus of needle-punched nonwoven jute composites with different fiber loading is shown in Figure 4.2. It is clearly observed that both the tensile strength and modulus are improving with increase in fiber loading. This shows an effective and uniform stress transfer within the composite after the incorporation of fibers into matrix. Similar observations have also been made by researchers in case of nonwoven flax reinforced polypropylene composites [134]. It has been reported in their study that the tensile modulus depends mainly on the fiber volume fraction and not on the physical structure of the fibers. It is also observed that the composite with 48 wt.% fiber loading exhibits better tensile strength and modulus as compared to other composites.

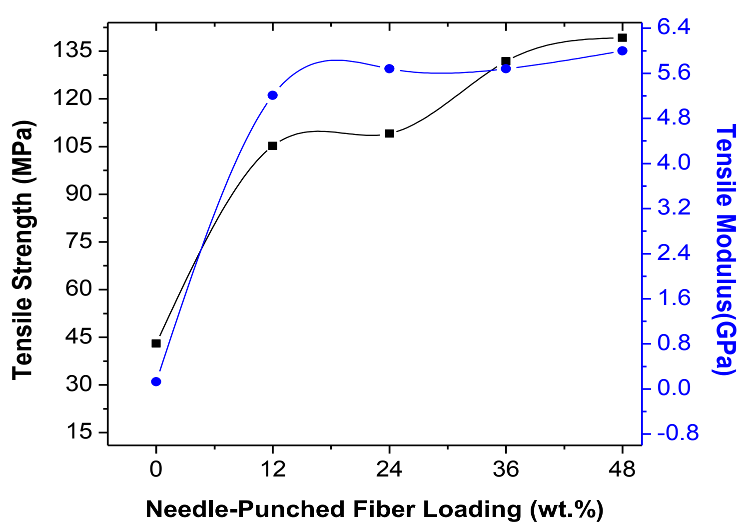

Figure 4.2 Effect of needle-punched jute fiber loading on tensile properties of composites

4.1.1.4 Flexural Properties

Figure 4.3 illustrates the effect of fiber loading on flexural behaviour of composites. It is observed from the figure that the flexural strength and modulus of composite decreased at 12 wt.% fiber loading but further addition of fiber in the matrix increases the flexural properties, as it increased in case of NJFE-3, NJFE-4 and NJFE-5. Similar trend is also observed by researchers in case of straw-reinforced polyester composites [306]. The initial reduction in flexural properties may be due to the weak interfacial bonding. But, the further addition of fiber improves the flexural strength of composite. This may be due to the favorable entanglement of the polymer chain with reinforcement which has overcome the weak fiber matrix adhesion with increase in fiber loading [307]. Composite with 48 wt.% fiber loading shows maximum flexural strength and modulus as compared to all other set of composites under the present study.

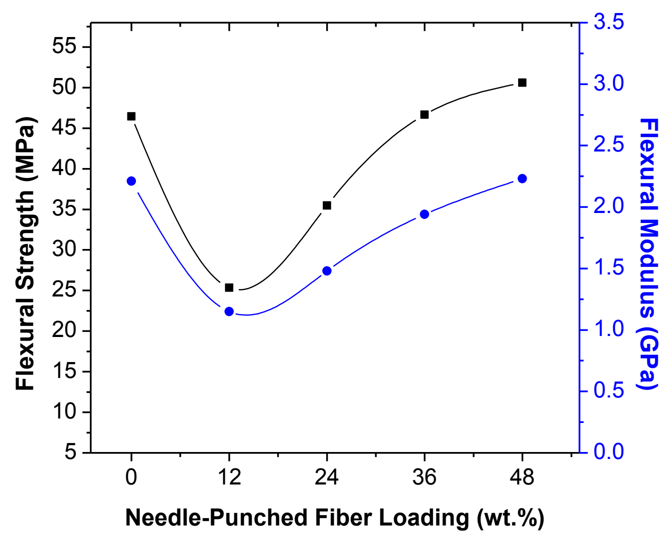

Figure 4.3 Effect of needle-punched jute fiber loading on flexural properties of composites

4.1.1.5 ILSS

Effect of fiber loading on ILSS of composites is shown in Figure 4.4. It is observed from the figure that composite with 12 wt.% fiber loading exhibit low ILSS as compared to other samples. Further addition of fibers in the matrix results in improvement of ILSS of the composites. It is found that NJFE-4 composite exhibit slight improvement in ILSS, however the ILSS of NJFE-5 composite improved by 29% when compared to neat epoxy. Similar trend of decrease and then increase in ILSS property of silane treated glass reinforced polyester composites with the increase in fiber volume fraction is also reported by Cheon and Lee [308].

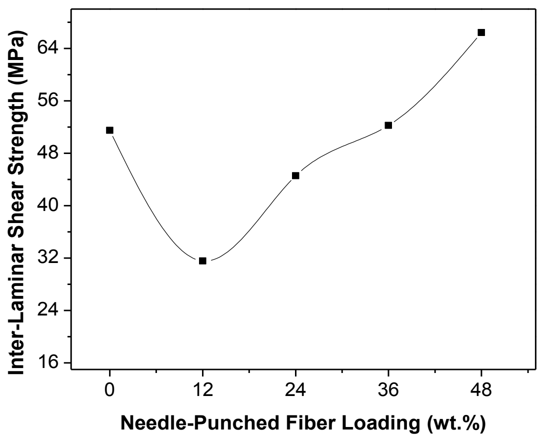

Figure 4.4 Effect of needle-punched jute fiber loading on ILSS of composites

4.1.1.6 Impact Strength

Figure 4.5 depicts the effect of needle-punched jute fiber loading on the impact strength of composites. It is observed from the figure that the impact strength of composites increases with increase in fiber loading. Similar trend of increase in impact strength with increase in needle-punched nonwoven fiber loading has also been reported by few researchers [108, 309]. The impact failure of composites occurs mainly due to the factors such as fiber pull out, fiber and/or matrix fracture and fiber/matrix debonding. Fiber pullout dissipates more energy compared to fiber fracture. The fiber fracture is common in composites with strong interfacial bonding, whereas occurrence of fiber pullout is a sign of weak bond. The load applied on composite, transfers to the fibers by shear may exceed the fiber-matrix interfacial bonding strength and debonding occurs. When the stress level surpasses the fiber strength, fiber fracture takes place [310]. The fractured fibers may be pulled out of the matrix, resulting in energy dissipation.

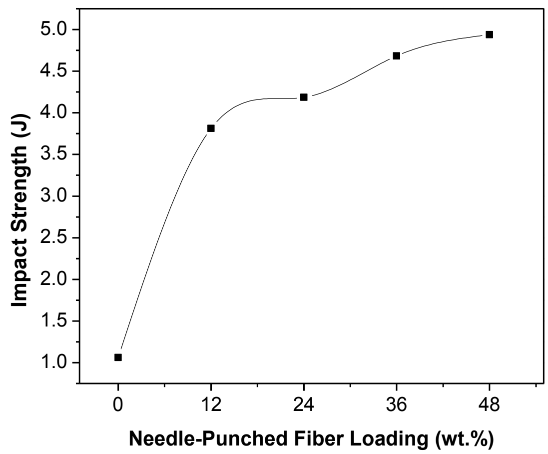

Figure 4.5 Effect of needle-punched jute fiber loading on impact strength of composites

4.1.2 Three-Body Abrasive Wear Behaviour of Composites

4.1.2.1 Effect of Sliding Velocity and Normal Load on Specific Wear Rate of Composites

Figure 4.6 shows the effect of normal load on the specific wear rate of composites keeping other parameters constant (i.e. at sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm). It is observed from the figure that the specific wear rate of composites increases with increase in normal load. Similar observations have also been reported by other researchers for woven glass fabrics reinforced composites [311], 3D braided carbon/Kevlar/epoxy hybrid composites [312], and 3D braided glass fibers reinforced light-cured dimethacrylate resin composites [313]. The increase in specific wear rate at higher load may be due to thermal softening [314]. At increased load, contact temperature between jute epoxy composite and rubber wheel increases and easy detachment of soften layer from the surface of material takes place. It can also be observed from Figure 4.6 that neat epoxy shows maximum specific wear rate irrespective of different normal load.

However, composites with 36 wt.% of fiber loading exhibits minimum specific wear rate at 20 N normal load.

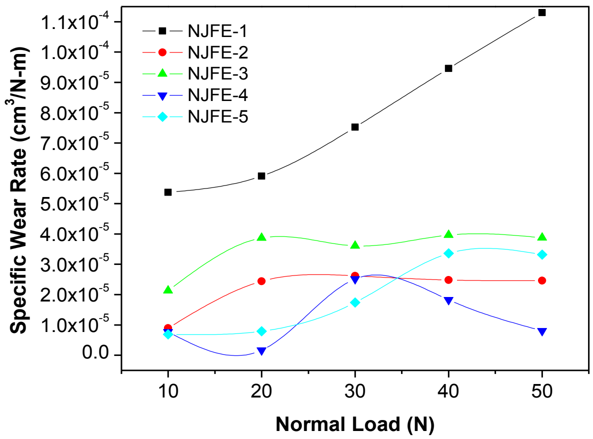

Figure 4.6 Effect of normal load on specific wear rate of needle-punched jute fiber epoxy composites (At sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm)

The effect of sliding velocity on specific wear rate of composites is shown in Figure 4.7 (at normal load: 30 N, sliding distance: 50 m and abrasive size: 300 μm). It is observed from the figure that specific wear rate of neat epoxy increases with increase in sliding velocity. The polyacetal composites containing glass fiber and beads as reinforcement exhibit much higher wear than unfilled polyacetal at lower velocity [315]. In the present study, at low sliding velocity, the initial removal of the resin layer from the surface exposes the fibers to the abrasive. The bonding at the interfacial regions between the fibers and matrix gets weaken due to the normal load and shear forces exerted by the abrasives over the worn fibers and the frictional heating at the contacting region. Serious fiber removal could occur, when the matrix failed to support the fibers and thus a rapid increase in the wear rate. The epoxy matrix exhibits higher specific wear rate at higher sliding velocity (Figure 4.7). The polymer will fracture at higher sliding velocity which leads to the formation of large wear particles and high wear [295]. However, specific wear rate of jute fiber composites decreases with the increase in sliding velocity. The reduction in the wear rate with increase in sliding velocity could be due to the fact that although the surface area of contact is same for all sliding velocities whereas the duration of contact reduces as the sliding velocity increases [198]. The composite with 36 wt.% fiber loading exhibit minimum specific wear rate among all the composites. Generally, hardness of any material plays a key role in enhancing the abrasive wear resistance of the composites. The wear resistance of materials is a function of their hardness and elasticity [183].

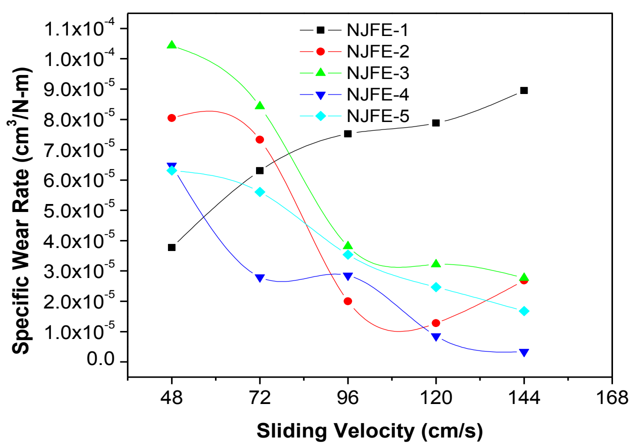

Figure 4.7 Effect of sliding velocity on specific wear rate of needle-punched jute fiber epoxy composites (At constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 μm)

From Figures 4.6 and 4.7, it is observed that the addition of fiber in matrix results in improved wear resistance of the composites. This is attributed to the fact that fiber reinforcement offers better resistance to abrasion and is responsible for the reduced specific wear rate as it is harder than the matrix and thus much more energy is required for its failure [21].

4.1.2.2 Effect of Sliding Velocity and Normal Load on Coefficient of Friction of Composites

The effect of sliding velocity on coefficient of friction of neat epoxy and jute fiber reinforced epoxy composites is shown Figure 4.8 (at constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 μm). It is clear from the figure that the coefficient of friction increased for sliding velocity up to 72 cm/s, however further increase in sliding velocity the value is decreasing irrespective of fiber loading. The variation of coefficient of friction of composites with normal load is shown in Figure 4.9 (i.e. at constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm). It is evident from the figure that the coefficient of friction increased for normal load up to 20 N, however further increase in normal load, it is decreasing irrespective of fiber loading. The decrease in coefficient of friction with increase in normal load is observed by previous researchers [316].

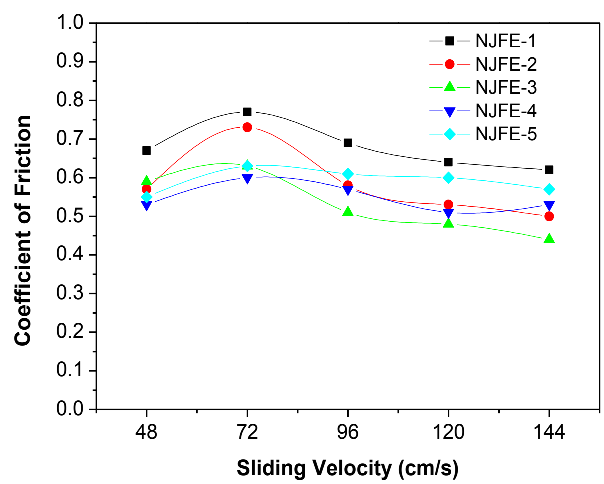

Figure 4.8 Effect of sliding velocity on coefficient of friction of needle-punched jute fiber epoxy composites (At constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 μm)

The reason of decrease in coefficient of friction may be due to the fact that generally, under dry sliding condition between counterface and composite specimen, as the applied load and sliding speed increases, temperature at the contact surface of rubbing part increases. Thermal gradient is developed due to rise in temperature and consequently thermal stresses are generated. Thermal stresses causes to debond the fiber-matrix interface and fibers get loose which in result shear easily due to repeated axial thrust and reduction in friction coefficient is observed.

From Figure 4.8 and Figure 4.9, it is also observed that the jute fiber reinforced composites exhibit lower coefficient of friction compared to neat epoxy. The addition of the fibers strengthened the interface between the fibers and the matrix and increased the elastic modulus of the composites. This may be the reason of reduction in friction coefficient of the jute fiber composites. Fibers, as a hard phase in soft polymer matrix can reduce the true contact area with the counter body under certain load [317]. Thus, it plays an important role in reducing the plough and the adhesion at the contacting region.

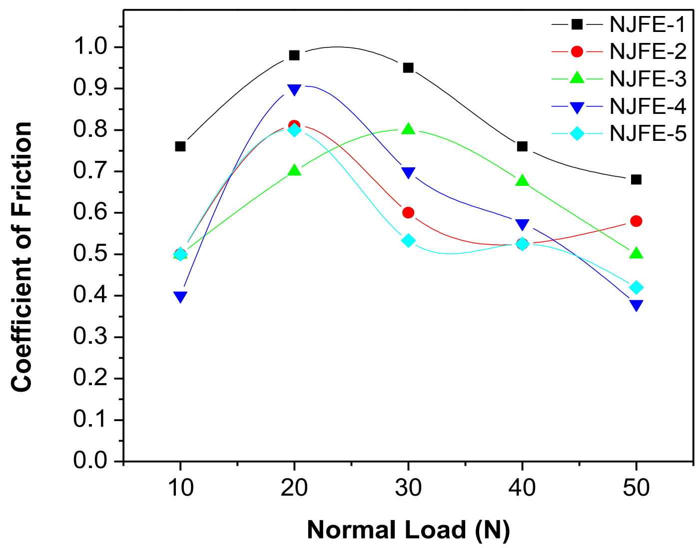

Figure 4.9 Effect of normal load on coefficient of friction of the needle-punched jute fiber epoxy composites (At constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm)

4.1.2.3 Taguchi Experimental Analysis

The specific wear rate, coefficient of friction and their corresponding *S/N* ratio obtained from the different experimental run with different parametric combinations are presented in Table 4.2. The overall mean value for the *S/N* ratio of specific wear rate and coefficient of friction for 25 different iterations is found to be 95.83 dB and 6.591 dB, respectively.

Table 4.2 Experimental design using L_{25} orthogonal array

Expt. No.	Sliding velocity (cm/s)	Fiber loading (wt.%)	Normal load (N)	Sliding distance (m)	Abrasive size (μm)	W_s $(\frac{cm^3}{N-m})$	S/N Ratio (dB)	Coefficient of Friction	S/N Ratio (dB)
1	48	0	10	50	100	1.92E-04	74.33	0.800000	1.9382
2	48	12	20	60	200	6.83E-05	83.32	0.700000	3.0980
3	48	24	30	70	300	1.22E-04	78.27	0.533333	5.4600
4	48	36	40	80	400	4.49E-05	86.96	0.525000	5.5968
5	48	48	50	90	500	1.05E-04	79.58	0.500000	6.0206
6	72	0	20	70	400	8.30E-05	81.61	0.500000	6.0206
7	72	12	30	80	500	7.70E-05	82.28	0.400000	7.9588
8	72	24	40	90	100	4.41E-05	87.11	0.825000	1.6709
9	72	36	50	50	200	3.77E-07	128.47	0.600000	4.4370
10	72	48	10	60	300	5.11E-06	105.84	0.200000	13.9794
11	96	0	30	90	200	3.81E-05	88.38	0.400000	7.9588
12	96	12	40	50	300	3.77E-05	88.47	0.550000	5.1927
13	96	24	50	60	400	5.85E-05	84.66	0.640000	3.8764
14	96	36	10	70	500	2.69E-06	111.40	0.200000	13.9794
15	96	48	20	80	100	8.13E-06	101.80	0.800000	1.9382
16	120	0	40	60	500	5.45E-05	85.27	0.525000	5.5968
17	120	12	50	70	100	1.37E-05	97.25	0.400000	7.9588
18	120	24	10	80	200	2.21E-05	93.12	0.500000	6.0206
19	120	36	20	90	300	2.56E-06	111.85	0.250000	12.0412
20	120	48	30	50	400	2.84E-07	130.92	0.533333	5.4600
21	144	0	50	80	300	6.78E-06	103.37	0.180000	14.8945
22	144	12	10	90	400	2.90E-06	110.75	0.400000	7.9588
23	144	24	20	50	500	2.99E-05	90.49	0.550000	5.1927
24	144	36	30	60	100	1.71E-06	115.32	0.566667	4.9334
25	144	48	40	70	200	1.80E-05	94.91	0.525000	5.5968

Figures 4.10 and 4.11 shows the effect of control factors on the specific wear rate and coefficient of friction of the composites, respectively. From Figure 4.10, it is found that the combination of factors A_4 (Sliding velocity: 120 cm/s), B_4 (Fiber loading: 36 wt.%), C_1 (Normal load : 10 N), D_1 (Sliding distance : 50 m) and E_4

(Abrasive size : 400 μm) gives minimum specific wear rate. Whereas, the factor combination of A_5 (Sliding velocity: 144 cm/s), B_4 (Fiber loading: 36 wt.%), C_1 (Normal load :10 N), D_3 (Sliding distance : 70 m) and E_3 (Abrasive size : 300 μm) gives minimum coefficient of friction as observed from Figure 4.11.

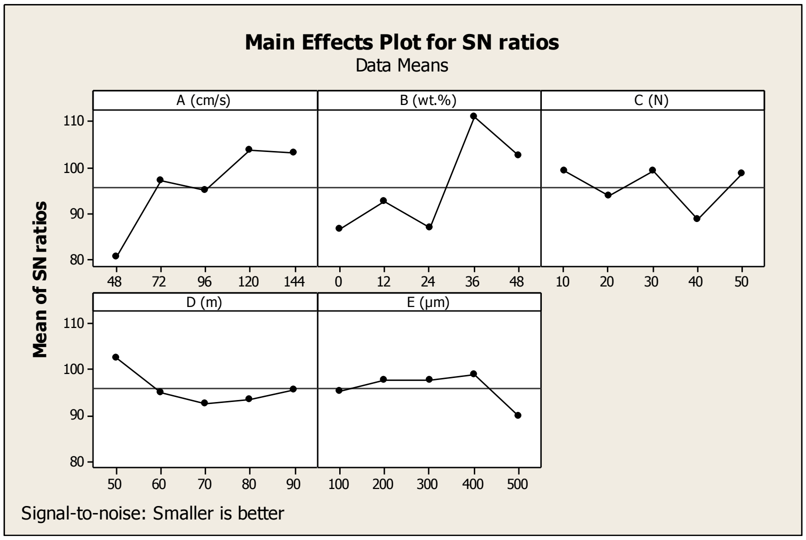

Figure 4.10 Effect of control factors on specific wear rate (for needle-punched jute fiber epoxy composites)

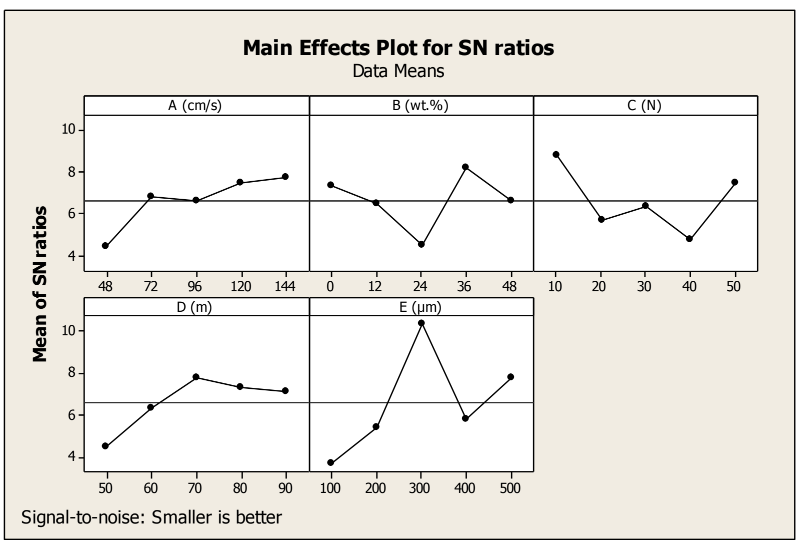

Figure 4.11 Effect of control factors on coefficient of friction (for needle-punched jute fiber epoxy composites)

4.1.2.4 Confirmation Experiment

Confirmation test is a crucial step and is highly suggested by Taguchi to verify the experimental results [318]. The optimal combination of parameters has been obtained from the Taguchi experimental design. The optimal factor combination for minimum specific wear rate is $A_4B_4C_1D_1E_4$, did not correspond to any experiment in the orthogonal array. Therefore, the predicted *S/N* ratio for minimum specific wear rate of needle-punched nonwoven jute epoxy composites is given by equation:

$$\eta_{Ws} = \eta_{A_4} + \eta_{B_4} + \eta_{C_1} + \eta_{D_1} + \eta_{E_4} - 4\eta_m \qquad (4.1)$$

where, η_m is the total mean of *S/N* ratio. η_{A_4}, η_{B_4}, η_{C_1}, η_{D_1} and η_{E_4} are the mean of *S/N* ratio at the optimal factor levels A_4, B_4, C_1, D_1 and E_4, respectively.

The optimal factor combination for minimum coefficient of friction i.e. $A_5 B_4C_1D_3E_3$, also didn't correspond to any experiment in the orthogonal array. Thus, the predicted *S/N* ratio for minimum coefficient of friction at optimal setting is given by:

$$\eta_{COF} = \eta_{A_5} + \eta_{B_4} + \eta_{C_1} + \eta_{D_3} + \eta_{E_3} - 4\eta_m \qquad (4.2)$$

where, η_{A_5}, η_{B_4}, η_{C_1}, η_{D_3} and η_{E_3} are the mean of *S/N* ratio at the optimal factor levels A_5, B_4, C_1, D_3 and E_3, respectively.

The predicted *S/N* ratio values for minimum specific wear rate and coefficient of friction at optimal settings are 131.7761 and 16.4408 dB, respectively.

Table 4.3 Results of confirmation experiment

	Optimal Condition		
	Predicted	Experiment	Error (%)
Specific Wear Rate			
Level	$A_4B_4C_1D_1E_4$	$A_4B_4C_1D_1E_4$	
S/N ratio (dB)	131.7761	136.9582	3.93
Coefficient of Friction			
Level	$A_5 B_4C_1D_3E_3$	$A_5 B_4C_1D_3E_3$	
S/N ratio (dB)	16.4408	15.5070	5.68

The confirmation test for specific wear rate and coefficient of friction at the optimal condition is performed and Table 4.3 shows the results of confirmation experiment. An error of 3.93 % and 5.68 % for the *S/N* ratio of specific wear rate and coefficient of friction are observed, respectively.

4.1.2.5 ANOVA and the Effect of Factors

The significant effect of the control factors (i.e. sliding velocity, fiber loading, normal load, sliding distance and abrasive size) on specific wear rate and coefficient of friction is analyzed by ANOVA. Table 4.4 presents the results of ANOVA study and it is found that the fiber loading (P=39.41%) and sliding velocity (P=30.68%) shows the significant effect on the specific wear rate of the composites whereas other factors shows relatively less effect. The results of ANOVA study for coefficient of friction of composites is presented in Table 4.5. It is observed from the table that abrasive size (P=40.05 %), normal load (P=15.42 %) and fiber loading (P=13.01 %) shows significant effect on the coefficient of friction whereas sliding distance and sliding velocity shows relatively less effect.

Table 4.4 ANOVA for specific wear rate of needle-punched jute fiber epoxy composites

Source	DF	Seq SS	Adj SS	Adj MS	F	P (%)
Sliding velocity (cm/s)	4	1750.8	1750.8	437.7	2.48	30.68
Fiber loading (wt.%)	4	2249.4	2249.4	562.4	3.19	39.41
Normal load (N)	4	430.4	430.4	107.6	0.61	7.54
Sliding distance (m)	4	306.1	306.1	76.5	0.43	5.36
Abrasive size (µm)	4	264.8	264.8	66.2	0.38	4.64
Error	4	705.7	705.7	176.4		
Total	24	5707.3				

Table 4.5 ANOVA for coefficient of friction of needle-punched jute fiber epoxy composites

Source	DF	Seq SS	Adj SS	Adj MS	F	P (%)
Sliding velocity (cm/s)	4	33.473	33.473	8.368	0.93	10.45
Fiber loading (wt.%)	4	38.461	38.461	9.615	1.07	13.01
Normal load (N)	4	49.371	49.371	12.343	1.37	15.42
Sliding distance (m)	4	34.663	34.663	8.666	0.96	10.82
Abrasive size (µm)	4	128.238	128.238	32.060	3.56	40.05
Error	4	35.980	35.980	8.995		
Total	24	320.185				

4.1.2.6 Morphology of Worn Surfaces

In order to understand the details of abrasive wear mechanisms operating on composites, SEM study is done to investigate the morphology of the abraded surfaces. In three-body abrasive wear, the hard asperities are in the form of loose and dry abrasive particles and the material removal rate depends on a number of parameters which controls the extent of work required to facilitate failure in the material [194]. It should be noted that in three-body abrasion experiment, the abrasive particles which act as third body comes in contact with composite material mainly by any of the following three ways: (i) Firstly, freely falling particles gain energy, after coming in contact with the high speed rubber wheel, and strike the material, resulting in pits formation, or plastic deformation either of the matrix or fiber; (ii) Secondly, particles becomes embedded into the softer rubber wheel and slides over the surface of the material; (iii) Thirdly, particles roll between the rubber wheel and material, causing plastic deformation to the composite material [21].

Figure 4.12 and Figure 4.13 shows the SEM images of abraded surfaces of composites reinforced with 36 wt.% of jute fiber loading at sliding velocity of 48 cm/s and 144 cm/s respectively. From Figure 4.12 it is clearly observed that the broken fiber along with severe matrix removal at low sliding velocity. The deterioration of fiber matrix adhesion due to repeated motion is also observed. On the other hand, micro cracks on the matrix surface are observed at high sliding velocity (Figure 4.13). The micro cracking mechanism generally accepted to involve the formation of cracks on the surface due to localized stress without actually removing the surface material. The repeated application of these localized surface loads results in the propagation of these micro cracks until eventually material is detached from the surface as quite large particles [319]. Severe damage of composites at low sliding velocity (48 cm/s) is may be due to the fact that although the surface area of contact is same for both the sliding velocities whereas the duration of contact is more in case of low sliding velocity.

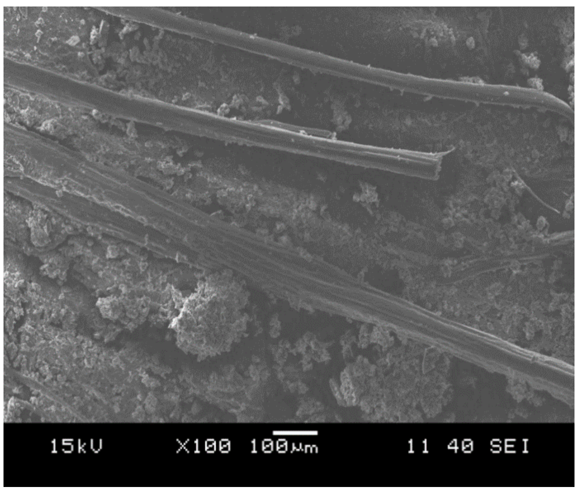

Figure 4.12 SEM micrograph of abraded composite at 36 wt.% of fiber loading subjected to sliding velocity of 48 cm/s

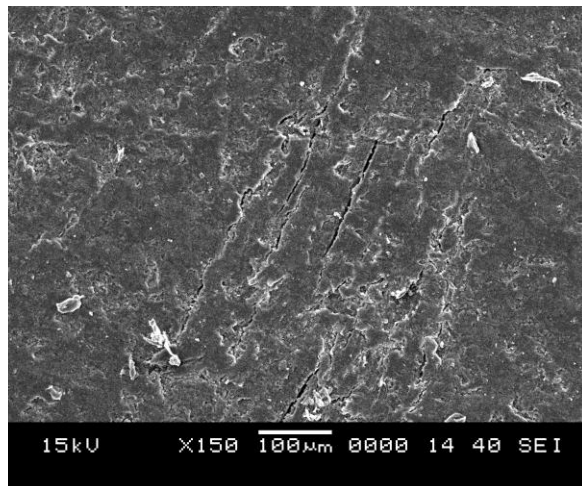

Figure 4.13 SEM micrograph of abraded composite at 36 wt.% of fiber loading subjected to sliding velocity of 144 cm/s

Figure 4.14 and Figure 4.15 shows the SEM images of abraded surfaces of composites reinforced with 12 wt.% of jute fiber at normal load of 10 N and 50 N, respectively. The worn surface shows the damage to matrix and formation of debris at low load as shown in Figure 4.14. Further increase in the load (50 N) shows that the surface damage is caused by combination of fracture at the ends of the fibers and severe damage of the matrix leading to fracture and debonding of the fibers and subsequent matrix removal as shown in Figure 4.15.

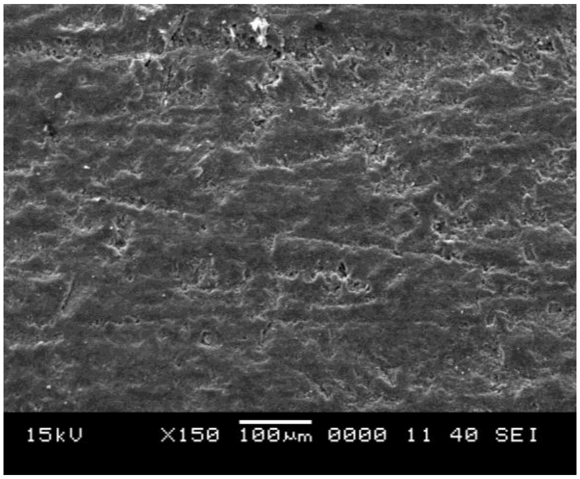

Figure 4.14 SEM micrograph of abraded composite at 12 wt.% of fiber loading subjected to normal load of 10 N

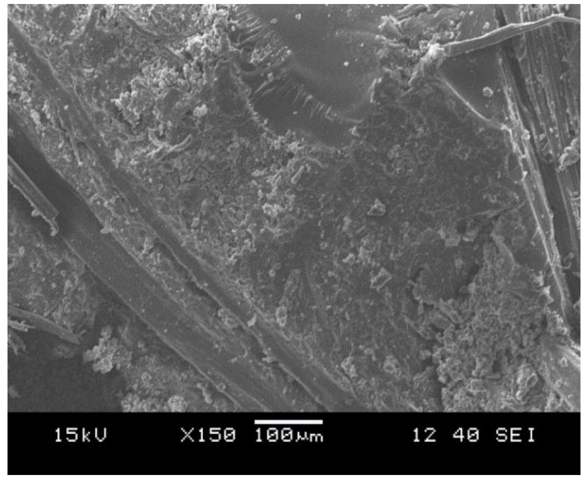

Figure 4.15 SEM micrograph of abraded composite at 12 wt.% of fiber loading subjected to normal load of 50 N

Figure 4.16 and 4.17 shows the SEM images of the worn surfaces of composites with 12 wt.% and 36 wt.% of fiber loadings, respectively. Figure 4.16 depicts the severe damage to the matrix and higher debris formation at low fiber loading (12 wt.%). The epoxy matrix is distorted and appears fragmented with visible cracks due to repeated movement of abrasive particles. However, composites reinforced with 36 wt.% of fiber shows less matrix phase wear out as shown in Figure 4.17.

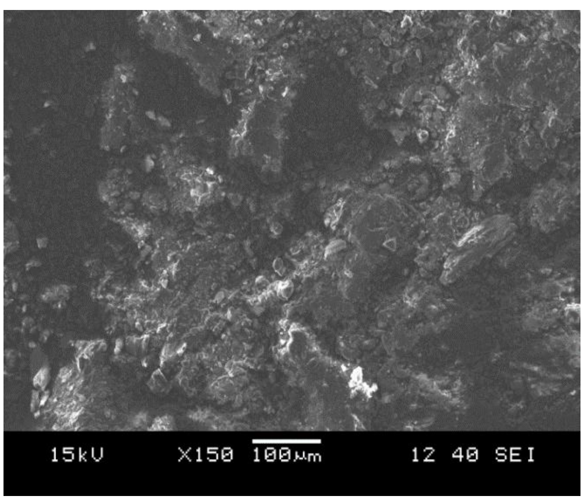

Figure 4.16 SEM micrograph of abraded composite at 12 wt.% of fiber loading

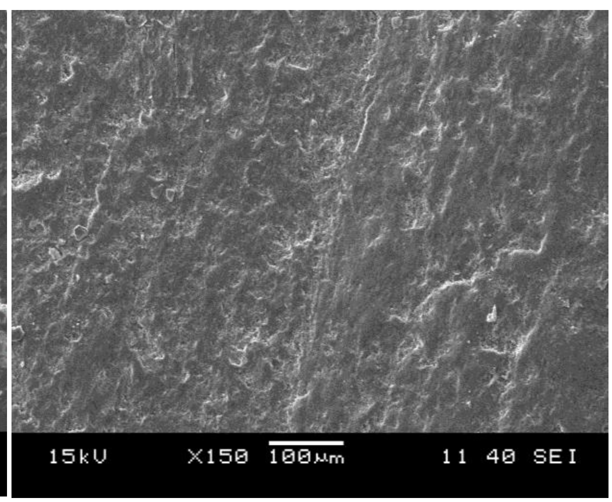

Figure 4.17 SEM micrograph of abraded composite at 36 wt.% of fiber loading

4.2 Part 2: Bidirectional Jute Fiber Reinforced Epoxy Composites

This part of the chapter presents the physical, mechanical and three-body abrasive wear behaviour of bidirectional jute fiber reinforced epoxy composites.

4.2.1 Physical and Mechanical Properties of Composites

4.2.1.1 Density

The theoretical density, experimental density and the corresponding void fraction of the bidirectional jute fiber reinforced epoxy composites is presented in Table 4.6. The void formation in the polymer composites can occur due to the air entrapment during the preparation of resin system and moisture absorption during the material processing or storage. A higher void content in the composites shows that resin has not thoroughly surrounded the fibers and resulting in weaker interfacial strength which in turn reduces strength and stiffness of composites, mutual abrasion of fiber leads to fiber fracture and damage and crack initiation and growth due to void coalescence [320]. From Table 4.6, it is found that pure epoxy has the minimum void content and with the addition of 12 wt. % fiber, the void content increases instantly to 5.312 %. However, with the further increase in the fiber content from 12 wt.% to 48 wt. % the void content of the specimens decreases.

Table 4.6 Comparison between experimental and theoretical density of bidirectional jute epoxy composites

Composites	Theoretical Density (ρ_{ct}) g/cm^3	Expt. Density (ρ_{ex}) g/cm^3	Void Fraction (%)
BJFE-1	1.150	1.147	0.261
BJFE-2	1.170	1.108	5.312
BJFE-3	1.184	1.125	5.022
BJFE-4	1.198	1.148	4.178
BJFE-5	1.213	1.164	4.050

4.2.1.2 Hardness

Figure 4.18 shows the effect of fiber loading on the hardness of composites. It is found that the hardness of the composite increases with the increase in the fiber loading. In general, the fiber increases the modulus of composites which in turn increases the hardness of fiber. This is because hardness is a function of relative fiber volume and modulus [321]. Hardness value of 40 HRB is obtained for pure epoxy specimen. However, the hardness value increases by 77% with the incorporation of 12 wt.% fiber in the matrix. The maximum hardness value of 85.5 HRB is obtained for composites reinforced with 48 wt.% of jute fiber.

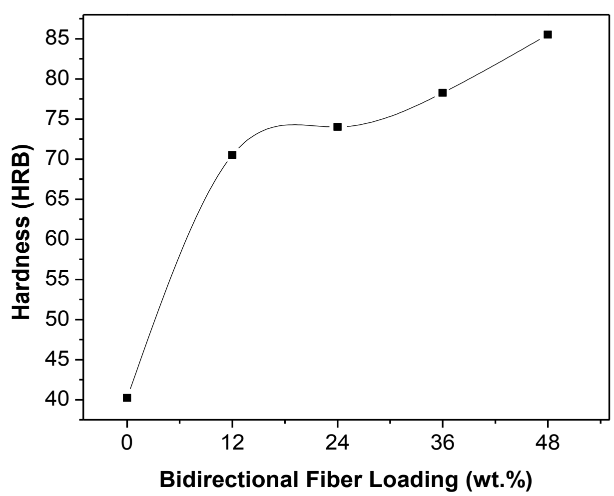

Figure 4.18 Effect of bidirectional jute fiber loading on hardness of composites

4.2.1.3 Tensile Properties

The variation in tensile strength and tensile modulus of composites with increase in fiber loading is shown in Figure 4.19. It is clearly visible that with the increase in fiber content in the epoxy matrix, the tensile strength and modulus also increases. There is a proper transmission and distribution of the applied stress by the epoxy resin resulting in higher strength. Similar trend has also been observed in case of aramid fabric/polyethersulfone composites by Bijwe [322]. The bidirectional jute fiber composites can bear higher load before failure compared to neat or unfilled epoxy. The tensile strength varies from 43 MPa to 110 MPa and tensile modulus from 0.15 GPa to 4.45 GPa with the fiber loading varies from 0 to 48 wt.%.

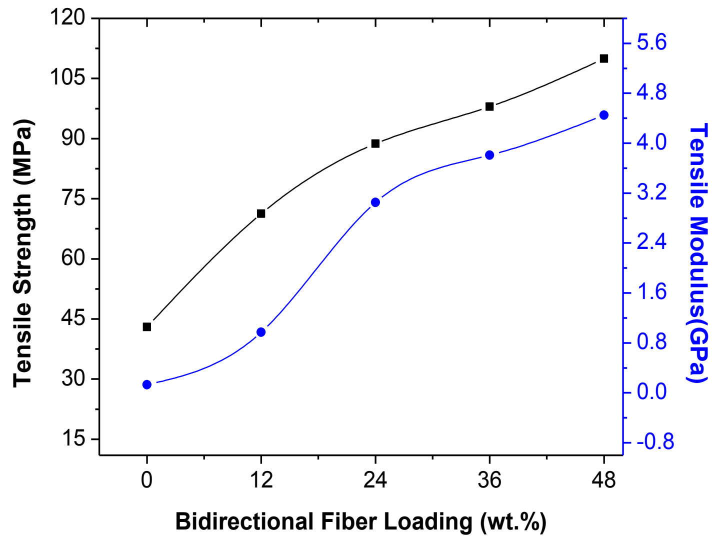

Figure 4.19 Effect of bidirectional jute fiber loading on tensile properties of composites

4.2.1.4 Flexural Properties

The result obtained from the three point bend test is shown in Figure 4.20. It is found that there is a reduction in the flexural properties of specimen with 12 wt.% fiber loading. Similar observations have also been made in case of wheat straw reinforced polyester composites by Dong and Davies [323]. According to their study, the reduction in the flexural properties of the composites is due to weak interfacial bonding and existence of voids. With further addition of fiber up to 48 wt. %, the flexural strength and modulus of the composites increases with the increase in the fiber loading. The maximum flexural strength and modulus of 55.8 MPa and 3.02 GPa, respectively is obtained at 48 wt.% of fiber loading. The flexural strength and modulus of 48 wt. % fiber loading are increased by 20 % and 37 % in comparison to the neat epoxy. The increase in flexural strength may be due to the inclusions of jute fiber as it enhances the load bearing capacity and ability to withstand the bending of the composites [152].

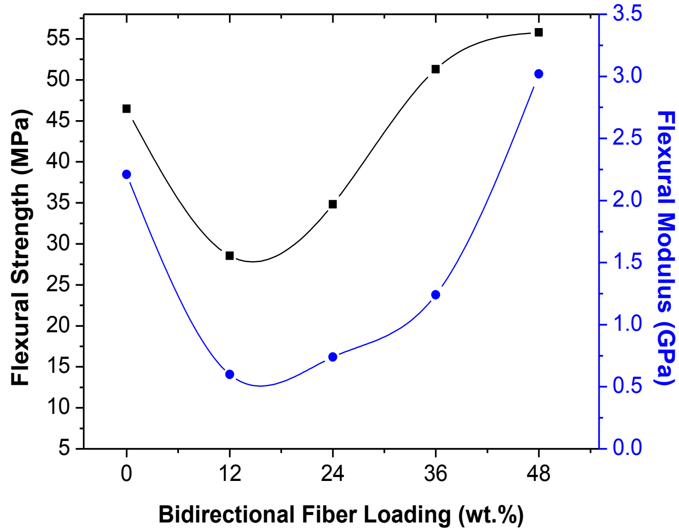

Figure 4.20 Effect of bidirectional jute fiber loading on flexural properties of composites

4.2.1.5 ILSS

ILSS is an important property for the laminated composites as the failure occurs more often at the inter-laminar region of such composites. The presence of porosity and voids has a detrimental effect on the matrix dominated properties like bending strength, compressive strength and ILSS [324, 325].

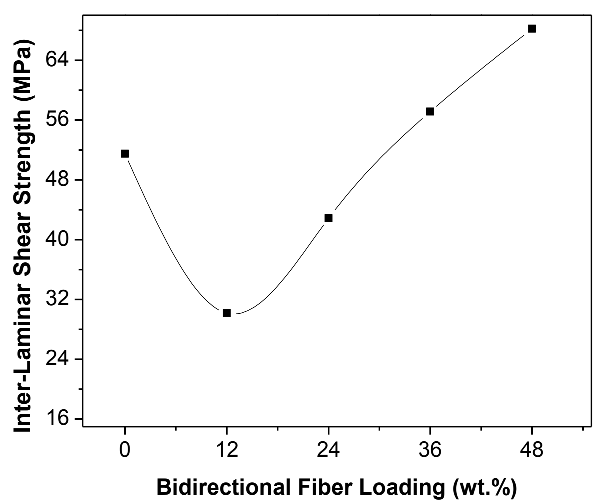

Figure 4.21 Effect of bidirectional jute fiber loading on ILSS of composites

As larger voids are situated at the ply interfaces, the larger effect is expected on the ILSS of laminated composites [324]. The effect of fiber loading on the ILSS of the composites is shown in Figure 4.21. The ILSS value decreases drastically for the composites with fiber loading from 0 wt.% to 12 wt.%, however it increases on further increase in fiber loading from 12 wt.% to 48 wt.%. The maximum ILSS of 66.5 MPa is obtained at 48 wt.% fiber loading.

4.2.1.6 Impact Strength

The impact strength of the bidirectional jute epoxy composites in shown in Figure 4.22. The energy absorbed by the composite due to impact load is 2.87, 3.69, 4.264, 4.59 times of pure epoxy matrix for composites with fiber content of 12 wt. %, 24 wt.%, 36 wt.% and 48 wt.%, respectively. The maximum impact strength of 4.875 J is obtained in case of composite with 48 wt.% of fiber loading. The increase in the impact strength with the increase in fiber loading may be due to the fact that more energy will have to be used up to break the coupling between the interlaced fiber bundles.

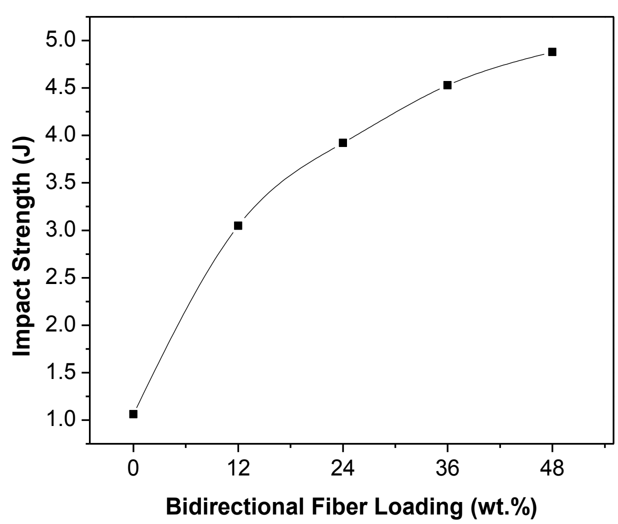

Figure 4.22 Effect of bidirectional jute fiber loading on impact strength of composites

Good adhesion between the fiber and matrix is also responsible for the good resistance to crack propagation during impact test. The increase in fiber content will increase the contact area between the fiber and matrix, if there is good impregnation of fibers in the resin. At higher fiber loading the impact transfer should be more efficient [326].

4.2.2 Three-Body Abrasive Wear Behaviour of Composites

4.2.2.1 Effect of Sliding Velocity and Normal Load on Specific Wear Rate of Composites

Figure 4.23 shows the variation of the specific wear rate of bidirectional jute fiber reinforced epoxy composites with different sliding velocity. It is observed from the figure that the specific wear rate of neat epoxy increases with the increase in sliding velocity. However, the effect of sliding velocity on jute fiber reinforced composites shows different trend.

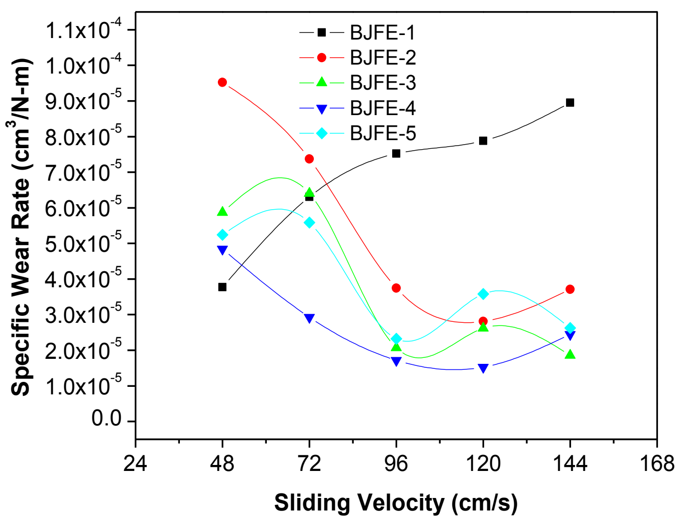

Figure 4.23 Effect of sliding velocity on specific wear rate of bidirectional jute epoxy composites (At constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 µm)

The decreasing trend is observed with increase in sliding velocity which may be due to the decrease in surface contact between sample and rubber wheel at higher sliding velocity as reported by past researchers [327]. It is also evident from the figure that composites with 36 wt.% fiber loading shows less specific wear rate as compared to other composite specimens under the present study.

The effect of the normal load on the specific wear rate of composites is shown in Figure 4.24. It is observed from the figure that neat epoxy shows higher specific wear rate in comparison to other specimens irrespective of normal load and the value increases with the increase in fiber loading. However, the effect of normal load on specific wear rate of jute fiber reinforced composites shows no regular trend. Similar observation is also reported by the past researchers [208, 194].

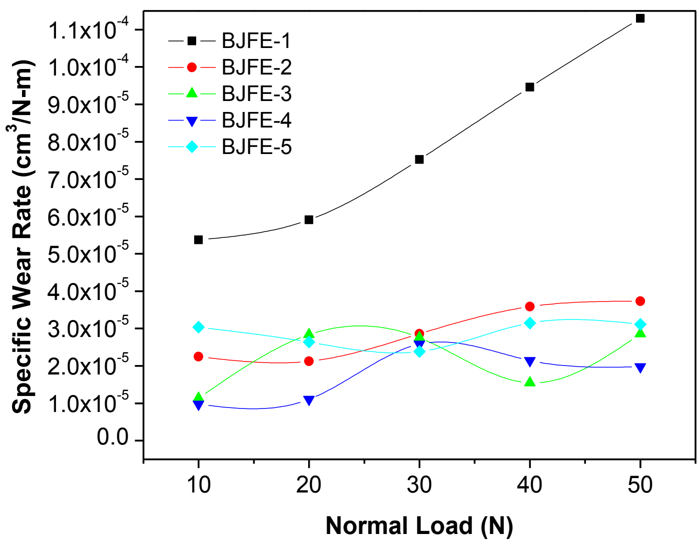

Figure 4.24 Effect of normal load on specific wear rate of the bidirectional jute epoxy composites (At constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm)

Composites with 36 wt.% of fiber loading shows better wear properties as compared to other specimens under study and the minimum specific wear rate is obtained at normal load of 20 N. The more wear rate of the composites observed at a particular load may be due to the fact that there are fewer fibers to support the matrix and due to this abrasive particle forms large depth grooves and sever cutting mode of the abrasive wear may be a dominant wear mechanism. The possible wear mechanism for less specific wear rate in the composite specimens may be ploughing or wedge formation [208]. The addition of the fiber on the epoxy resin leads to reduction in the losses due to wear. The resistance to wear is improved and hence less specific wear rates are obtained. According to Chand and Dwivedi [328], the abrasive wear resistance of the composites improved with the addition of fibers due to the cellular structure of natural fibers. The epoxy specimens exhibit brittle fracture and the fibers are flexible in nature and hence reduce the disintegration of matrix i.e. reduces the brittle fracture of the epoxy matrix and offers higher shearing resistance.

It is observed that the composites with 36 wt.% fiber loading exhibit minimum specific wear rate at different sliding velocity and normal load. This may be due to the good interfacial bonding between the fiber and matrix. The less fiber content in composites with 12 wt.% and 24 wt.% fiber loading results in poor abrasive wear resistance than composites with 36 wt.% fiber loading. The specific wear rate of composites with 48 wt.% fiber loading is higher than the composites with 36 wt.% fiber loading. The increase in specific wear rate at higher fiber loading may due to improper wetting of fibers which leads to weak interfacial bonding between the fiber and matrix. The poor interfacial adhesion at higher fiber content results in increased wear rate of lantana camara fiber reinforced composites is also reported by previous researchers [329].

4.2.2.2 Effect of Sliding Velocity and Normal Load on Coefficient of Friction of Composites

The variation of friction coefficient of composites with sliding velocity is shown in Figure 4.25. From the figure, it is clear that the coefficient of friction increases for sliding velocity up to 72 cm/s, however further increase in sliding velocity the value decreases irrespective of fiber loading. The effect of normal load on the coefficient of friction of composites is shown in Figure 4.26. It is evident from the figure that initially, coefficient of friction increased with normal load, however further increase in normal load, it decreases irrespective of fiber loading. Similar trend of decrease in coefficient of friction with increase in normal load is also observed by past researchers [316, 330]. The decrease in coefficient of friction may be due to the fact that under dry sliding condition increased applied normal load and sliding velocity increases the temperature at the interface. This increased temperature in turn causes thermal penetration to occur, which results in weakness in bond at the fiber-matrix interface. Consequently the fibers become loose and shear easily due to the axial thrust.

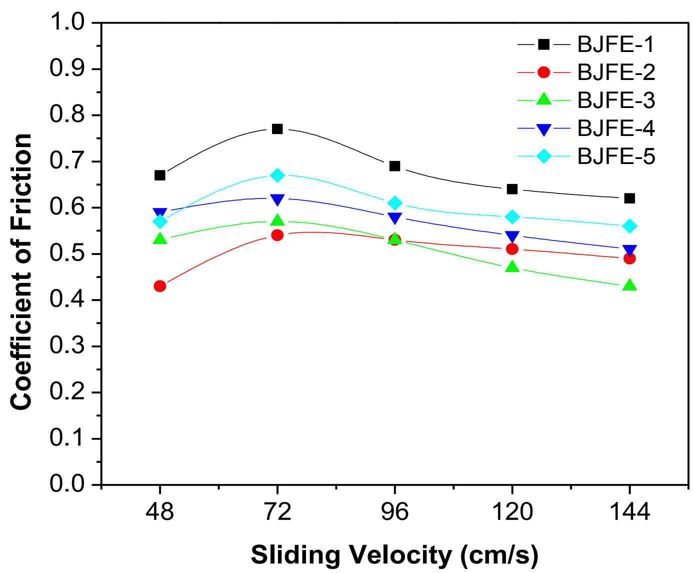

Figure 4.25 Effect of sliding velocity on coefficient of friction of bidirectional jute epoxy composites (At constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 μm)

The composites with 24 wt. % exhibits minimum coefficient of friction at higher sliding velocity as well as normal load. The minimum coefficient of friction at 20-30 wt.% fiber loading is also observed in case of carbon fiber reinforced composites

[331]. The rolling action of sample debris may reduce the friction coefficient of the composites [332, 333]. At higher fiber loading (i.e. more than 24 wt.% fiber loading) less amount of debris formation may cause higher coefficient of friction.

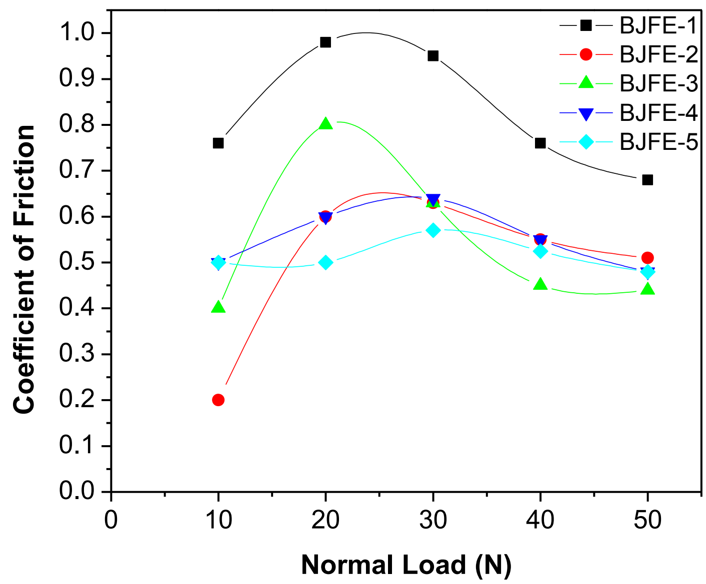

Figure 4.26 Effect of normal load on coefficient of friction of the bidirectional jute epoxy composites (At constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 µm)

4.2.2.3 Taguchi Experimental Analysis

In Table 4.7, column 8 and column 10 represents the *S/N* ratio of specific wear rate and coefficient of friction, respectively. The overall mean for the *S/N* ratio of specific wear rate and coefficient of friction are found to be 87.39 dB and 7.855 dB, respectively. Analysis of the result leads to the conclusion that factor combination of A_5, B_5, C_4, D_3 and E_2 gives minimum specific wear rate as shown in Figure 4.27**,** and A_5, B_2, C_1, D_4 and E_3 gives minimum coefficient of friction as shown in Figure 4.28.

Table 4.7 Experimental design using L_{25} orthogonal array

Expt. No.	Sliding velocity (cm/s)	Fiber loading (wt.%)	Normal load (N)	Sliding distance (m)	Abrasive size (µm)	W_s $(\frac{cm^3}{N-m})$	*S/N* Ratio (dB)	Coefficient of Friction	*S/N* Ratio (dB)
1	48	0	10	50	100	1.92E-04	74.33	0.800000	1.9382
2	48	12	20	60	200	1.04E-04	79.63	0.700000	3.0980
3	48	24	30	70	300	8.43E-05	81.49	0.466667	6.6199
4	48	36	40	80	400	1.07E-04	79.45	0.500000	6.0206
5	48	48	50	90	500	1.17E-04	78.66	0.520000	5.6799
6	72	0	20	70	400	8.30E-05	81.61	0.500000	6.0206
7	72	12	30	80	500	7.79E-05	82.17	0.200000	13.9794
8	72	24	40	90	100	4.22E-05	87.49	0.550000	5.1927
9	72	36	50	50	200	5.81E-05	84.72	0.400000	7.9588
10	72	48	10	60	300	4.47E-05	86.99	0.200000	13.9794
11	96	0	30	90	200	3.81E-05	88.38	0.400000	7.9588
12	96	12	40	50	300	4.91E-05	86.18	0.400000	7.9588
13	96	24	50	60	400	6.62E-05	83.58	0.440000	7.1309
14	96	36	10	70	500	2.18E-05	93.24	0.400000	7.9588
15	96	48	20	80	100	3.17E-05	89.97	0.750000	2.4988
16	120	0	40	60	500	5.45E-05	85.27	0.525000	5.5968
17	120	12	50	70	100	2.20E-05	93.17	0.540000	5.3521
18	120	24	10	80	200	2.09E-05	93.59	0.300000	10.4576
19	120	36	20	90	300	2.79E-05	91.09	0.250000	12.0412
20	120	48	30	50	400	3.73E-05	88.56	0.333333	9.5424
21	144	0	50	80	300	6.78E-06	103.37	0.180000	14.8945
22	144	12	10	90	400	3.65E-05	88.77	0.200000	13.9794
23	144	24	20	50	500	3.11E-05	90.14	0.350000	9.1186
24	144	36	30	60	100	4.61E-05	86.72	0.566667	4.9334
25	144	48	40	70	200	4.87E-06	106.24	0.475000	6.4661

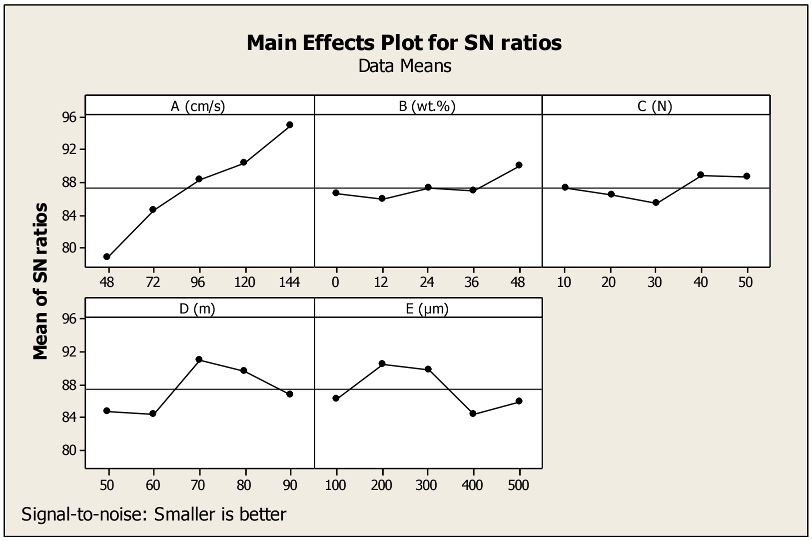

Figure 4.27 Effect of control factors on specific wear rate (for bidirectional jute epoxy composites)

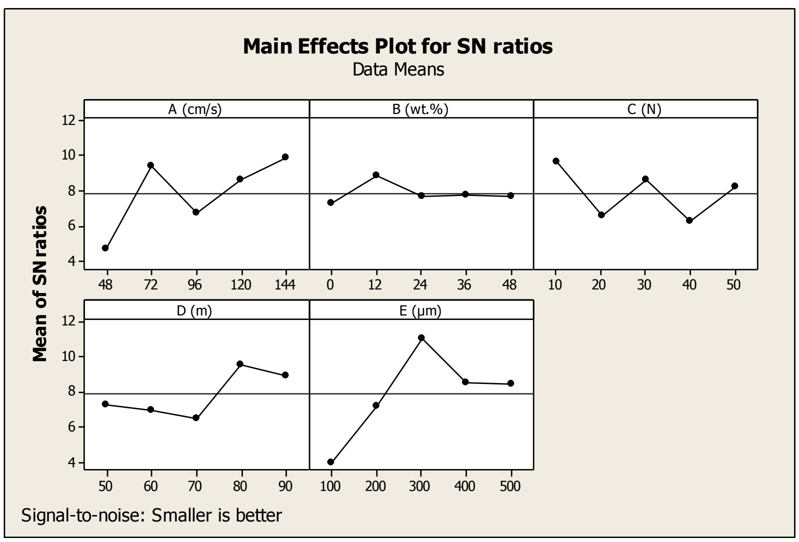

Figure 4.28 Effect of control factors on coefficient of friction (for bidirectional jute epoxy composites)

4.2.2.4 Confirmation Experiment

The confirmation experiment is performed by considering the previously determined optimal combination of the control factors and its level. After determining the optimum settings and predicting the *S/N* ratio under these conditions, a new experiment is designed and conducted with the optimum levels of the parameter. In the present study, the optimal combination of parameters and its levels for the minimum specific wear rate (i.e. $A_5B_5C_4D_3E_2$) coincidently matches with one of the experiments in the orthogonal array, hence confirmatory test is not required. In case of coefficient of friction the optimal setting i.e. $A_5B_2C_1D_4E_3$ did not correspond to any of the test in the orthogonal array. Thus, prediction and confirmation experiment is required for minimum coefficient of friction at optimal setting. The predicted *S/N* ratio equation for minimum coefficient of friction of bidirectional jute epoxy composites at optimal setting is given by:

$$\eta_{COF} = \eta_{A_5} + \eta_{B_2} + \eta_{C_1} + \eta_{D_4} + \eta_{E_3} - 4\eta_m \tag{4.3}$$

where, $\eta_{A_5}, \eta_{B_2}, \eta_{C_1}, \eta_{D_4}$ and η_{E_3} represents the mean of *S/N* ratio at the optimal factor levels A_5, B_2, C_1, D_4 and E_3, respectively. η_m is the total mean of *S/N* ratio. The predicted *S/N* ratio values of coefficient of friction at optimal settings is 17.6636 dB. The confirmation test of minimum coefficient of friction at the optimal condition was performed in abrasion tester. Table 4.8 shows the results of confirmation experiment. An error of 3.72 % for the *S/N* ratio of coefficient of friction is observed.

Table 4.8 Results of confirmation experiment

	Optimal Condition		
	Predicted	Experiment	Error (%)
Coefficient of Friction			
Level	$A_5B_2C_1D_4E_3$	$A_5B_2C_1D_4E_3$	
S/N ratio (dB)	17.6636	17.0065	3.72

4.2.2.5 ANOVA and the Effect of Factors

In order to find out the statistical significance of various factors on wear rate, ANOVA is performed on experimental data. Table 4.9 and Table 4.10 show the

ANOVA results for the specific wear rate and coefficient of friction, respectively. From Table 4.9, it can be observed that the specific wear rate of composites is significantly influenced by sliding velocity (P = 60.86 %), sliding distance (P = 14.15 %) and abrasive size (P = 11.3 %). However, the fiber loading (P = 4.03 %) and normal load (P = 3.43 %) have relatively less effect on specific wear rate of composites.

Table 4.9 ANOVA for specific wear rate of bidirectional jute fiber epoxy composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P (%)**
Sliding velocity (cm/s)	4	756.72	756.72	189.18	9.77	60.86
Fiber loading (wt.%)	4	50.08	50.08	12.52	0.65	4.03
Normal load (N)	4	42.71	42.71	10.68	0.55	3.43
Sliding distance (m)	4	175.91	175.91	43.98	2.27	14.15
Abrasive size (µm)	4	140.51	140.51	35.13	1.81	11.3
Error	4	77.46	77.46	19.37		
Total	24	1243.39				

Table 4.10 ANOVA for coefficient of friction of bidirectional jute fiber epoxy composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P (%)**
Sliding velocity (cm/s)	4	92.910	92.910	23.227	11.10	29.07
Fiber loading (wt.%)	4	7.216	7.216	1.804	0.86	2.26
Normal load (N)	4	41.143	41.143	10.286	4.91	12.87
Sliding distance (m)	4	35.972	35.972	8.993	4.30	11.25
Abrasive size (µm)	4	134.004	134.004	33.501	16.00	41.93
Error	4	8.373	8.373	2.093		
Total	24	319.618				

Similarly, from Table 4.10 it can be observed that the factors like abrasive size (P = 41.93 %), sliding velocity (P = 29.07 %) and normal load (P = 12.87 %) have larger effect on the coefficient of friction of the composites. The remaining factors i.e. sliding distance (P = 11.25 %) and fiber loading (P = 2.26 %) have relatively less effect.

4.2.2.6 Morphology of Worn Surfaces

To understand the material removal mechanism, the worn surfaces of composite specimens were examined using SEM. In general, abrasive wear occurs by three different mechanisms i.e. micro-cutting, micro-ploughing and micro-cracking [25, 208]. Figures 4.29 and 4.30 shows the SEM images of composites reinforced with 36 wt.% of jute fiber at sliding velocity of 48 cm/s and 144 cm/s, respectively. Wear debris, micro-cracks and micro ploughing are clearly observed over the surface of the abraded specimen at low sliding velocity. On the other hand at higher sliding velocity, micro-cuts and wear debris are visible over the surface of the composite. Wear tracks are clearly visible on both the samples i.e. sample abraded at low and high velocity. On comparing, larger depth grooves and more damage of the sample is observed at low velocity abrasion.

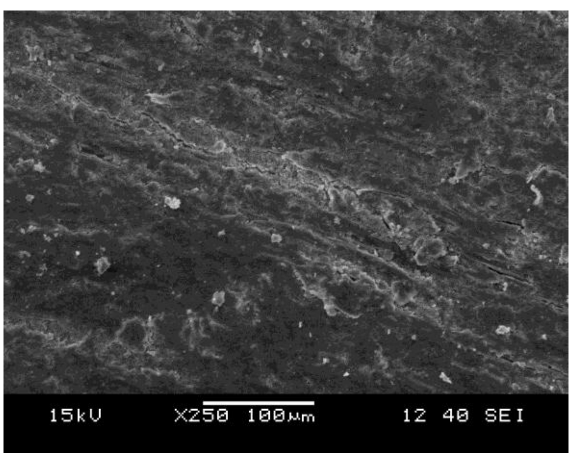

Figure 4.29 SEM micrograph of abraded composite at 36 wt.% of fiber loading subjected to sliding velocity of 48 cm/s

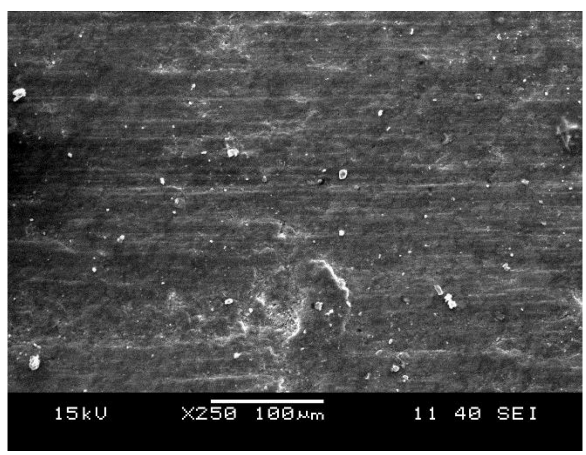

Figure 4.30 SEM micrograph of abraded composite at 36 wt.% of fiber loading subjected to sliding velocity of 144 cm/s

Figures 4.31 and 4.32 shows the SEM images of composites with 12 wt.% of fiber loading subjected to normal of 10 N and 50 N, respectively. The surface morphology shows the presence of micro-cracks and formation of debris at low normal load (Figure 4.31). The increase in the normal load (50N) exhibits that the surface damage is caused by fracture of the fiber and damage of the matrix which results in debonding of the fibers as shown in Figure 4.32. Micro-cuts are also visible over the abraded surface.

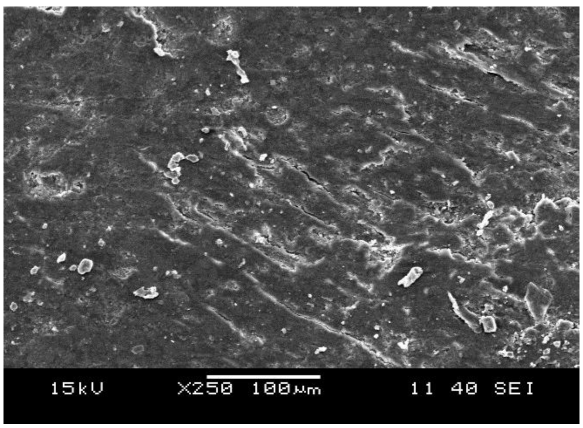

Figure 4.31 SEM micrograph of abraded composite at 12 wt.% of fiber loading subjected to normal load of 10 N

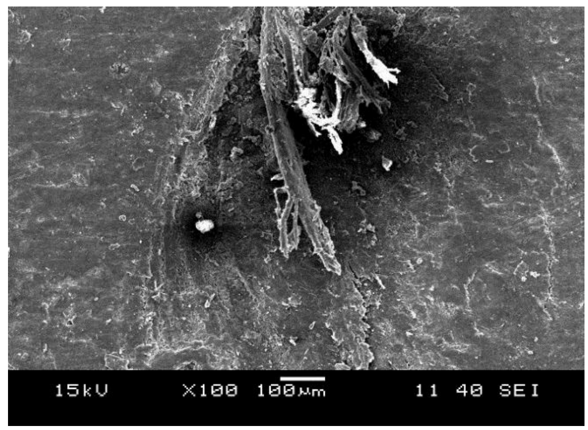

Figure 4.32 SEM micrograph of abraded composite at 12 wt.% of fiber loading subjected to normal load of 50 N

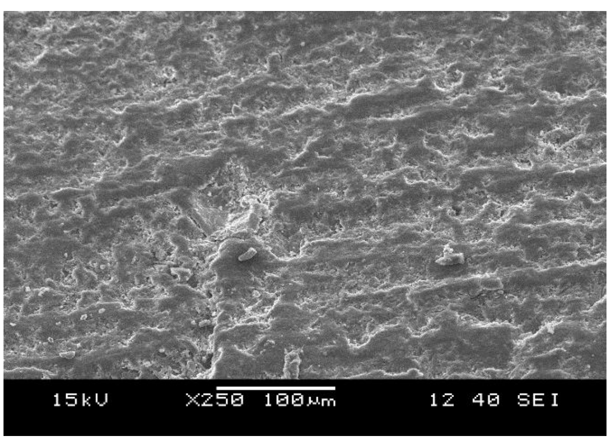

Figure 4.33 SEM micrograph of abraded composite at 12 wt.% of fiber loading

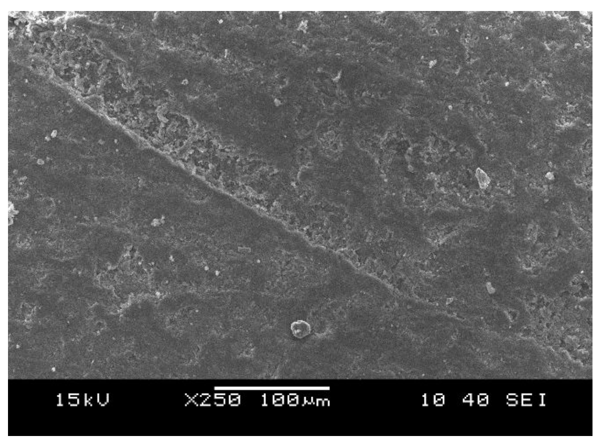

Figure 4.34 SEM micrograph of abraded composite at 36 wt.% of fiber loading

Figure 4.33 and Figure 4.34 shows the surface morphology of composites with 12 wt.% and 36 wt.% of jute fiber loading, respectively. Figure 4.33 indicates severe damage to the matrix and higher debris formation at low fiber loading (12 wt.%). The movement of the abrasive particles over the surface of the sample results in the distortion of the matrix. However, composites with 36 wt.% of fiber loading exhibit less matrix distortion as seen in Figure 4.34. Wear debris and tracks are also visible on the surface of both the samples.

4.3 Part 3: Short Jute Fiber Reinforced Epoxy Composites

This part of the chapter presents the physical, mechanical and three-body abrasive wear behaviour of short jute fiber reinforced epoxy composites.

4.3.1 Physical and Mechanical Properties of Composites

4.3.1.1 Density

In general, voids are air bubbles entrapped in matrix during fabrication which have a pervasive effect on composite properties even at low volume percentage [334]. The stiffness, ultimate mechanical properties, especially inter-laminar shear strength and resistance to environmental degradation may suffer due to presence of voids [334, 335]. The theoretical and experimental density along with the void fraction of short jute epoxy composites is reported in Table 4.11. The theoretical density of composite increases as the weight percentage of fiber increases. Theoretical density of composites ranges from 1.15 g/cm^3 to 1.277 g/cm^3. The experimental density of the composites varies from 1.147 to 1.181 g/cm^3. The minimum void fraction is observed in case of neat epoxy. It is observed that the percentage of void content increases with the increase in fiber content. Narkis et al. [336] found that the void fraction of the short glass fiber reinforced thermoplastic composite increases as the fiber loading of composite increases.

Table 4.11 Comparison between experimental and theoretical density of short jute epoxy composites

Composites	Theoretical Density (ρ_{ct}) g/cm^3	Expt. Density (ρ_{ex}) g/cm^3	Void Fraction (%)
SJFE-1	1.150	1.147	0.261
SJFE-2	1.179	1.158	1.781
SJFE-3	1.21	1.168	3.47
SJFE-4	1.242	1.177	5.233
SJFE-5	1.277	1.181	7.52

4.3.1.2 Hardness

Effect of fiber loading on hardness of composites is shown in Figure 4.35. It is observed from the figure that the hardness of short jute epoxy composites increases with increase in fiber loading. Hardness is a function of the relative fiber volume and modulus [337]. The composite with 0 wt.% fiber loading i.e. neat epoxy has the minimum hardness value of 40.23 HRB whereas composites reinforced with 48 wt.% of fiber content exhibit maximum hardness value of 70.75 HRB. Similar trend of increase in hardness with increase in fiber content is also observed by researchers [338].

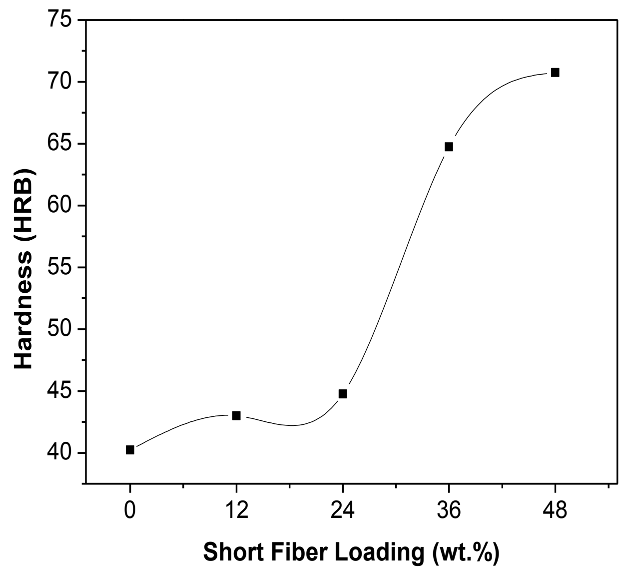

Figure 4.35 Effect of short jute fiber loading on hardness of composites

4.3.1.3 Tensile Properties

The effect of fiber loading on the tensile properties of short jute epoxy composites is shown in Figure 4.36. It is found that the tensile strength of composites decreases with the increase in weight percentage of fiber. The decrease in tensile strength of short jute epoxy composite may be due to poor bonding between jute fiber and epoxy resin. The inclusion of fiber into the matrix leads to the poor distribution of fibers because of strong inter fiber hydrogen bonding which keeps fibers together, as a result the resin does not wet the gathered fibers properly [339]. Observations show that the tensile modulus of short jute fiber composite increases significantly with the increase in fiber content. Similar observations are obtained in case of short banana/sisal hybrid fiber reinforced polyester composites [340]. Increase in tensile modulus indicates that the stiffness of jute fiber composite increases with the increase in fiber loading.

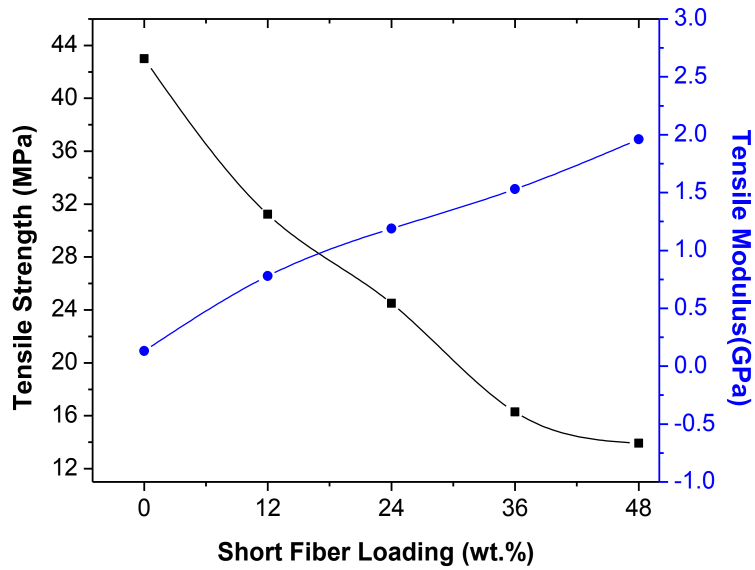

Figure 4.36 Effect of short jute fiber loading on tensile properties of composites

4.3.1.4 Flexural Properties

The effect of fiber loading on the flexural properties of short jute epoxy composites is shown in Figure 4.37. A gradual drop in the flexural properties of the composites is observed. A similar observation in case of short random oil palm fiber reinforced epoxy composites is also reported by Yusoff et al. [341]. According to their study, the decrease in flexural properties is due to the alignment of fibers, interaction between fiber– matrix and void arise during the processing of the composites plate.

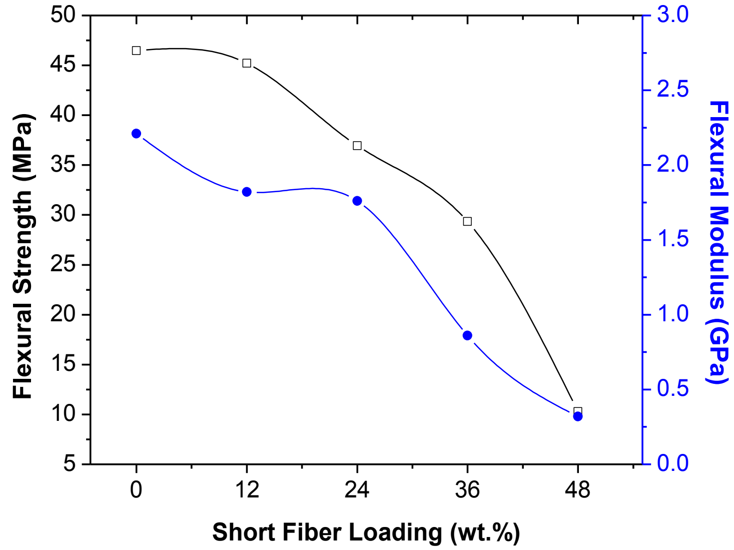

Figure 4.37 Effect of short jute fiber loading on flexural properties of composites

4.3.1.5 Impact Strength

The impact properties of the material give an idea about its capability to absorb and dissipate energies under the impact or shock loading. The impact strength of short jute epoxy composites increases with the increase in fiber loading as shown in Figure 4.38.

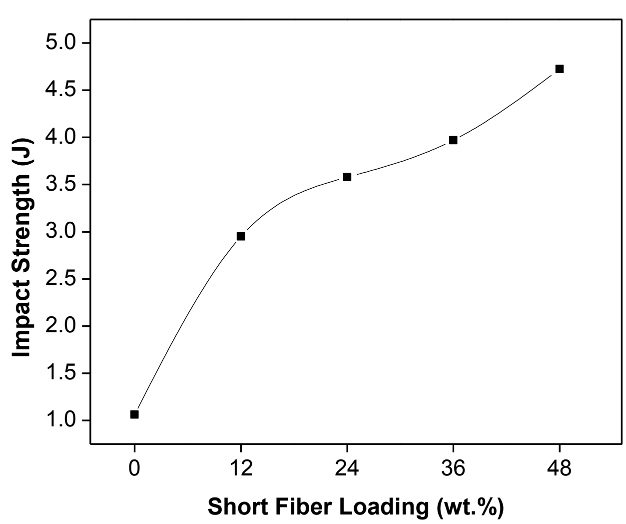

Figure 4.38 Effect of short jute fiber loading on impact strength of composites

The impact strength of short jute epoxy composites varies from 1.062 to 4.724 J as the fiber loading of the composites increases. The impact strength of composites with 48 wt.% fiber loading is 4.45 times more than neat epoxy. On the application of the impact force, fibers pull out and fiber breakage occurs at lower fiber loading of the polymer composites. At high fiber loading, the fiber crowding leads to easy debonding which in turn increases the impact resistance [340].

4.3.2 Three-Body Abrasive Wear Behaviour of Composites

4.3.2.1 Effect of Sliding Velocity and Normal Load on the Specific Wear Rate of Composites

Figure 4.39 shows the effect of sliding velocity on the specific wear rate of the composites. It is observed that the specific wear rate of the composites with 12, 24, 36 and 48 wt.% of fiber loading decreases as the sliding velocity increases. This decrease may be due to the reduction in the contact duration of the specimens with rubber wheel as the sliding velocity increases.

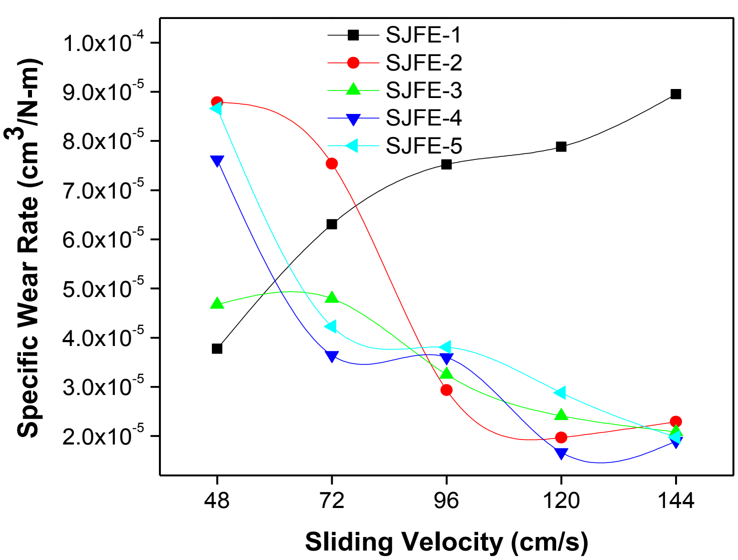

Figure 4.39 Effect of sliding velocity on specific wear rate of short jute epoxy composites (At constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 µm)

The short jute fiber reinforced composites exhibit higher specific wear rate than neat epoxy at low sliding velocity. During low velocity condition, the fibers get exposed to the abrasive due to the removal of resin layer from the surface. The frictional heat generated at the contacting region along with the normal load and shear forces exerted by the abrasives over worn surfaces makes bonding weaker at interfacial regions between the fibers and matrix. Thus, a rapid increase in the specific wear rate is observed due to severe fiber removal when matrix failed to support the fibers. The higher specific wear rate of polymer composites than polymer at low sliding velocity has been reported by the researchers in the past [315]. On the other hand, the epoxy shows higher specific wear rate at high sliding velocity, as observed from the Figure 4.39. At higher sliding velocity, the polymer will fracture and this results in formation of large wear particles and high wear. The minimum specific wear rate is observed at sliding velocity of 120 cm/s for the composite with 36 wt.% fiber loading.

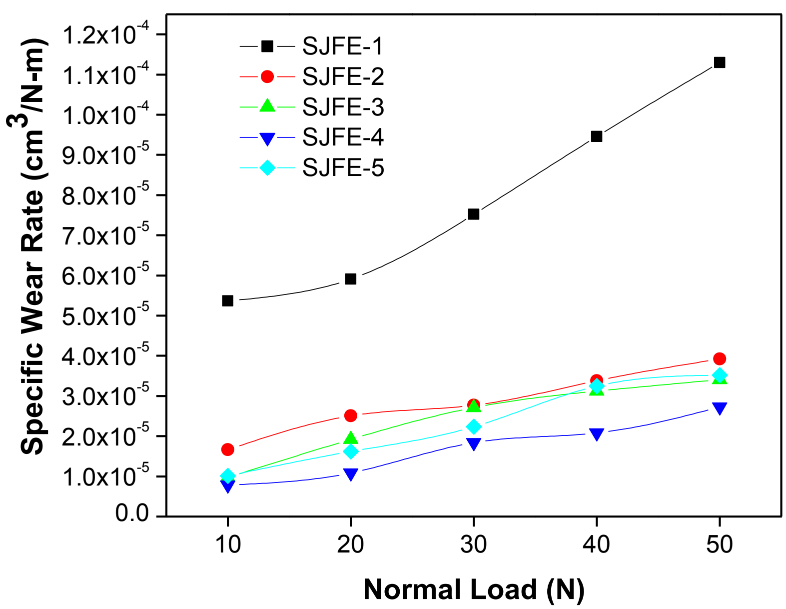

Figure 4.40 Effect of normal load on specific wear rate of the short jute epoxy composites (At constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm)

The effect of normal load on specific wear rate of short fiber reinforced epoxy composites by keeping other parameters constant (At constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 µm) is shown in Figure 4.40. It is observed from the figure that the specific wear rate increases with increase in normal load. This is due to energy barrier created at the junction of the surface. At low normal loads, the energy produced by abrasive particles is not enough to break the surface energy barrier, i.e., difficult to penetrate into the surface due to the resistance offered by the composite samples in the form of surface energy. In contrast at higher loads, particles gain energy from the high speed rubber wheel and hence high wear loss is observed.

From the study it is found that the composite with 36 wt.% fiber loading exhibits minimum specific wear rate compared to the other composites. This indicates a proper stress transfer and distribution by the matrix to the fibers which in turn increases the wear resistance of the composites. When the fiber content increases beyond optimum value (i.e. 36 wt.%), short jute fiber gets agglomerated, thus reducing the interaction between the fiber and matrix. This causes debonding of fiber from the epoxy matrix. Thus, at higher fiber loading, the interfacial adhesion between the matrix and fiber is not adequate enough to resist the sliding force resulting in higher wear [193].

4.3.2.2 Effect of Sliding Velocity and Normal Load on Coefficient of Friction of Composites

The coefficient of friction of neat epoxy and short jute fiber reinforced epoxy composites as a function of sliding velocity is shown in Figure 4.41. The neat epoxy exhibits higher coefficient of friction than other composites at different velocities. It has also been observed that with the increase in sliding velocity the coefficient of friction of the samples increases up to a certain value but further increase in sliding velocity the coefficient of friction of the samples decreases. The complex relationships between sliding velocity and friction are most often seen. Such relationships may be associated with viscoelastic behaviour of polymeric materials.

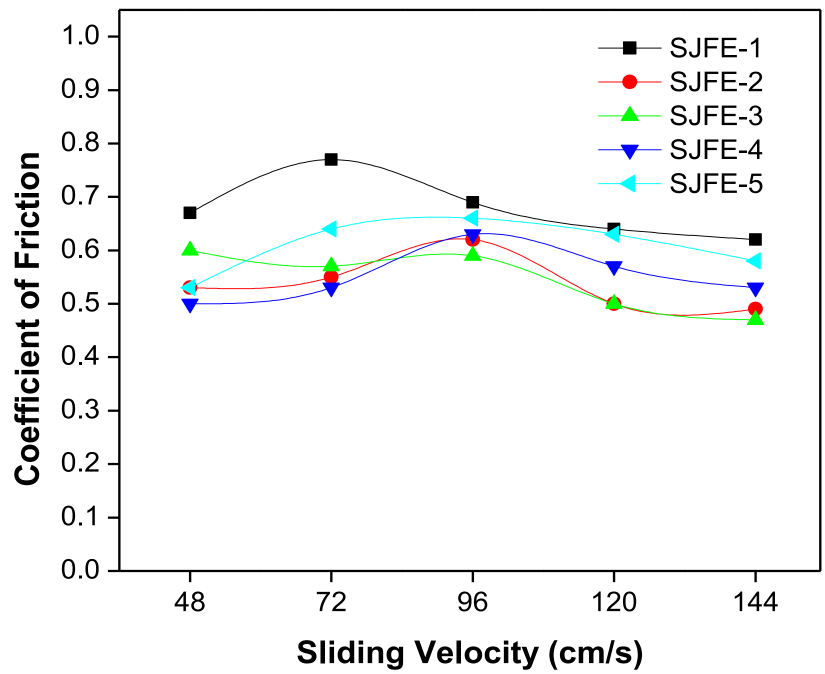

Figure 4.41 Effect of sliding velocity on coefficient of friction of short jute epoxy composites (At constant normal load: 30 N, sliding distance: 50 m and abrasive size: 300 µm)

The variation of coefficient of friction of the samples with the increase in normal load is shown in Figure 4.42. The coefficient of friction of pure epoxy and short jute fiber composites shows a similar trend, as they exhibit in case of sliding velocity. The increase in coefficient of friction of the pure epoxy as well as its composites with the increase in normal load may be due to increased surface contact, whereas the decrease in coefficient of friction may be due to the occurrence of thermal softening process during wear [342].

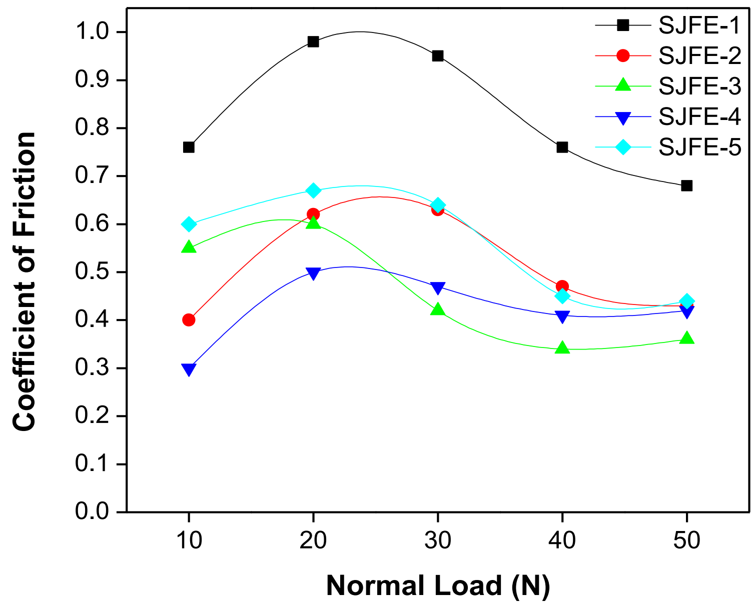

Figure 4.42 Effect of normal load on coefficient of friction of the short jute epoxy composites (At constant sliding velocity: 96 cm/s, sliding distance: 50 m and abrasive size: 300 μm)

4.3.2.3 Taguchi Experimental Analysis

The results of experiments carried out according to the Taguchi experimental design on short jute reinforced epoxy composites are presented in Table 4.12. This table provides the experimental specific wear rate and coefficient of friction along with the *S/N* ratio for each distinct test run. The overall mean of the *S/N* ratios are found to be 90.53 dB and 7.497 dB for specific wear rate and coefficient of friction of composites, respectively. Figures 4.43 and 4.44 illustrate the effect of control factors on specific wear rate and coefficient of friction of composites, respectively. Analysis of the results leads to the conclusion that factor combination of A_5 (sliding velocity: 144 cm/s), B_4 (Fiber content: 36 wt.%), C_5 (Normal load: 50 N), D_5 (Sliding distance: 90 m) and E_3 (Abrasive size: 300 μm) gives minimum specific wear rate (Figure 4.43) and the factor combination of A_5 (Sliding velocity:144 cm/s), B_3 (Fiber content: 24 wt.%), C_1(Normal load: 10 N), D_5 (Sliding distance: 90

m) and E_3 (Abrasive size: 300µm) gives minimum coefficient of friction (Figure 4.44).

Table 4.12 Experimental design using L_{25} orthogonal array

Expt. No.	Sliding velocity (cm/s)	Fiber loading (wt.%)	Normal load (N)	Sliding distance (m)	Abrasive size (µm)	W_s $(\frac{cm^3}{N-m})$	S/N Ratio (dB)	Coefficient of Friction	S/N Ratio (dB)
1	48	0	10	50	100	1.92E-04	74.334	0.800000	1.9382
2	48	12	20	60	200	8.41E-05	81.504	0.600000	4.4370
3	48	24	30	70	300	6.51E-05	83.728	0.466667	6.6199
4	48	36	40	80	400	5.78E-05	84.761	0.450000	6.9357
5	48	48	50	90	500	1.81E-05	94.846	0.420000	7.5350
6	72	0	20	70	400	8.30E-05	81.618	0.500000	6.0206
7	72	12	30	80	500	6.22E-05	84.124	0.533330	5.4601
8	72	24	40	90	100	5.67E-05	84.928	0.575000	4.8066
9	72	36	50	50	200	4.8 E-05	86.375	0.700000	3.0980
10	72	48	10	60	300	2.01E-05	93.936	0.300000	10.4576
11	96	0	30	90	200	3.81E-05	88.382	0.400000	7.9588
12	96	12	40	50	300	4.12E-05	87.702	0.400000	7.9588
13	96	24	50	60	400	6.04E-05	84.379	0.360000	8.8739
14	96	36	10	70	500	1.99E-05	94.023	0.400000	7.9588
15	96	48	20	80	100	2.84E-05	90.934	0.700000	3.0980
16	120	0	40	60	500	5.45E-05	85.272	0.525000	5.5968
17	120	12	50	70	100	1.71E-05	95.340	0.480000	6.3752
18	120	24	10	80	200	3.92E-05	88.134	0.260000	11.7005
19	120	36	20	90	300	4.03E-06	107.894	0.220000	13.1515
20	120	48	30	50	400	2.14E-05	93.392	0.466667	6.6199
21	144	0	50	80	300	6.78E-06	103.375	0.180000	14.8945
22	144	12	10	90	400	3.37E-05	89.447	0.200000	13.9794
23	144	24	20	50	500	3.03E-05	90.371	0.300000	10.4576
24	144	36	30	60	100	3.78E-06	108.450	0.533333	5.4600
25	144	48	40	70	200	5.03E-06	105.969	0.500000	6.0206

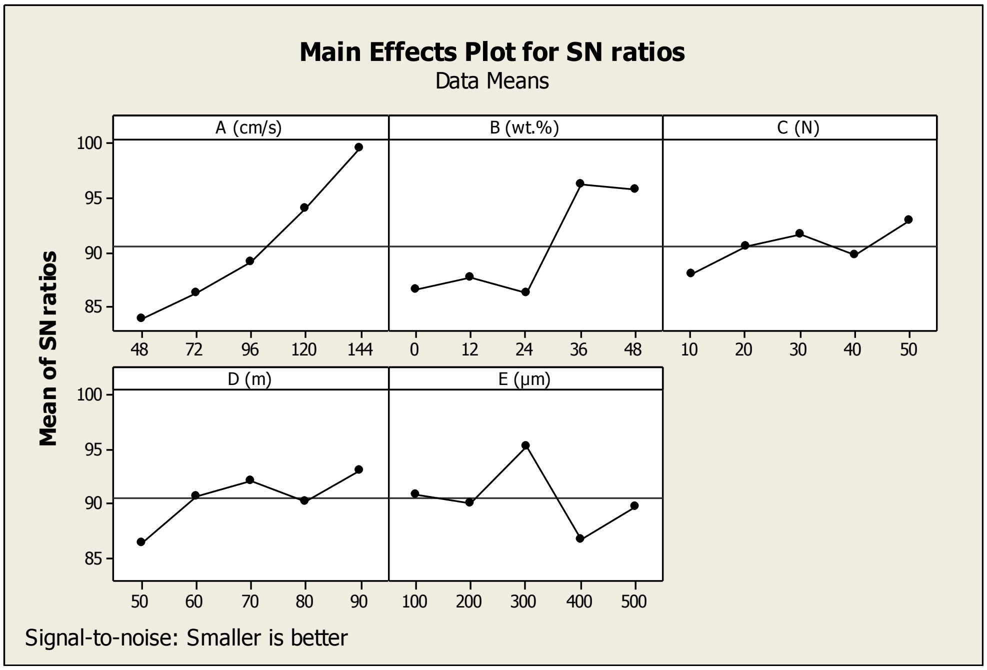

Figure 4.43 Effect of control factors on specific wear rate (for short jute epoxy composites)

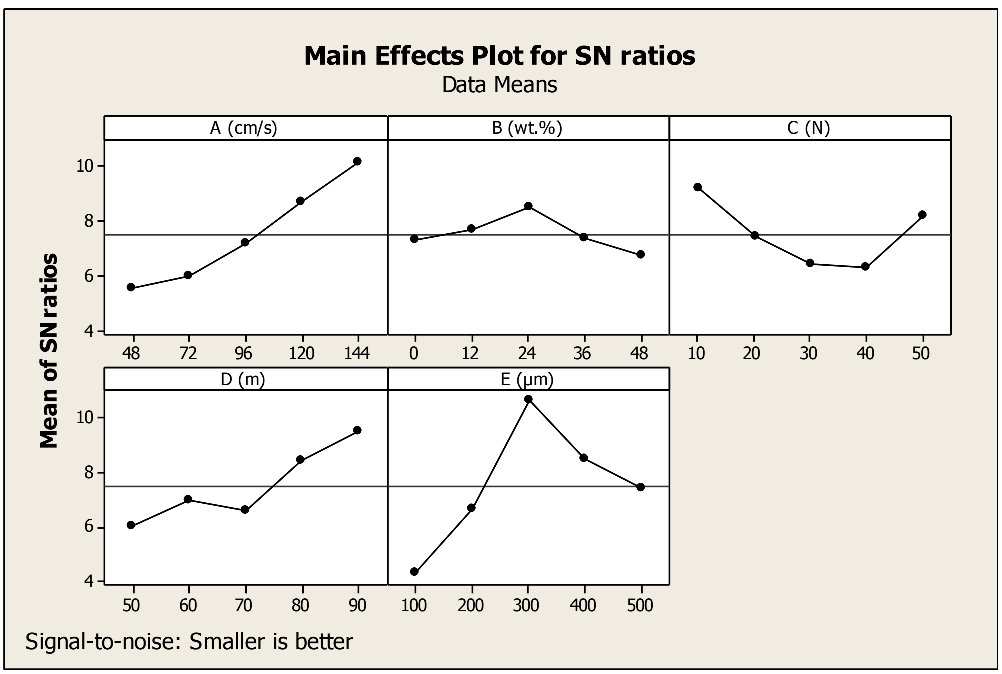

Figure 4.44 Effect of control factors on coefficient of friction (for short jute epoxy composites)

4.3.2.4 Confirmation Experiment

The confirmation test at optimal parameter setting is required to validate the predicted results. The present study required confirmation test as the optimal parameter setting for the specific wear rate (i.e. $A_5B_4C_5D_5E_3$) and coefficient of friction (i.e. $A_5B_3C_1D_5$ E_3) did not correspond to any experiment of the orthogonal array. The predicted *S/N* ratio equation for minimum specific wear rate and coefficient of friction at optimal setting are given by:

$$\eta_{Ws} = \eta_{A_5} + \eta_{B_4} + \eta_{C_5} + \eta_{D_5} + \eta_{E_3} - 4\eta_m \tag{4.4}$$

$$\eta_{COF} = \eta_{A_5} + \eta_{B_3} + \eta_{C_1} + \eta_{D_5} + \eta_{E_3} - 4\eta_m \tag{4.5}$$

where, η_{A_5}, η_{B_4}, η_{B_3}, η_{C_5}, η_{C_1}, η_{D_5}, and η_{E_3} are the mean *S/N* ratio of control factors at optimal level.

The predicted *S/N* ratio values of specific wear rate and coefficient of friction at optimal settings are 114.998 and 17.977 dB, respectively. For the confirmatory test, new experiments are designed and conducted with the optimum levels of the parameter using a dry sand rubber/wheel abrasion tester. Table 4.13 shows the results of confirmation experiment. An error of 4.91 % and 2.89 % for the *S/N* ratio of specific wear rate and coefficient of friction are observed, respectively

Table 4.13 Results of confirmation experiment

	Optimal Condition		
	Predicted	Experiment	Error (%)
Specific Wear Rate			
Level	$A_5B_4C_5D_5E_3$	$A_5B_4C_5D_5E_3$	
S/N ratio (dB)	114.998	109.352	4.91
Coefficient of Friction			
Level	$A_5B_3C_1D_5$ E_3	$A_5B_3C_1D_5$ E_3	
S/N ratio (dB)	17.977	17.457	2.89

4.3.2.5 ANOVA and the Effect of Factors

Table 4.14 and Table 4.15 show the results of the ANOVA for the specific wear rate and coefficient of friction of composites, respectively. The last column of the table indicates percentage contribution of the control factors. From Table 4.14, it can be observed that sliding velocity (P=44.63 %), fiber loading (P=28.97 %), and abrasive size (P=10.818 %) have considerable influence on specific wear rate.

Table 4.14 ANOVA results for specific wear rate of short jute fiber epoxy composites.

Source	DF	Seq SS	Adj SS	Adj MS	F	P (%)
Sliding velocity (cm/s)	4	793.24	793.24	198.31	10.21	44.63
Fiber loading (wt.%)	4	514.90	514.90	128.73	6.63	28.97
Normal load (N)	4	69.00	69.00	17.25	0.89	3.882
Sliding distance (m)	4	130.26	130.26	32.57	1.68	7.329
Abrasive size (μm)	4	192.28	192.28	48.07	2.48	10.818
Error	4	77.67	77.67	19.42		
Total	24	1777.35				

Table 4.15 ANOVA results for coefficient of friction of short jute fiber epoxy composites.

Source	DF	Seq SS	Adj SS	Adj MS	F	P (%)
Sliding velocity (cm/s)	4	74.917	74.917	18.729	6.80	27.54
Fiber loading (wt.%)	4	8.258	8.258	2.064	0.75	3.035
Normal load (N)	4	30.171	30.171	7.543	2.74	11.09
Sliding distance (m)	4	40.461	40.461	10.115	3.67	14.87
Abrasive size (μm)	4	107.209	107.209	26.802	9.72	39.41
Error	4	11.025	11.025	2.756		
Total	24	272.041				

Similarly, from Table 4.15, it can be observed that abrasive size (P=39.41 %), sliding velocity (P=27.54 %), sliding distance (P=18.47 %) and normal load (P=11.09 %) have significant influence on coefficient of friction. However, the remaining factors have relatively less effect.

4.3.2.6 Morphology of Worn Surfaces

Figures 4.45 and 4.46 shows the consequences of abrasion on composites reinforced with 36 wt.% of jute fiber at sliding velocity of 48 cm/s and 144 cm/s, respectively. Figure 4.45 depicts the formation of pits and scratch-like grooves over the abraded surface of composite. Scratch and pits are also observed over the surface of sample which is subjected to higher sliding velocity (Figure 4.46). But the surface appeared smoother for sample at high sliding velocity than sample at low sliding velocity which seems much rougher. This indicates that wear is larger for the sample at low sliding velocity. Wear debris is also observed in both the figures (Figures 4.45 and 4.46).

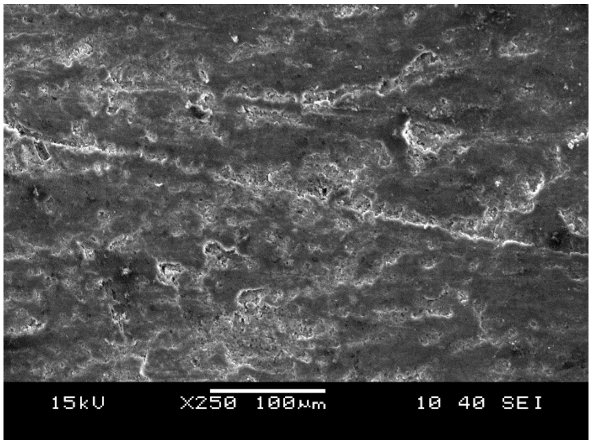

Figure 4.45 SEM micrograph of abraded composite at 36 wt.% of fiber loading subjected to sliding velocity of 48 cm/s

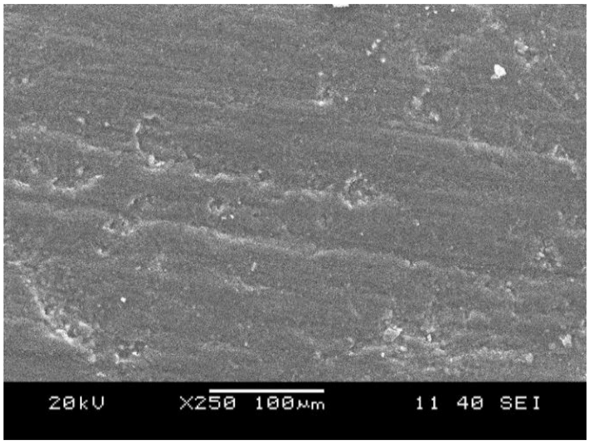

Figure 4.46 SEM micrograph of abraded composite at 36 wt.% of fiber loading subjected to sliding velocity of 144 cm/s

Figures 4.47 and 4.48 depicts the SEM images of composites with 12 wt.% of fiber loading subjected to normal load of 10 N and 50 N, respectively. Wear debris, micro-crack and wear scars are clearly observed over the surface of the abraded specimen at low normal load (Figure 4.47). On the other hand at higher load, micro-cracks, broken fibers, wear debris and voids created due to the removal of fibers from the surfaces are clearly visible (Figure 4.48). During wear process, the exposed fibers due to matrix failure gets fractured and worn away from the surface which creates voids.

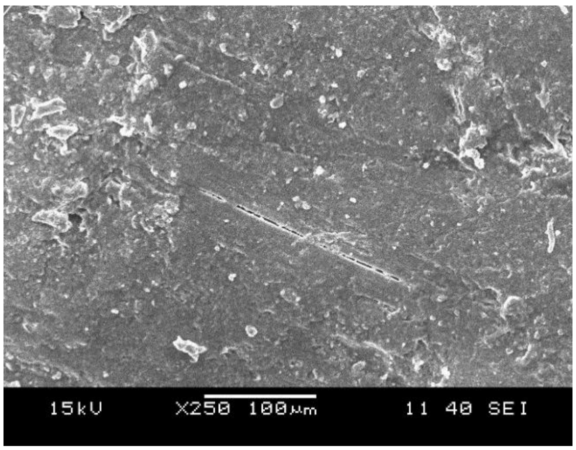

Figure 4.47 SEM micrograph of abraded composite at 12 wt.% of fiber loading subjected to normal load of 10 N

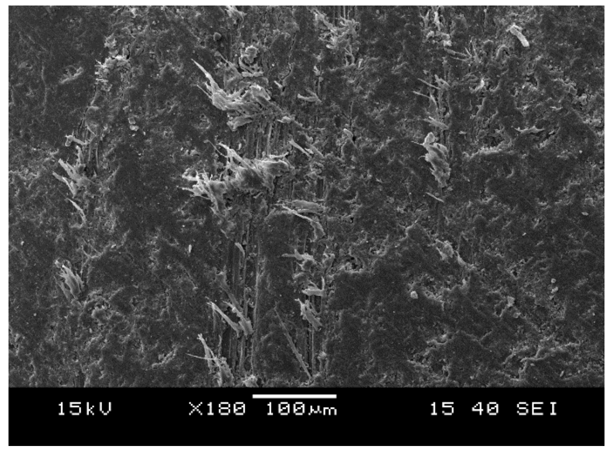

Figure 4.48 SEM micrograph of abraded composite at 12 wt.% of fiber loading subjected to normal load of 50 N

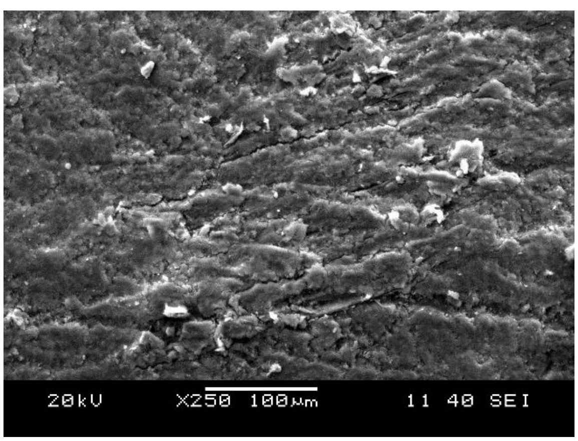

Figure 4.49 SEM micrograph of abraded composite at 12 wt.% of fiber loading

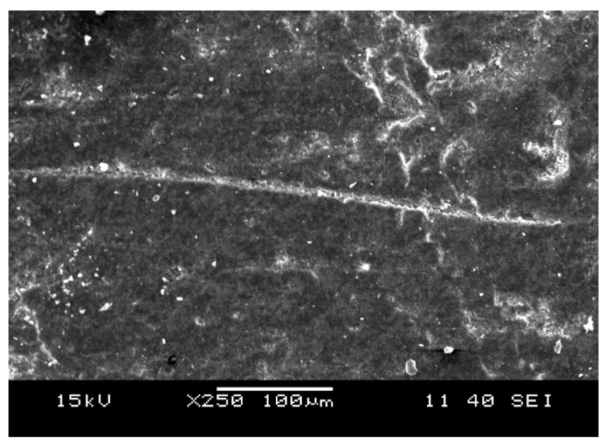

Figure 4.50 SEM micrograph of abraded composite at 36 wt.% of fiber loading

Figure 4.49 and Figure 4.50 shows the micrograph of composites with 12 wt.% and 36 wt.% jute fiber, respectively. Figure 4.49 shows, severe matrix damage, micro-cracks and deeper groove at low fiber content (12 wt.%). Lesser matrix distortion is observed in case of composites with 36 wt.% of fiber loading as seen in Figure 4.50. Fine wear debris and scratches are detected on the surface of abraded sample of composite with higher fiber loading.

Chapter Summary

This chapter has provided:

1. The results of the physical, mechanical and three-body abrasive wear behaviour of composites reinforced with three different forms of jute fiber.
2. The effect of fiber loading on the physical and mechanical behaviour of composites.
3. The effects of sliding velocity and normal load on the three-body abrasive wear response of the composites.
4. The results of experimental analysis using Taguchi method.
5. The morphology of the abraded surfaces of composites using SEM.

The next chapter refers to the ranking of materials using AHP-TOPSIS methodology to obtain the best alternatives based on physical, mechanical and abrasive attributes.

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CHAPTER 5

RANKING OF THE MATERIALS

In the present study, a MCDM technique called AHP-TOPSIS is applied to select the best alternatives from the fabricated composite materials based on the physical, mechanical and abrasive wear properties. The AHP-TOPSIS method is divided into two steps. In the first step, AHP method is used to obtain the weights for the different properties. In the second step, TOPSIS method is used for ranking of the composite materials.

5.1 Ranking Method

Stage A: AHP method (for weighting criteria)

A pair-wise comparison table or matrix is prepared based on the goal and criteria for the material selection. The intensity of the properties is decided on the basis of pair-wise comparison scale, as shown in Table 3.5. Table 5.1 represents the pair-wise comparison of the criteria. Last row of the table shows the total column sum for each column. The standardized matrix is presented in Table 5.2. The calculated row sum and weights of criteria are given in Table 5.3. The priority vector is determined and reported in Table 5.4. The calculated eigenvector and principal eigenvalue are presented in Table 5.5. The obtained value of principal eigenvalue is 10.4316. Consistency Index (*CI*) is determined using the Equation 3.10. The number of criteria (*n*) for the current study is 9. The obtained CI value is 0.1789. The calculated consistency ratio (*CR*) value is 0.1226, which is well under the allowable range.

Stage B: TOPSIS method (for ranking of alternatives)

Based on different criterion, a decision matrix is prepared as shown in Table 5.6. The normalized decision matrix is made using Equation 3.13 and is presented in Table 5.7. The weights of each creation obtained from the AHP method is utilized in the formation of the weighted normalized decision matrix using Equation 3.14 and is shown in Table 5.8. From the weighted decision matrix the positive ideal and negative ideal solution of each criterion are determined Equations 3.15 and 3.16 and is presented in Table 5.9. The separation of each alternative from the positive ideal and negative ideal solution is calculated using Equations 3.17 and 3.18 and given in Table 5.10. The value of separation (from the positive ideal and negative ideal) of each alternative is used to find the relative closeness of each alternative. The relative closeness of the alternatives is calculated using Equation 3.19 and is presented in Table 5.10. Finally, the ranking of the alternatives is shown in Table 5.11. The ranking of the alternatives is done on the basis of relative closeness value. From the Table 5.11 it is clear that NJFE-4 (needle-punched nonwoven jute epoxy composites with 36 wt.% fiber loading) is the best alternative among others with the highest relative closeness value of 0.9389. Similarly, it is observed that NJFE-5 (needle-punched nonwoven jute epoxy composites with 48 wt.% fiber loading) is observed as the second best alternative with the relative closeness value of 0.8537. It is also evident from the table that the neat epoxy is the worst alternative with the relative closeness value of 0.1659 for the wear resistant application.

Table 5.1 Pair-wise comparison of criteria

	Density	Ws (n)	Ws (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength
Density	1	1/9	1/9	1/4	1/7	1/3	1/5	1/2	1/5
Ws (n)	9	1	1/2	5	3	4	3	4	3
Ws (v)	9	2	1	5	3	4	3	4	3
Hardness	4	1/5	1/5	1	1/6	5	1/4	5	1/4
Tensile Strength	7	1/3	1/3	6	1	5	3	5	3
Tensile Modulus	3	1/4	1/4	1/5	1/5	1	1/4	3	1/4
Flexural Strength	5	1/3	1/3	4	1/3	4	1	5	1/4
Flexural Modulus	2	1/4	1/4	1/5	1/5	1/3	1/5	1	1/5
Impact Strength	5	1/3	1/3	4	1/3	4	4	5	1
Total Sum ($\sum_i C_{ij}$)	45	4.8111	3.3111	25.65	8.3762	27.6667	14.9	32.5	11.15

Table 5.2 Standardized matrix

	Density	Ws (n)	Ws (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength
Density	0.0222	0.0231	0.0336	0.0097	0.0171	0.0120	0.0134	0.0154	0.0179
Ws (n)	0.2000	0.2079	0.1510	0.1949	0.3582	0.1446	0.2013	0.1231	0.2691
Ws (v)	0.2000	0.4157	0.3020	0.1949	0.3582	0.1446	0.2013	0.1231	0.2691
Hardness	0.0889	0.0416	0.0604	0.0390	0.0199	0.1807	0.0168	0.1538	0.0224
Tensile Strength	0.1556	0.0693	0.1007	0.2339	0.1194	0.1807	0.2013	0.1538	0.2691
Tensile Modulus	0.0667	0.0520	0.0755	0.0078	0.0239	0.0361	0.0168	0.0923	0.0224
Flexural Strength	0.1111	0.0693	0.1007	0.1559	0.0398	0.1446	0.0671	0.1538	0.0224
Flexural Modulus	0.0444	0.0520	0.0755	0.0078	0.0239	0.0120	0.0134	0.0308	0.0179
Impact Strength	0.1111	0.0693	0.1007	0.1559	0.0398	0.1446	0.2685	0.1538	0.0897

Table 5.3 Calculated row sum and weights

	Density	Ws (n)	Ws (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength	R_i	W_i
Density	0.0222	0.0231	0.0336	0.0097	0.0171	0.0120	0.0134	0.0154	0.0179	0.1645	0.0183
Ws (n)	0.2000	0.2079	0.1510	0.1949	0.3582	0.1446	0.2013	0.1231	0.2691	1.8500	0.2056
Ws (v)	0.2000	0.4157	0.3020	0.1949	0.3582	0.1446	0.2013	0.1231	0.2691	2.2089	0.2454
Hardness	0.0889	0.0416	0.0604	0.0390	0.0199	0.1807	0.0168	0.1538	0.0224	0.6235	0.0693
Tensile Strength	0.1556	0.0693	0.1007	0.2339	0.1194	0.1807	0.2013	0.1538	0.2691	1.4838	0.1649
Tensile Modulus	0.0667	0.0520	0.0755	0.0078	0.0239	0.0361	0.0168	0.0923	0.0224	0.3935	0.0437
Flexural Strength	0.1111	0.0693	0.1007	0.1559	0.0398	0.1446	0.0671	0.1538	0.0224	0.8648	0.0961
Flexural Modulus	0.0444	0.0520	0.0755	0.0078	0.0239	0.0120	0.0134	0.0308	0.0179	0.2778	0.0309
Impact Strength	0.1111	0.0693	0.1007	0.1559	0.0398	0.1446	0.2685	0.1538	0.0897	1.1334	0.1259

Table 5.4 Calculated priority vector

	Density	Ws (n)	Ws (v)	Hardness	Tensile Strength	Tensile modulus	Flexural Strength	Flexural Modulus	Impact Strength	W_i	Priority Vector
Density	1	1/9	1/9	1/4	1/7	1/3	1/5	1/2	1/5	0.0183	0.1837
Ws (n)	9	1	1/2	5	3	4	3	4	3	0.2056	2.2981
Ws (v)	9	2	1	5	3	4	3	4	3	0.2454	2.6264
Hardness	4	1/5	1/5	1	1/6	5	1/4	5	1/4	0.0693	0.6885
Tensile Strength	7	1/3	1/3	6	1	5	3	5	3	0.1649	1.8977
Tensile modulus	3	1/4	1/4	1/5	1/5	1	1/4	3	1/4	0.0437	0.4062
Flexural Strength	5	1/3	1/3	4	1/3	4	1	5	1/4	0.0961	1.0305
Flexural Modulus	2	1/4	1/4	1/5	1/5	1/3	1/5	1	1/5	0.0309	0.2860
Impact Strength	5	1/3	1/3	4	1/3	4	4	5	1	0.1259	1.4132
Total Sum ($\sum_i C_{ij}$)	45	4.8111	3.3111	25.65	8.3762	27.6667	14.9	32.5	11.15	1.0000	

Table 5.5 Calculated eigenvector and principal eigenvalue

	Density	Ws (n)	Ws (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength	W_i	Priority Vector	λ_i
Density	1	1/9	1/9	1/4	1/7	1/3	1/5	1/2	1/5	0.0183	0.1837	10.0503
Ws (n)	9	1	½	5	3	4	3	4	3	0.2056	2.2981	11.1799
Ws (v)	9	2	1	5	3	4	3	4	3	0.2454	2.6264	10.7011
Hardness	4	1/5	1/5	1	1/6	5	1/4	5	1/4	0.0693	0.6885	9.9374
Tensile Strength	7	1/3	1/3	6	1	5	3	5	3	0.1649	1.8977	11.5109
Tensile Modulus	3	1/4	1/4	1/5	1/5	1	1/4	3	1/4	0.0437	0.4062	9.2916
Flexural Strength	5	1/3	1/3	4	1/3	4	1	5	1/4	0.0961	1.0305	10.7251
Flexural Modulus	2	1/4	1/4	1/5	1/5	1/3	1/5	1	1/5	0.0309	0.2860	9.2657
Impact Strength	5	1/3	1/3	4	1/3	4	4	5	1	0.1259	1.4132	11.2223
Total Sum ($\sum_i C_{ij}$)	45	4.8111	3.3111	25.65	8.3762	27.6667	14.9	32.5	11.15	1.0000		
λ_{max}												10.4316

Table 5.6 Decision matrix

Composite Material	Density (g/cm^3)	W_s (n) (cm^3/Nm)	W_s (v) (cm^3/Nm)	Hardness (HRB)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Impact Strength (J)
Epoxy	1.147	7.9120E-05	6.8864E-05	40.23	43	0.13	46.46	2.21	1.062
NJFE-2	1.12	2.1783E-05	4.2675E-05	60	105.19	5.21	25.36	1.15	3.812
NJFE-3	1.124	3.4906E-05	5.7346E-05	68	109.11	5.68	35.46	1.48	4.185
NJFE-4	1.123	1.2178E-05	2.6636E-05	72	131.82	5.68	46.67	1.94	4.684
NJFE-5	1.126	1.9802E-05	3.9214E-05	82	139.23	6	50.6	2.23	4.939
BJFE-2	1.108	2.9098E-05	5.4325E-05	70.5	71.28	0.97	28.55	0.6	3.048
BJFE-3	1.125	2.2275E-05	3.7624E-05	74	88.74	3.05	34.83	0.74	3.92
BJFE-4	1.148	1.7584E-05	2.6924E-05	78.25	97.98	3.81	51.3	1.24	4.528
BJFE-5	1.164	2.8637E-05	3.8711E-05	85.5	109.96	4.45	55.8	3.02	4.88
SJFE-2	1.158	2.8484E-05	4.7047E-05	43	31.23	0.78	45.21	1.82	2.95
SJFE-3	1.168	2.4283E-05	3.4424E-05	44.75	24.51	1.19	36.94	1.76	3.577
SJFE-4	1.177	1.7047E-05	3.6858E-05	64.75	16.29	1.53	29.34	0.86	3.969
SJFE-5	1.181	2.3277E-05	4.3102E-05	70.75	13.92	1.96	10.27	0.32	4.724

Table 5.7 Normalized decision matrix

Composite Material	Density	W_s (n)	W_s (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength
Epoxy	0.2781	0.6887	0.4329	0.1661	0.1372	0.0097	0.3210	0.3686	0.0736
NJFE-2	0.2715	0.1896	0.2683	0.2477	0.3356	0.3878	0.1752	0.1918	0.2643
NJFE-3	0.2725	0.3038	0.3605	0.2807	0.3481	0.4228	0.2450	0.2468	0.2901
NJFE-4	0.2723	0.1060	0.1674	0.2972	0.4205	0.4228	0.3225	0.3236	0.3247
NJFE-5	0.2730	0.1724	0.2465	0.3385	0.4442	0.4466	0.3496	0.3719	0.3424
BJFE-2	0.2686	0.2533	0.3415	0.2910	0.2274	0.0722	0.1973	0.1001	0.2113
BJFE-3	0.2727	0.1939	0.2365	0.3055	0.2831	0.2270	0.2407	0.1234	0.2718
BJFE-4	0.2783	0.1531	0.1693	0.3230	0.3126	0.2836	0.3545	0.2068	0.3139
BJFE-5	0.2822	0.2493	0.2434	0.3530	0.3508	0.3313	0.3856	0.5037	0.3383
SJFE-2	0.2807	0.2479	0.2958	0.1775	0.0996	0.0581	0.3124	0.3035	0.2045
SJFE-3	0.2832	0.2114	0.2164	0.1847	0.0782	0.0886	0.2552	0.2935	0.2480
SJFE-4	0.2853	0.1484	0.2317	0.2673	0.0520	0.1139	0.2027	0.1434	0.2752
SJFE-5	0.2863	0.2026	0.2710	0.2921	0.0444	0.1459	0.0710	0.0534	0.3275

Table5.8 Weighted normalized decision matrix

Composite Material	Density	W_s (n)	W_s (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength
Epoxy	0.0051	0.1416	0.1062	0.0115	0.0226	0.0004	0.0308	0.0114	0.0093
NJFE-2	0.0050	0.0390	0.0658	0.0172	0.0553	0.0170	0.0168	0.0059	0.0333
NJFE-3	0.0050	0.0625	0.0885	0.0194	0.0574	0.0185	0.0235	0.0076	0.0365
NJFE-4	0.0050	0.0218	0.0411	0.0206	0.0693	0.0185	0.0310	0.0100	0.0409
NJFE-5	0.0050	0.0354	0.0605	0.0235	0.0732	0.0195	0.0336	0.0115	0.0431
BJFE-2	0.0049	0.0521	0.0838	0.0202	0.0375	0.0032	0.0190	0.0031	0.0266
BJFE-3	0.0050	0.0399	0.0580	0.0212	0.0467	0.0099	0.0231	0.0038	0.0342
BJFE-4	0.0051	0.0315	0.0415	0.0224	0.0515	0.0124	0.0341	0.0064	0.0395
BJFE-5	0.0052	0.0512	0.0597	0.0245	0.0578	0.0145	0.0370	0.0155	0.0426
SJFE-2	0.0051	0.0510	0.0726	0.0123	0.0164	0.0025	0.0300	0.0094	0.0258
SJFE-3	0.0052	0.0434	0.0531	0.0128	0.0129	0.0039	0.0245	0.0091	0.0312
SJFE-4	0.0052	0.0305	0.0569	0.0185	0.0086	0.0050	0.0195	0.0044	0.0347
SJFE-5	0.0052	0.0416	0.0665	0.0202	0.0073	0.0064	0.0068	0.0016	0.0412

Table 5.9 Positive and negative ideal solution matrix

	Density	W_s (n)	W_s (v)	Hardness	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus	Impact Strength
Positive Ideal Solution	0.0049	0.0218	0.0411	0.0245	0.0732	0.0195	0.0370	0.0155	0.0431
Negative Ideal Solution	0.0052	0.1416	0.1062	0.0115	0.0073	0.0004	0.0068	0.0016	0.0093

Table 5.10 Separation of each alternative from the ideal solution and its relative closeness to the ideal solution.

Composite Material	Separation from positive ideal solution d_i^+	Separation from negative ideal solution d_i^-	Relative closeness from ideal solution
Epoxy	0.1513	0.0301	0.1659
NJFE-2	0.0434	0.1243	0.7412
NJFE-3	0.0668	0.1026	0.6056
NJFE-4	0.0102	0.1565	0.9389
NJFE-5	0.0243	0.1420	0.8537
BJFE-2	0.0711	0.0998	0.5838
BJFE-3	0.0428	0.1237	0.7428
BJFE-4	0.0269	0.1421	0.8407
BJFE-5	0.0384	0.1243	0.7639
SJFE-2	0.0768	0.1015	0.5693
SJFE-3	0.0705	0.1155	0.6209
SJFE-4	0.0725	0.1251	0.6332
SJFE-5	0.0818	0.1127	0.5795

Table 5.11 Ranking table

Rank	Composite Material	Relative closeness
1	NJFE-4	0.9389
2	NJFE-5	0.8537
3	BJFE-4	0.8407
4	BJFE-5	0.7639
5	BJFE-3	0.7428
6	NJFE-2	0.7412
7	SJFE-4	0.6332
8	SJFE-3	0.6209
9	NJFE-3	0.6056
10	BJFE-2	0.5838
11	SJFE-5	0.5795
12	SJFE-2	0.5693
13	Epoxy	0.1659

5.2 Comparative Study

From the above ranking, the best material found is NJFE-4 (needle-punched nonwoven jute fiber reinforced epoxy composites with fiber content of 36 wt.%). The material is compared with the most commonly used FRP composites for tribological applications are GFRP (Glass fiber reinforced polymer) and CFRP (Glass fiber reinforced polymer) composites. Therefore a comparative study has been made between the proposed needle-punched nonwoven jute fiber reinforced composite with GFRP and CFRP composites. Table 5.12 shows the comparison of needle-punched nonwoven jute fiber reinforced epoxy composites with most commonly used glass and carbon fiber reinforced composites. From the table it can be observed that the density of needle-punched nonwoven jute fiber reinforced epoxy composite is less as compared to glass and carbon fiber based composites. The strength properties of glass fiber and carbon fiber based composites are substantially higher than that of natural fibers however, when the specific mechanical properties are considered, the jute fiber based composites show values that are comparable to the synthetic fiber based composites. Similarly, it has also been observed from the table that needle-punched non woven jute epoxy composites shows comparable wear properties. In addition, the jute fiber reinforced epoxy composites are cost effective, biodegradable, eco-friendly and easy to fabricate.

Table 5.12 Comparison of NJFE-4 composites with most commonly used synthetic fiber based composites

Composites	Materials and Parameters	Wear Rate (cm^3/Nm)	Tensile strength (MPa)	Flexural strength (MPa)	Density (g/cm^3)
NJFE-4	Needle-punched nonwoven jute epoxy (36 wt.%) Operating Conditions: 10-50 N, 48-144 cm/s, 50 m, 300 µm	1.65622E-06 to 6.47766E-05	131.82	46.67	1.123
GFRP [32]	Short glass polyurethane (10-40 wt. %) 215 cm/s Operating Conditions: 22 - 32 N, 150-600 m AFS 60 grade silica	1.2E-05 to 3.35E-05	28.0±1.6 to 50.7±1.4	-	1.258-1.5
GFRP [191]	Short glass Polyester (45 wt.%) Operating Conditions: 3-7.5 N, 83-416 cm/s, 200-300 µm	2E-05 to 3.3 E-05	117.7	-	1.8
GFRP [205]	Bidirectional & chopped glass epoxy (15-35 wt.%) Operating Conditions: 2.5-12.5 Kgf, 48 cm/sec, 50 m, 125 µm	1.2E-05to 2.75E-05 & 9E-06 to 6.3E-05	25-55 & 5-7.5	27-133 & 20-37	1.3071 -1.4814 & 1.3020-1.4684
GFRP [343]	Bidirectional & short glass epoxy	1E-06 to 1.95E-04	225-260	114-157 &	1.254-1.597

	(10-50 wt.%) Operating Conditions: 20-100 N, 48-144 cm/s, 60 m, 375 µm	& 1.05E-05 to 1.64E-04	& 25-46	20-36.5	& 1.258-1.58
CFRP [97]	Woven carbon epoxy (40 wt.%) Operating Conditions: 20-25 µm, 270-1080 m, 23-33 N	1.55E-05 to 2.7E-05	908	-	1.412
CFRP [202]	Woven carbon epoxy (60 wt.%) Operating Conditions : 200 rpm, 200-250 µm, 160-480 m, 25-35 N	3.2863E-05 to 5.7682E-05	-	-	1.42
CFRP [203]	Bidirectional carbon epoxy (40 wt.%) 215 cm/s, 24 N, 360-1440 m	2E-05 to 3.9E-05	655	-	1.412

It has also been observed from the table that the different researchers have taken different parameters to study at different operating conditions, fiber loading etc. Therefore, the thorough comparison is possible only at similar operating and surface conditions. Further, the performance of polymer composites also depends on the fabrication process. The fabrication method used in the current research work is hand lay- up technique. However the performance of the proposed composites can be further improved using advanced fabrication techniques.

Chapter Summary

This chapter has provided

- The weights of the criteria used for ranking of the materials.
- The best alternative used for the abrasive wear applications.
- Comparison of best material with synthetic fiber based composites.

The next chapter refers to the conclusions of the present study, recommendations for the potential applications and scope for future research.

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CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

The study on the physical, mechanical and three-body abrasive wear behaviour of jute fiber reinforced polymer composites led to the following conclusions:

- Fabrication of needle-punched nonwoven, bidirectional and short jute fiber reinforced epoxy composites has been done successfully.
- The study on physical and mechanical properties of jute fiber reinforced epoxy composites revealed that these properties are affected by fiber type, fiber content and void content. Addition of needle-punched nonwoven and bidirectional jute fibers in epoxy resin results in improved mechanical properties of composites. The agglomeration of short fibers in the epoxy matrix led to decrease in tensile strength, flexural strength and flexural modulus of the short jute fiber composites.
- Three-body abrasive wear study depicted an improvement in the wear resistance and frictional behaviour of the epoxy with the addition of needle-punched nonwoven mats, bidirectional mats and short jute fibers. The composites having 36 wt.% fiber loading exhibited minimum specific wear rate. The addition of fibers in the epoxy led to improvement in the frictional performance. As far as comparison of composite reinforced with three forms of jute fiber, needle-punched based composites shows better wear resistance property.
- Abrasive wear characteristics of the composites using Taguchi methodology have been analyzed. The optimal parameter settings are obtained for jute fiber reinforced epoxy composites. The experimental results are also validated using confirmation test and it is found that the predicted and

experimental values of *S/N* ratio of specific wear rate and coefficient of friction are in close agreement.

- ANOVA study on needle-punched nonwoven jute composites revealed that the sliding velocity and fiber loading has greater impact on specific wear rate whereas abrasive size and normal load has larger influence on the coefficient of friction. It is observed from the ANOVA study on bidirectional jute composites that the sliding velocity has significant effect on the specific wear rate of composites; on the other hand coefficient of friction of composites is largely affected by abrasive size and sliding velocity. The ANOVA study on short jute fiber composites shows that the sliding velocity and fiber loading has significant influence on specific wear rate whereas the abrasive size and sliding velocity has larger impact on coefficient of friction. However, the other parameters have relatively less influence.
- Surface morphology of the abraded composites confirmed less abrasion in case of composites having 36 wt.% fiber loading. Micro-cracks, micro-cut, micro-ploughing, fiber fracture, pits and wear debris were observed on the abraded surfaces of the jute epoxy composites.
- Integrated AHP-TOPSIS method is used for ranking the fabricated composites for abrasive wear applications. It is observed that the needle-punched nonwoven composite with 36 wt.% of fiber loading is the best alternative whereas epoxy resin is the least preferred alternative among all the composite materials under study.

6.2 Recommendation for Potential Application

The jute fiber reinforced epoxy composites fabricated and experimented upon in this investigation are found to have adequate potential for a wide range of applications particularly in hostile environment. Jute composites can be used for sports applications like skateboard, in automotive industries for preparing interior panels, headliners, seat backs and dashboards, for making mobile and laptop case etc. The present study reveals that these composites exhibited better three-body abrasive wear performance. Therefore, use of these composites, may also be recommended for applications like elevator buckets (for handling grains, fertilizers, feeds, salt, seeds, chemicals, food products and sand), grain tank auger floor liners, chute liner etc.

6.3 Scope for Future Research

The present study on jute fiber reinforced epoxy composites leaves a wide scope for future researchers to find many other aspects of these composites. Few recommendations for the future investigation comprise:

- The present study has been carried out using simple hand lay-up technique. However, the research work can be extended further by considering other methods of composite fabrication and the effect of manufacturing techniques on the performance of composites can similarly be analyzed.
- Besides many advantages of natural fibers, the main disadvantages of natural fibers in composites are the poor compatibility between fiber and matrix and the relative high moisture absorption due to their hydrophilic nature. The limited compatibility between the constituents of a composite usually results in a decrease in the mechanical and wear properties. Therefore, the study can be extended further by considering the chemical treatments in modifying the fiber surface properties to improve the adhesion between fiber and matrix materials and the study can be analyzed similarly.
- The present study can be extended further by the development of hybrid composites using hard particulate fillers along with jute fiber and the study can similarly be analyzed.

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Appendix: A1

List of Research Publications out of this research work

International Journals

1. Vivek Mishra and Sandhyarani Biswas, Evaluation of Three Body Abrasive Wear Behavior of Bidirectional Jute Fiber Reinforced Epoxy Composites, Journal of Industrial Textiles, DOI: 10.1177/1528083713516663.

2. Vivek Mishra and Sandhyarani Biswas, Three-Body Abrasive Wear Behavior of Needle-Punched Nonwoven Jute Fiber Reinforced Epoxy Composites, International Polymer Processing, XXIX (2014), pp. 356-363.

3. Vivek Mishra and Sandhyarani Biswas, Physical and Mechanical Properties of Bi-directional Jute Fiber Epoxy Composites, Procedia Engineering, 51 (2013) pp. 561-566.

4. Vivek Mishra and Sandhyarani Biswas, Three-body Abrasive Wear Behaviour of Short Jute Fiber Reinforced Epoxy Composites, Polymer Composites, DOI: 10.1002/pc.23178

5. Vivek Mishra and Sandhyarani Biswas, Jute Fiber Reinforced Polymer Composites: A Review, Journal of Polymer Research (Under Review)

International Conferences

1. Vivek Mishra and Sandhyarani Biswas, Physical and Mechanical Characterisation of Short Jute-Epoxy Composites, 4th International Conference on Recent Advances in Composite Materials (ICRACM-2013), February 18-21, 2013, Goa.

2. Vivek Mishra and Sandhyarani Biswas, Physical and Mechanical Behaviour of Needle-Punched Nonwoven Jute Fiber Reinforced Composites, International Conference on Advances in Mechanical Engineering, 2013, May 29-31, 2013,COEP, Pune.

Appendix: A2

Brief Bio-Data of the Author

The author, **Vivek Mishra**, graduated in Mechanical Engineering from Pandit Ravishankar Shukla University, Raipur in the year 2006. He did his postgraduate study in Applied Mechanics with specialization in Engineering Materials from Maulana Azad National Institute of Technology, Bhopal, in the year 2009. Before joining for the Ph.D. programme at the National Institute of Technology, Rourkela, he had served as a faculty in the Department of Mechanical Engineering at Rungta College of Engineering and Technology, Bhilai.

He has authored five research papers in International Journals and has two research papers in International Conferences to his credit. Since 2011, he has been engaged in his Doctoral Research in the area of fiber reinforced polymer composites at N.I.T, Rourkela under the Institute Research Fellowship scheme.