Study of Water Absorption Behaviour of Natural Fibre Reinforced Composites

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Abstract: ***Environmental perception today encourages empiricism worldwide on the learning of plant or natural fibre reinforced polymer composite and cost efficient alternative to synthetic fibre reinforced composites. The accessibility to natural fibers and simplicity in manufacturing have persuaded researchers to aim for locally existing low cost fibers and to investigate their possibility of reinforcement intensions and up to what extent they can satisfy the essential detailing of superior reinforced polymer composite intended for different application program. Natural fibre represents a superior biodegradable and renewable alternative to the most popular synthetic reinforcement, i.e. glass fibre possessing high mechanical properties and low cost. Regardless the curiosity and environmental request of natural fibers, there usage is restricted to non-bearing uses, because of its lower strength than that of synthetic fibre reinforced polymer composite. The stiffness and strength limitations of bio composites can be chased by operational arrangement by placing the fibers at particular locations to have higher strength performance. Research regarding preparation and properties of polymer matrix composite (PMC) replacing the synthetic fibre with natural fibre like Jute, Sisal, Jute, Bamboo, Pineapple, Bagasse and Kenaf were carried out. Renewable, environmental friendly, low cost, lightweight and high specific mechanical performances are the advantages of these plant fibres over the glass fibre or carbon fibre. Composites are exciting materials which are finding increasing application in transportation, aerospace, defence, communication, sporting, electronics and number of other commercial and consumer products. Composite materials have become one of the fastest growing research and development areas of Material Science because of their high potential. In current years there is swift growth in the arena of fibers, matrix, materials, processing, boundary structure, bonding and their characteristics on the final properties of composites. The technological developments in composite materials help in meeting the global industrial demand for materials with improved performance capabilities.***

Keywords: polymer matrix composite (epoxy resin) using Luffa Cylindrica fibre and to study its moisture absorption behavior and mechanical properties

1. Introduction

It is a platitude that technological advances depends on fosters in the sector of materials. If sufficient materials to bear the service loads and conditions are not available then one does not have to be a skilful to realize the most advanced turbine or air-craft pattern. Whatsoever the field may be, the ultimate restriction on progression is to be governed by materials. Composite materials in this regard signify a big step in the constant accumulation of optimization in materials. Composites are mixture of two or more materials such as reinforced plastics, metals, or ceramics. The reinforcements may be in the form of fibers, particles, whiskers or lamellae and are embedded in a suitable matrix, thereby providing a material that contains the most useful properties of the constituents. High structural strength, glass fibre reinforced plastics were developed in the early 1940's and the application of reinforced plastics composites, the glass fibre provides strength and stiffness while the plastic matrix provides the temperature capabilities of the composite. Initially the glass fibres were incorporated in a polyester matrix which could withstand temperature up to 200°C. They were applied in car bodies, appliances, boats etc., because of their light weight and mitigate of production. Intricate composites parts can be made by injection moulding. Polymer matrices are usually thermosets such as epoxies. Later, resins which can withstand high temperatures, of the order of 300^{o}C were developed such as polyamides. Other thermo setting resins include benzocyclobutene – bismaleimides. Advanced composites are manufactured by using the above polymers with reinforcements of stronger fibres such as aramid and carbon. As a result advanced composites are finding increasing applications in aircraft, automotive industry, etc. In order to reduce the manufacturing time, thermoplastics polymers such as polyether – ether ketone (PEEK) have been developed. The plastic requires only a short revelation to heat to soften the plastics, thereby allowing faster processing of the composite.

The limitations of the polymer matrix composites at high temperatures can be overcome by the use of metal matrix composites. These composites are processed by powder metallurgy methods, by penetration of the molten metal with the fibre or particulate or by mixing particulates with molten metal. Plasma spraying, vapour deposition, plasma spraying or electro deposition followed by dispersal bonding are the other methods of fabrication. Metal matrix composites are discovering applications in defence, aerospace, automotive and electronic packaging. In addition to metal matrix composites, intermetallics such as nickel, iron, titanium and niobium aluminides matrix composites are also being actively considered for use at elevated temperatures.

The temperature range of application of metal matrix composites is lower than that of ceramic matrix composites. Ceramic matrices such as zirconia, alumina, silicon nitride, silicon carbide, mullite etc. can be reinforced with ceramic continuous fibres, whiskers or particulates. Carbon-carbon composites is a ceramic composite which can retained its strength at temperatures up to 2500^{0}C and is applied as a critical component in aerospace. Adduce composites have both structural and functional applications. Adaptable composites will have the potentiality not only of load bearing but will also have an agile and flexible response to structure functional conditions. These advanced growths will increase and sensing potential of structures such as vertical tails, aircraft bulkheads, intrinsic avionics, smart skins and antenna systems. For elevated temperatures, smart metal matrix composites with fibre optic sensors in a titanium matrix composite are being boisterously considered.

The study of composites materials is a multifaceted memorandum as it is difficult for any individual to grasp the compound behaviour of many of the current composites. This field provides lot of analytical problems for experimental schedules, theoreticians for research workers and new defiance for designers. Even the technologically advanced fibre glass reinforced plastics in the 1940s require a information of ceramics, glass technology, surface science, polymers, modelling, design and analysis in order to redeem the properties, structure and purpose of the final composite product.

Composites

Over the last three decades years composite materials, plastics and ceramics have been the ascendant developing materials. Numerous uses of composite materials have grown evenly, pervasive and dominant new markets interminably. Modern composite materials comprise a significant amount of the engineering materials market varies from commonplace products to worldly niche applications. Although composites have already manifested their value as weight reduction materials, the existing job is to make them cost productive. The endeavours to yield economically smart composite components have evolved in some unorthodox manufacturing techniques currently being used in the composite industries. It is vibrant, specifically for composites, that the development in manufacturing technology only is not sufficient to overcome the cost hurdle. It is important that there must be an unsegregated implementation in material processing, designing, manufacturing, tooling, quality assurance and even programmes organisation for composites to make them competitive with metals.

Further, need of composites for lighter building materials and more shock resilient structures has placed high prominence on the usage of fresh and innovative materials that not only reduces weight but also assimilates the shock and vibration by tailored microstructures. Composites at the present are largely used for rehabilitation or strengthening of preceding structures that need to be render in order to make them seismic resilient, or to restore damage due to seismic activities.

The properties of composite material can be designed by bearing in mind the structural aspects, unlike conventional materials (e.g., steel); both material and structural design operations are there in the plan of a structural component using composites. Properties of composites such as thermal expansion, stiffness etc. can be assorted frequently over a wide range of values beneath the designer control. Correct assortment of reinforcement category allows concluded product features to be customized nearly every specific engineering necessity.

A typical composite material consists of two or more materials (bonded and mixed) on macroscopic rules which are not soluble in each other.

Normally, a composite materials are composed of reinforcement (fibers, flakes, particles and fillers) implanted in a matrix such as polymers, metals, or ceramics. The function of matrix is to hold the reinforcement to form the craved shape while the reinforcement ameliorates the whole mechanical properties of the matrix. The new combined material possesses better strength than the each individual material in a system, when designed correctly.

Classification of Composites

Composite materials perhaps categorized in distinct ways [5]. Arrangement based on the geometry of a characteristic unit of reinforcement is suitable since it is the geometry of the reinforcement which is liable for the mechanical properties and better presentation of the composites. The classification is presented in Table1.1. The two broad classes of composites are:

- Fibrous composites
- Particulate composites

Types of composite materials

The composite materials are classified into the following categories as shown in Figure-1.1 (a - e). Fibre-reinforced composites Because of intrinsic high specific strength and stiffness these composites are universally used in numerous industrial applications. These composites are acquiring high potential in tribological applications also as they possess brilliant structural presentation. Fiber reinforced composites materials comprises of fiber of high strength in or bonded to a matrix with discrete interfaces between them [4, 5]. In this form physical and chemical identities are retained by both fibres and matrix. Yet they produce an amalgamation of properties which is difficult to achieve with either of the composite constituents individually. In general, the role of fibers is to carry load, whereas the role of matrix is to keeps them in the crave position and alignment [5, 6].Fibrous composite can be further classified into two groups: continuous (long) fiber composite and discontinuous (short) fiber composite.

Continuous or long fiber composite

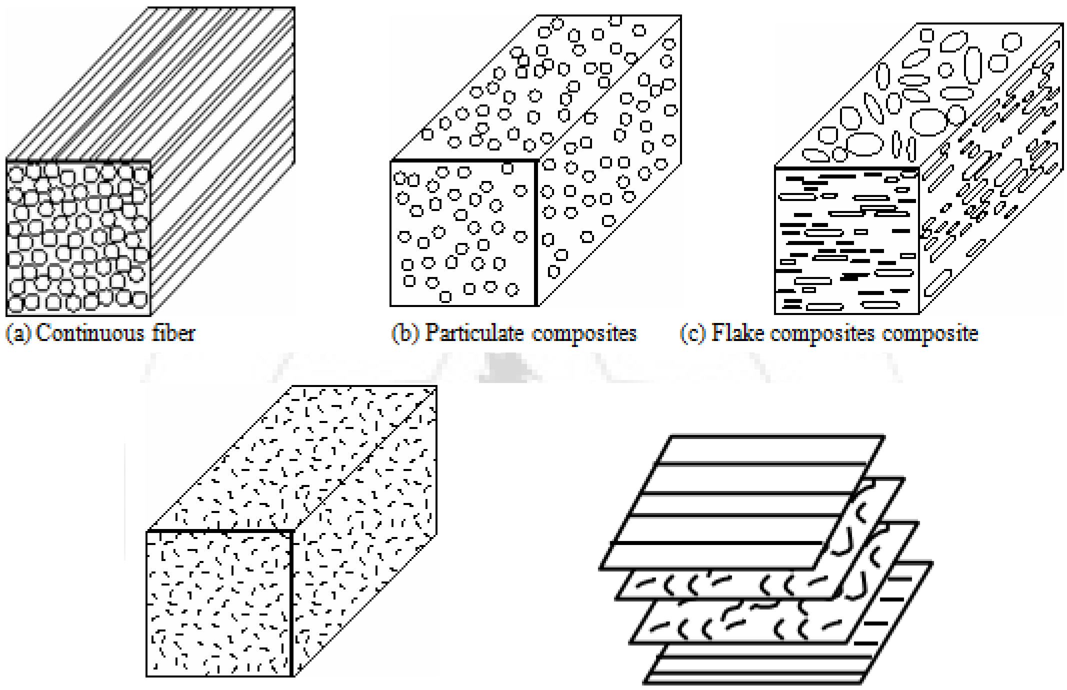
Geometrically, a continuous fibre is distinguished as it possesses a high length to diameter ratio. It also comprises of reinforcement matrix by a disseminate phase in the type of continuous fibre. These are basically tougher and stiffer when compared to matrix i.e. bulk phase material. Based on the manner in which fibers are stuffed within the matrix, it is again subdivided in to two categories: (a) unidirectional reinforcement and (b) bidirectional reinforcement. In unidirectional reinforcement, the fibers are aligned in one direction only where as in bidirectional reinforcement the fibers are aligned in two directions either at some desired angle (angle-ply) or at right angle to one another (cross-ply). When fibers are continuous and large, they transmit certain degree of anisotropy to the properties of the composites especially when they are oriented. Multi-axially oriented continuous fibre composites are also exhibit near isotropic properties.

Discontinuous or short fiber composite

Short-fiber reinforced composites comprises of a reinforced matrix by a distributed phase in the type of discontinuous fibers which are having, length < 100×diameter. The low cost, proficiency of fabricating intricate parts, and isotropic nature are sufficient to make the short fiber composites the material of selection for large-scale production. Accordingly, the short-fiber reinforced composites have profitably established its place in lightly loaded component production. Furthermore the discontinuous fiber reinforced composite divided into: (a) biased or preferred oriented fiber composite and (b) random oriented fiber composite. In the prior, the fibers are oriented in pre-decided directions, whereas in the later type, fibers remain randomly. The alignment of short fibers can be done by scattering of fiber on to given plane or inclusion of matrix in liquid or solid state before or after the fiber displacement.

Laminate Composites

Laminate Composites consists layers of material held together by matrix. Mainly, these layers are organized alternatively in order to provide a better bonding between the reinforcement and the matrix. According to the end use of the composite these laminates can have uni- directional or bi-directional orientation of the fiber reinforcement. The different types of composite laminates are angle-ply, unidirectional, symmetric laminates and cross- ply. A blended laminate can also be fabricated by the use of alternate constituent materials or of the same material with alternate reinforcing design. In most of the applications of laminate composites, man-made fibers are used because of their good amalgamation of physico- mechanical and thermal behaviour.



(a) Continuous fiber (b) Particulate composites (c) Flake composites composite

(d) Random fiber (short fiber) Composite (e) Laminate Composite Figure-1.1 (a-e)

Different types of Composite

NATURAL FIBER COMPOSITES: Initiative in Product Development

The cost effective option to synthetic fibre reinforced composites and the interesting studies of plant or natural fibre inspires the researchers to make advances in the field of composites. Ease in access and built-up simplicity of natural fibre have convinced these researchers to try natural fibres which are available locally and to study their practicability of reinforcement motives. These are also studied to have the information that up to what limit they can fulfil the desired specifications and properties for various uses. Natural fibre appears as a good renewable and biodegradable substitute to most of the synthetic fibre such as glass fibre.Vegetables, animal, mineral fibers etc. fall under the area of natural fibre. Generally it is referred as wood and agro based fibre, leaf, stem and seed fibers in the composite engineering. A natural fibre frequently contributes to the structural presentation of plant and they can deliver substantial reinforcement, when used in the production of plastics composites.

Is curtailed to non-bearing applications because of their bring down strength compared to synthetic fibre reinforced polymer complex in malice of the interest and environmental appeal of natural fibers. By the sense of positioning the fibers in particular locations for maximum strength presentation, the limitations in stiffness and strength of bio composites can be succeeded.

Accordingly vast studies on construction and properties of polymer matrix composite (PMC) substituting the synthetic fibre with natural fibre like Jute, Pineapple, Sisal, Kenaf, Bamboo, luffa cylindrica, ipomea carnea and Bagasse were executed [7-12]. Above natural fibers have numerous advantages over the glass fibre or carbon fibre such as renewable, low cost, lightweight, high specific mechanical performance.

Applications

Automobile industry: For inner and outer parts fibre reinforced plastics are used. These are used in industries because of their advantages over the glass fibre reinforced composites such as cheaper, environment friendly, etc. By these fibers cars according to End-of-Life directive can be developed as the resulting products from these composites can be re-used and do not have to be land filled unlike glass fibre. Because of their softness and non-harsh behaviour unlike glass fibers they are used in interior automotive uses and are having advantages of not injuring the passengers.

Packaging industry: In these industries these are used for light weight pallets. Weight reduction is the chief reason for using composite material in place of wood, which saves fuel during transportation.

Consumer products: Natural fibre can be used for any injection moulded product. Reduction of plastic use, flame retardancy and re-use. Examples are household appliances like cell phones, refrigerators and computers. They are less vulnerable to fire due to the fibre structure of composite. Also the high fibre loads results in major material cost reduction. Building and construction industry: In these they are used for roofings and instance profiles. Cost reduction, re-use and flame retardancy are the advantages.

Luffa cylindrical as a natural fiber

Numbers of potential natural resources are there, which India has in abundance. Most of which comes from the forest and agriculture.

Figure 12: The Luffa cylindrica plant (a), the inner fiber core (b) and the outer core open as a mat (c, d).

Luffa cylindrica, locally called as ‘Sponge-gourds’ is that natural resource whose capability as fiber reinforcement in polymer composite has not been explored to date. The fibrous cords are liable in a multidirectional array resulting in a natural mat in ligneous netting system possess by ‘Sponge gourds’. It comprises 62% cellulose, 20% hemicellulose and 11.2% lignin [1]. The sponge-gourd (Luffa Cylindrica) plant with fruit which belongs to the curcubitacea family is shown in Fig. 1.1(a).

The main objective of this project is to prepare a PMC using luffa fiber as reinforcement and epoxy as matrix material and to study its moisture absorption characteristics under different environmental conditions and then to find its mechanical properties i.e.; tensile and flexural strength. Out of the available manufacturing techniques, we have chosen hand-lay-up method to construct the composite. Then the composites were manufactured by varying the no. of layers of fiber i.e.; single, double and triple layers composite using these techniques. The surface of fracture and worn out samples have been studied using Scanning Electron Microscope (SEM) to have an idea about the fracture behaviour of the composite.

In the 2nd chapter, detailed discussion on reinforcement material, outline of fabrication processes and effort related to current investigation available in literature are presented.

In the 3rd chapter, the effect of environment on mechanical properties of both treated and untreated fiber reinforced composite along with moisture absorption characteristics have been presented.

2. Literature Review

Natural Fibers: Source and Classification

Growing environmental awareness has activated the researchers worldwide to enhance and utilize materials that are companionable with the environment. In the procedure natural fibers have become suitable options to traditional synthetic or manmade fibers and have the prospective to be used in cheaper, more sustainable and more environment friendly composite materials. Natural organic fibers can be obtained from either animal or plant sources. Most of the useful natural textile fibers are obtained from plant, with the anomaly of wool and silk. All plant fibers comprises of cellulose, whereas protein act as a chief content of fibers of animal origin. Hence, the natural fibers are categorized on the basis of their origin, whereas the plant fibers can be further classified on the basis of plant parts from which the parts are originated. An overview of natural fibers is showed in Figure-2.1 [13].

Normally, plant or vegetable fibers are cast to reinforce polymer matrices and a categorization of vegetable fibers is given in Figure-2.1 [14]. Plant fibers are a renewable resource and have the capability to be recycled. The plant fibers leave slight residue if they are burned for disposal, returning less carbon dioxide (CO_2) to the atmosphere than is separated during the plant's growth.

The chief driver for switching natural fibers for glass is that they can be grown with lesser cost than glass. The price of glass fiber is around Rs. 300.0/- per kg and has a density of 2.5 gm/cc. On the other hand, natural fiber costs Rs. 15.0/- to 25.0/- per kg and has a density of 1.2-1.5 gm/cc. As can be seen from Table-2.1 [13], although the modulus is of the same order of magnitude, the tensile strength of natural fibre is considerably lower than the glass fibers. On the other hand, when the specific modulus of natural fibers is measured, the natural fibers show values that are similar to or even better than glass fibers. Material cost savings, suitable to the use of natural fibers and high fiber filling levels, coupled with the benefit of being non-abrasive to the mixing and moulding tools make natural fibers a thrilling outlook. These reimbursement mean natural fibers could be used in many applications, including building, automotive, household appliances, and several other applications.

Table 2.1: Properties of glass and natural fibers

Mechanical Properties	Fibers						
	E-glass	Hemp	Flax	Jute	Sisal	Coir	Ramie
Density (gm/cc)	2.25	1.48	1.4	1.46	1.33	1.25	1.5
Tensile Strength (MPa)	2400	550-900	800-1500	400-800	600-700	220	500
Young's Modulus (MPa)	73	70	60-80	10-30	38	6	44
Specific Modulus (MPa)	29	-	26-46	7-21	29	5	2
Failure Strain (%)	3	1.6	1.2-1.6	1.8	2-3	15-25	2
Moisture Absorption (%)	-	8	7	12	11	10	12-17

3. Mechanical Characterization of Luffa Cylindrica Fibre Epoxy Composite

In common natural fibers are absorptive in nature and they take up or liberate moisture relying on to the environmental conditions. For high moisture absorption rate amorphous cellulose and hemicellulose present in the fibre are the main reasons, as they possess innumerable easily available -OH groups which provide an increased level of hydrophilic property to the fibre. The high moisture absorption of the fiber happens due to hydrogen bonding of water molecules to the -OH groups in the fiber cell wall. This guides to a moisture growth in the fibre cell wall (fibre swelling) and also in the fibre-matrix border. This in turn becomes liable for variations in the dimensions of cellulose-based composites, mainly in the thickness and the linear expansion because of reversible and irreversible swelling of the composites. In order to solve this problem, chemical treatment has been taken into account as a good method to reduce the -OH group in the fibers. Different chemical treatments such as alkali treatment, acrylation, benzoylation, isocyanate treatment, acetone treatment, acetylation, silane treatment, permanganate treatment etc. are reported by many researchers [22, 23].

The moisture uptake of composites comprising natural fibers has some unfavourable causes on their properties and hence disturbs their long-term presentation. In view of the sternness of moisture absorption and its consequences on composite properties, a number of efforts have already been made by several researchers to address this issue

Composite Fabrication

For preparation of composite the following materials have been used;

- Luffa Cylindrica fiber
- Epoxy
- Hardener
- Preparation of Luffa Cylindrica Fiber Mats

Dried Luffa Cylindrica was collected locally. These fibres were then treated with water for 24 hrs in order to remove wax, lignin and oil from the external surface of luffa fibre and then dried at room temperature. After these the fibres were cut with appropriate dimensions (150×140 mm) and then these fibres were kept between two wooden boards

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followed by pressing it into the bench vice to straighten the fibres.

Epoxy Resin

The epoxy resin used in this examination is Araldite LY-556 which chemically belongs to epoxide family. Its common name is Bisphinol-A-Diglycidyl-Ether. The hardener with IUPAC name NNO-bis (2aminoethylethane-1,2diamin) has been used with the epoxy designated as HY 951.

Composite preparation

Initially, wooden moulds with dimensions of 140 x 120 × 10 mm^3 were prepared for the fabrication. For different number a layer of fibre, epoxy resin and hardener (ratio of 10:1 by weight) with a calculated amount was mixed thoroughly in a glass jar. Figure 3.1(a) illustrates the mould used to construct the composite. Mould release sheet was put over the glass plate and a mould release spray was sprayed over the inner surface of the mould for quick and easy removal of composite. After keeping the mould on a ply board a thin layer of the mixture was poured. Then the fiber lamina was distributed on the mixture. Then again resin was applied over the fiber laminate and the procedure was repeated to get the desired thickness. The remaining mixture was then poured into the mould. Precaution was taken to prevent the air bubbles formation. Then from the top pressure was applied and the mould was kept at room temperature for 72 hrs. During application of pressure some amount of mixture of epoxy and hardener squeezes out. Care has been taken to consider this loss during manufacturing of composite sheets. After 72 hrs the samples were taken out of the mould. Figure 3.2 (a, b) shows the photograph of the composite specimen cut for further experimentation.

Figure 3.1: Mould used for fabrication of the composite

Figure 3.2 (a): Flexural test samples

Figure 3.2 (b): Tensile test samples

Study of Environmental Effect

To study the effect of environmental conditions on performance of Luffa Cylindrica fiber epoxy composite, the composite sample with both untreated and chemically treated fibers were subjected to various environments such as:

- Saline treatment
- Distil treatment

Moisture absorption test

Moisture absorption and thickness swelling tests were conducted in accordance with ASTM D570-98. Four specimens for different layers (Single, Double and Triple layers) were cut with dimensions of 140 x 15mm (length x width) and the experiment was performed using test samples. The specimens prior to testing were dried in an oven at 80^0 C and then were allowed to cool to room temperature and kept in a desiccator. The weight of the samples were taken before subjected to steam, saline water and distil water environments. After expose for 12 hr, the specimens were taken out from the moist environment and all surface moisture was removed with a clean dry cloth or tissue paper. The specimens were reweighed to the nearest 0.001 mg within 1 min. of removing them from the environment chamber. The specimens were weighed regularly from 12-156 hrs with a gap of 12hrs of exposure. The moisture absorption was calculated by the weight difference.

4. Results and discussion

Moisture absorption behaviour

The results of both untreated and treated fibre composite samples exposed to different environments are shown in Table-3.1 to 3.24. Figure-3.22 to 3.29 shows the percentage of moisture absorption characteristics of composite samples with untreated and treated fiber exposed to Saline water and Distil environment with time. It is quite obvious from the figure that as the fibre content increases, the initial rate of moisture absorption and the maximum moisture absorption for both the environment increases. Moisture absorption is maximum for three layered composites. It is known that, the factors like adhesion between fibre and matrix, porosity content and the lumen are responsible for the moisture absorption behaviour of the natural fibre composites. But in this case the hydrophilicity of Luffa Cylindrica fiber, in addition to poor adhesion between fiber–matrix and voids content might have affect the moisture uptake characteristics of the composite.

Again it is observed that, the moisture absorption increases as the immersion time increases, and got saturated after certain time period. Time required to reach the saturation point is not same for both the environments. The saturation time is approximately 120 hrs for distil, and 108 hrs for saline water. Environmental conditions also play a significant role in moisture absorption process. Figure-3.30 to 3.33 shows the maximum moisture absorption of composite in all three environments. In Distil Water environment moisture absorption is maximum as compare to saline water environment. The rate of absorption in case of saline water is low as compared to steam. This happens because of the gathering of NaCl ions in the fibre's surface immersed in saline water, which increases with time and delays moisture diffusion [122].

Figure-3.22 to 3.29 shows that the moisture absorption behaviour of the chemically treated fibre reinforced epoxy composites was lesser than that of the untreated fibre when exposed to different environmental treatment. It is clear from these plots that the change in surface chemistry of the fibre reduces the attraction of fibers to moisture. Due to surface modification by chemical treatment, the fibers get covered with the epoxy resin with a stronger adhesion, resulting in less moisture uptake.

Table 3.22: Variation of weight gain and thickness swelling of treated Luffa Cylindrica fibre epoxy composite (tensile) with immersion time expose at saline environment

No. of Layers	Time of immersion	Final Wt.	Wt. Change	Thickness	Thickness Swelling
Single layer	0	11.902	0	0.514	0
	12	11.961	0.495715006	0.515	0.194552529
	24	12.015	0.949420266	0.516	0.389105058
	36	12.069	1.403125525	0.517	0.583657588
	48	12.121	1.840026886	0.518	0.778210117
	60	12.168	2.234918501	0.519	0.972762646
	72	12.224	2.705427659	0.52	1.167315175
	84	12.274	3.125525122	0.521	1.361867704
	96	12.324	3.545622584	0.522	1.556420233
	108	12.398	4.167366829	0.523	1.750972763
	120	12.398	4.167366829	0.523	1.750972763
	132	12.398	4.167366829	0.523	1.750972763
	144	12.398	4.167366829	0.523	1.750972763
	156	12.398	4.167366829	0.523	1.750972763

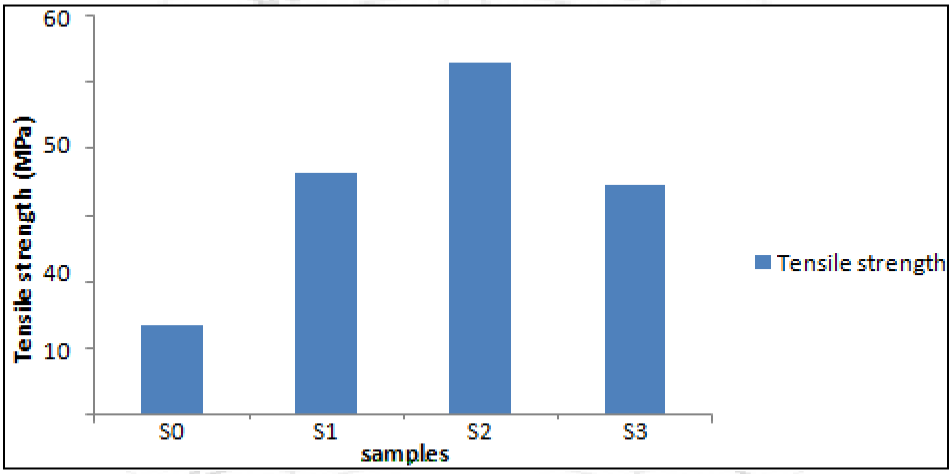

Figure 3.6: Variation of tensile strength with different layers of untreated Luffa Cylindrica fibre epoxy composites exposed to saline water environment

5. Conclusions

Based on experimental results, this study has led to the following conclusions:

1) The Luffa Cylindricafibre can successfully be used as reinforcing agent to fabricate composite by suitably bonding with epoxy resin. .
2) On increasing the fibre content the strength, modulus and work of fracture increases and the best combination is found with Double Layered composite.
3) The fibre surface modification by chemical treatments significantly improves the fibre matrix adhesion, which in turn improves the mechanical properties of composite.
4) The moisture uptake and thickness swelling values increases with increase in fiber loading. Both values are found to be higher in saline environment than in distil water environments. However these values are considerably reduced with chemical treatments of the fibre.
5) Under all environment conditions, the moisture diffusion process of both treated and untreated Luffa Cylindricafibre composites are found to follow the Fick's law.
6) Fibre breakages are found to be the predominant mode of failure as ascertained from the morphology of the treated fibre composites.

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