

Review Article

A Review on Brake Pad Materials and Methods of Production

Danladi Ozokwere Ayogwu^{*}, Ibrahim Saidu Sintali, Mohammed Ahmed Bawa

Department of Mechanical/Production Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, Bauchi, Bauchi State, Nigeria

Email address:

ddayogwu81destiny@gmail.com (D. O. Ayogwu)

^{*}Corresponding author**To cite this article:**Danladi Ozokwere Ayogwu, Ibrahim Saidu Sintali, Mohammed Ahmed Bawa. A Review on Brake Pad Materials and Methods of Production. *Composite Materials*. Vol. 4, No. 1, 2020, pp. 8-14. doi: 10.11648/j.cm.20200401.12**Received:** May 23, 2020; **Accepted:** June 9, 2020; **Published:** June 20, 2020

Abstract: Brake pads most especially in the automotive industry play a vital role in controlling the speed of a moving vehicle or machines in some instances. This can only be achieved through careful formulations of selected materials in the right proportions. However, not all brake pads materials are safe for use in automobile and other industrial applications, due to environmental pollution and other health related factors. Thus, the need to develop materials which are considerably suitable and at the same time energy efficient in nature becomes necessary in order to minimize and reduce further damage to an already damaged environment. Thus, environment friendly and non-toxic materials are gaining popularity, and hence, a priority among researchers and industries. The heralding introduction of environmentally friendly natural fibres to replace asbestos in a control composition with other additives in the production of brake pads proves to be a popularly embraced concept among recent researchers. This paper presents review on mechanical properties, tribological behavior, water absorption capacity, dynamic mechanical analysis, morphological and thermal properties of organic reinforced brake pad composites with respect to the materials used and methods of production employed. Findings of this study show that hybridization, modification, chemical treatment and composition control of constituent materials can improve mechanical, thermal and dynamic mechanical properties as well as reduce wear rate and water absorption property. It can be concluded that many researchers were able to improve the performance of braking systems by introducing environmental and user friendly composite materials that can withstand the test of time.

Keywords: Chemical Treatments, Organic Fibres, Physico-Chemical Properties, Polymer Composites

1. Introduction

In the automotive industry, brake pad is highly important in that its application in the braking systems is necessary for controlling the speed (s) of vehicles, automobiles and machines. This is achieved by transforming the kinetic energy of the vehicles, automobiles or the moving parts of machines to heat due to friction, which is eventually released into the atmosphere. The advent of brake pad and brake linings was widely a welcome idea in the industry but for ecological reason (s) the dust (particles) they release into the environment are a great concern to man's health. History records the use of many kinds of materials for brakes especially friction materials spanning from the 1800s.

Generally, materials for brake pad production are classified into Asbestos, Metals, Semi-metals, and Ceramics and Organic materials. Conventionally, for over 120 years, asbestos has been chiefly adopted in producing brake pads because of its robust chemical and physical/mechanical properties, in that it is insoluble in water and organic solvents, non-flammable, has good tensile strength which surpasses that of steel, has tremendous thermal stability, thermal and electrical resistance. Asbestos binds with better insulating materials to create the ultimate composite materials.

However, asbestos is no longer considered safe for application in brake pad production due to hazardous dust and/or gases it releases which cause damages to health and this is simply undesirable. Asbestos was discovered to be carcinogenic with associated diseases such as mesothelioma,

lung cancer, asbestosis, and other cancer related diseases [1-2]. For this reason, the imperativeness for the (suitable) replacement of asbestos in brake pads has opened up very wide research perspectives in the automotive industry. On this background, many researches on brake pad production have taken place around the globe in order to replace the ceramic brake pad. In fact, according to Weintraub [3] more than 2000 different materials and their variants are now in use for commercial brake components. Thus, the needs to review the brake pad materials and production methods.

2. Brake Materials and Methods of Production

2.1. Materials

A commercial brake lining usually contains over 10 different constituents. They can be grouped based on their expected functions into four classes of ingredients: Abrasives; Friction modifiers; Fillers and Reinforcements; and Binder materials [4]. According to Hee *et al.* [5], selection of the constituents is often based on experience or a trial-and-error method to make a new formulation. The demands on the brake pads are such that they must maintain a sufficiently high friction coefficient with the metal disc; they must not decompose such that friction coefficient with the brake disc is not compromised at high temperatures; they must show a stable and constant friction coefficient with the surface of the brake disc [6].

Brake friction materials have evolved significantly over the years. They have gone from asbestos to organic to semi-metallic formulations. Each of these materials has proven to have advantages and disadvantages regarding environmental friendliness, wear, noise and stopping capability. Many studies have been done and are still ongoing for the development of not only asbestos free brakes, but also less temperature generating pads with harmless materials for better human health and technical efficiency.

Although the use of asbestos for brake pads has not been banned, much of the brake pads industry is moving away from asbestos brake pads because of concerns regarding airborne particles in the factories and disposal of wastes containing asbestos. There are several patents for asbestos free organic friction materials [7] with more than 700 items classified into four categories consisting of binder, fibre, friction modifiers and fillers based on the major functions apart from controlling friction and wear resistance.

Since no single material could achieve all the desired attributes for an automobile brake pad, different constituents of materials were therefore introduced to overcome the challenges encountered in finding suitable materials as an

automobile brake pad. The brake pads generally consist of asbestos fibres embedded in a polymeric matrix along with several other ingredients, but it is no longer acceptable due to its carcinogenic nature. Thus new asbestos-free brake pads are being developed from preferential natural fibres which are found to be readily available, recyclable and cost effective.

Fibres that are extracted from the minerals, plant/vegetables, animals and agricultural wastes convertible into non-woven fabrics are generally considered as natural fibres. Currently, a wide variety of industrially viable natural fibres such as kapok, sisal, coconut, jute, bamboo, bagasse, hemp, nut shell, rice husk, and much more are available. Extensive work is being done on these fibres to explore the possibilities of using them in various application areas. Some of the prominent areas where these fibres have found application include fibre reinforced composites for building construction, thermal insulation, acoustic insulation, etc. The chemical constituents of these natural fibres generally comprise of lignin, wax, pectin, cellulose, hemi-cellulose and water soluble substances. Among these substances, the concentration of cellulose is the highest which is a semi-crystalline polysaccharide having D glucopyranose assembled together by glycosidic bonds. These fibres are hydrophilic in nature which is because of the huge amount of hydroxyl groups present in them. As a result of this hydrophilic nature, natural fibres and their composites have poor water and moisture resistant properties which pose a major challenge to researchers.

Generally, natural fibres are pre-treated with alkaline in order to increase the water and moisture resistant properties prior to composite making. Table 1 shows some of the important natural fibres along with its origin and species.

Table 1. Natural Fibres, Origin and Species.

Fibre name	Origin	Species
Jute	Stem	<i>Corchorus capsularis</i>
Abaca leaf	Leaf	<i>Musa textilis</i>
Piassava	Leaf	<i>Attalea funifera</i>
Bagasse	Grass	<i>Saccharum officinarum</i>
Pineapple	Leaf	<i>Ananas comosus</i>
Kapok	Fruit	<i>Ceiba pentrandia</i>
Oil palm	Fruit	<i>Elaeis guineensis</i>
Henequen	Leaf	<i>Agave fourcroydes</i>
Bamboo	Grass	<i>Acidosasa edulis</i>
Kenaf	Stem	<i>Hibiscus cannabinus</i>
Hemp	Stem	<i>Cannabis sativa</i>
Coir	Fruit	<i>Cocos nusifera</i>
Curaua	Leaf	<i>Ananas erectifolius</i>
Banana	Leaf	<i>Musa indica</i>
Cotton	Seed	<i>Gossypium sp.</i>
Flax	Stem	<i>Linum usitatissimum</i>
Date palm	Leaf	<i>Phoenix dactylifera</i>

Source: [8].

Table 2. Chemical Constituents of Different Natural Fibres.

Fibres	Lignin (%)	Pectin (%)	Cellulose (%)	Hemicellulose (%)	Ash (%)
Kenaf	15 – 19	-	31 – 57	21.5 – 23	2 – 5
Hemp	3.7 – 13	0.9	57-77	14 – 22.4	0.8
Flax	2.2	2.3	71	18.6 – 20.6	-
Jute	12 – 26	0.2	45 – 71.5	13.6 – 21	0.5 – 2

Fibres	Lignin (%)	Pectin (%)	Cellulose (%)	Hemicellulose (%)	Ash (%)
Ramie	0.6 – 0.7	1.9	68.6 – 91	5 – 16.7	-
Henequen	13.1	-	77.6	4 – 8	-
Sisal	7 – 11	10	47 – 78	10 – 24	0.6 – 1
Abaca	7 – 9	-	56 – 63	15 – 17	3

Source: [9].

The chemical constituents of some of the important natural fibres are shown in Table 2. From the table it can be clearly seen that the cellulose percentage is higher in all the fibres in comparison to other substances such as lignin, pectin, hemi-cellulose and ash content.

2.1.1. Composite Materials

A composite is generally defined as a heterogeneous combination of two or more chemically distinct materials with a distinct interface between them having some desirable properties which are different from its parent constituent materials. Composite consists of two phases i.e. a continuous phase and a discontinuous phase. The continuous phase of the composite is known as the matrix while the discontinuous phase is known as the reinforcement. The primary function of the matrix phase is to give shape to the composite and transfer the stresses from the discontinuous phase. Further, it protects the discontinuous phase from any environmental and mechanical damages thereby acting as a shield. The main function of the discontinuous phase or the reinforcement is to provide stiffness, strength and other desired properties [10].

The density of matrix material is typically more as compared to the reinforcing material. The different chemical and physical properties of the composites components are combined in a synergistic practice in order to take advantage of some superior properties of the constituent materials.

Recently, composites have successfully taken the place of traditional materials in the field of high strength and lightweight applications. This exponentially increasing popularity of composite materials can be attributed to several advantages offered by them such as high creep strength, improved strength-to-weight ratio, higher toughness, high tensile strength at increased temperature, etc. The property of strength of a composite largely depends on the design and correctness of its development process.

2.1.2. Classification of Composites

On the basis of the matrix materials used, Abdul Khalil *et al.* [11] broadly classified composites into three types. They are:

- i. Metal Matrix Composites (MMC)
- ii. Ceramic Matrix Composites (CMC)
- iii. Polymer Matrix Composites (PMC)

(i) Metal Matrix Composites (MMC)

A metal matrix composite offers several advantages over traditional metals such as higher specific modulus, low coefficient of thermal expansion, higher specific strength, and improved properties at higher temperatures. As a result of these advantages, MMCs are widely used in aerospace industries for the manufacturing of combustion chamber nozzle tubing, housings, heat exchangers, etc.

(ii) Ceramic Matrix Composites (CMC)

Ceramic matrix composites have very high toughness and have high heat resistant properties. CMCs are generally accompanied with improvement in stiffness and strength properties.

(iii) Polymer Matrix Composites (PMC)

Currently, polymers are the most widely used matrix materials. Although the processing of polymer matrix composites does not require any sophisticated technology, the strength and stiffness properties of polymer matrix are lower as compared to ceramic matrix and metal matrix. Because of this, these matrices are reinforced with reinforcing materials which have superior strength and other mechanical properties as compared to the polymer matrix. The popularity of polymer composites is increasing very rapidly in thermal, structural and even in micro-electronic applications.

Generally, polymer composites can be divided into two main categories based on the type of reinforcing material used. They are:

- i. Fibre reinforced polymers (FRP)
- ii. Particulate reinforced polymers (PRP)

Composites which consist of fibres as the reinforcing phase are classified under fibre reinforced polymer composites. The fibre is responsible for imparting strength to the composite while the matrix is responsible for holding together the fibres and transferring the stresses. The load is carried in the longitudinal direction of the fibre. At times, filler is added in order to ease the manufacturing process. Some of the commonly used fibres in industrial applications include glass fibre, carbon fibre, asbestos, natural fibre, etc. Likewise, phenolic resin, epoxy, vinyl ester, polypropylene, polyester, polyurethane, etc. are some of the commonly used matrix materials.

Generally, the use of particulates in the reinforcing phase decreases the ductility of the material and at the same time increases its modulus. The cost of the composite is also considerably reduced by incorporation of particulates in the reinforcing phase. Particles used for reinforcing include metal powders, small mineral particles, ceramics, etc. High strength, corrosion resistance, low density, wear resistance and high melting point are some of the viable properties of glasses and ceramics.

Apart from this two broad classification of polymer composite, there is another type which is known as hybrid composite. A hybrid composite is a combination of both fibre and particulate reinforced in a common matrix. This is done in order to get the combined advantages of both the fibre and the particulate.

2.2. Methods of Production

Natural fibre polymer composites (NFPC) are a composite material consisting of a polymer matrix embedded with high – strength natural fibres such as jute, kenaf, sisal, oil palm and flax [12]. The properties of natural fibre composite are different to each other according to previous studies, because of different kinds of fibres, sources, and moisture conditions. The performance of NFPCs relies on some factors, like mechanical composition, microfibrillar angle, structure, defects, cell dimensions, physical properties, chemical properties and also the interaction of a fibre with the matrix [13-18]. Since every product in the market has drawbacks, similarly, natural fibre reinforced polymer composites also have drawbacks. The couplings between natural fibre and polymer matrix are a problem taken into consideration, as a result of the difference in chemical structure between these two phases. This leads to ineffective stress transfer during the interface of the NFPCs. Thus, the chemical treatments for the natural fibre are necessary to achieve good interface properties. The reagent functional groups in the chemical treatments have ability to react on the fibre structures and alter the fibre composition [19].

Natural fibres include a functional group named as hydroxyl group which makes the fibres hydrophilic. During manufacturing of NFPCs, weaker interfacial bonding occurs between hydrophilic natural fibre and hydrophobic polymer matrices due to hydroxyl groups in natural fibres. This could produce NFPCs with weak mechanical and physical properties [8].

The bonding strength between fibre and polymer matrix in the composite is considered a major factor in order to get superior fibre reinforcement composites properties. Because of pendant hydroxyl and polar groups in fibre, this leads to extremely high moisture absorption of fibre, resulting in weak interfacial bonding between the fibre and the hydrophobic matrix polymers. To develop composites with good mechanical properties, chemical modification of fibre is carried out to reduce the hydrophilic behaviour of fibres and the absorption of moisture [20-21].

The different surface treatments of advanced composites applications were reviewed by several researchers [22-24]. The effects of different chemical treatments on cellulosic fibres that were employed as reinforcements for thermoplastics and thermoset were also examined. For the treatments, the different kinds of chemical treatment include silane, alkali, acrylation, benzoylation, maleated coupling agents, permanganate, acrylonitrile and acetylation grafting, stearic acid, peroxide, isocyanate, triazine [25-35], fatty acid derivative (oleoyl chloride), sodium chloride, and fungal [19]. The main purpose of surface treatments of natural fibres is to enhance fibre/matrix interfacial bonding and stress transferability of the composites.

The impact of alkaline treatment on surface properties of Iranian cultivated natural fibres was studied by [36]. The research revealed that alkaline treatment gets rid of some chemical components on the surface of the fibres, comprising

uronic acid (hemicellulose), aromatic moieties (extractives), and nonpolar molecules from the partial lignin depolymerisation. There is a stronger effect on chemical components of non-wood fibres. Improving the crystallinity of non-wood fibres, in the softwood fibres result in only a minor increase. Hence, alkaline treatment can result in a remarkable improvement in the specific interaction of the fibres as well as improving the fibres' wettability.

Le Troedec *et al.* [37] revealed the effects of some chemical treatments, comprising ethylenediaminetetraacetic acid (EDTA), NaOH, polyethyleneimine (PEI), CaCl₂, and Ca(OH)₂. The effects were on the mechanical properties of the composite materials from mixtures of hemp fibre and lime by differential thermal evaluation and tests. The observation was that every treatment had a direct effect on the fibre surface. The treatment was with 6% NaOH and led to cleaning fibres by removing the amorphous compounds, and the increase of the crystallinity index of fibre bundles, while the EDTA treatment led to separating fibres and complex calcium ions related to pectin's. In brief, PEI treatment shows all studied properties an intermediate character and lime water treatment depicts calcium ions' fixation at the surface of fibres in comparison to a calcium chloride treatment which does not.

May-Pat *et al.* [38] reported on the impact of the interphase properties from well controlled surface treatment in the case of natural fibres. The fracture behaviour and the mechanical properties of a NFPC depend on the properties of constituents and regions of the fibre surface, or interphase, where the stress transfer occurs. Furthermore, the tailoring of the interphase by different kinds of surface treatments and carefully characterizing it provides a better knowledge of the behaviour of the NFPCs. Moreover, different fibre surface treatments modify the natural fibre microstructure specifically under high loading rates.

Venkateshwaran *et al.* [39] studied the effect of alkali (NaOH) treatments of various concentrations (0.5%, 1%, 2%, 5%, 10%, 15%, and 20%) on the mechanical properties of banana/epoxy composite. The results reported that as compared to other treated and untreated fibre composites, 1% NaOH treated fibre reinforced composites have better properties. The alkali concentration on the fibre surfaces results in better mechanical properties of the resulting composite.

However, the rising of alkali concentration may cause fibre surface damage, leading to a decrease of mechanical properties. The effect of different chemical treatment on the mechanical properties and characteristics of sisal-oil palm hybrid fibre reinforced natural rubber composites have been studied by John *et al.* [40]. With chemical treatment, the torque values increased which lead to greater crosslinking. Similarly, alkali treatment showed a rise in the composites' tensile strength in comparison to untreated composites and with 4% NaOH treated fibres, optimum tensile strength was seen for resulting composites. In contrast, for composites treated with 4%NaOH a strong interface is apparent because a more superior adhesion between rubber and fibre is present

which avoids solvent entry and a little swelling occurs.

Van de Weyenberg *et al.* [17] examined the impact of flax processing parameters, and the fibre treatment, on the mechanical properties of flax fibre reinforced epoxy composites. It was discovered that the employment of long flax slivers may not necessarily lead to more superior composite properties. The highest enhancement of the flexural properties of the flax fibre reinforced epoxy composites can be gotten by chemical treatments. There was an increase of transverse strength of up to 250% and transverse modulus, of up to 500%. In addition, the longitudinal properties of the unidirectional (UD) composites (both modulus and strength) showed improvements with 40% or more. Some modifications in the chemical and physical properties of the lignocellulosic fibres can be observed after the treatment of the fibre of rubber wood with laccase enzymes.

These chemical treatments lead to the amorphous lignin content, changing the hemicellulose content and ultimately the natural crystallinity [41]. The fibre has a treatment effect on morphological and single fibre tensile strength of empty fruit bunch (EFB) fibre. The EFB fibre treated with boiling water, 2% sodium hydroxide (NaOH), and mixing of boiling water and NaOH was examined by Norul *et al.* [42]. It was revealed that it changed the properties of the fibre surface topography after the treatment. Compared to untreated EFB fibre, the treated EFB fibres with the two types of treatment were more thermal stable. On the other hand, the tensile strength and Young's modulus of the treated fibre showed a rise in comparison to untreated fibres. For tensile modulus, the alkaline treatment has enhanced the tensile properties of sugar palm fibre reinforced epoxy composites at better soaking times and concentrations of alkaline. On the other hand, the increase in alkaline concentration may lead to fibre damage [43].

Acrylonitrile Butadiene Styrene (ABS) with the coating effect of OPEFB fibres was tested BT. The coated process enhanced the mechanical and physical properties and also

improved the fibre performance. The ABS treatment led to reducing the water absorption and also decreased the biodegradation potential of the fibre in contact with soil. With the coating, the tensile strength and elasticity moduli of the OPEFB fibres became better than what they were in the past. The surface area between fibre and soil particles increased by coating fibre, which led to improving the shear strength parameters of the fibre reinforced soils [44].

Thiruchitrambalam *et al.* [45] investigated the static and dynamic mechanical properties of Palmyra palm leaf fibre treated in alkali and jute fibre reinforced in a polyester matrix. The hybrid composites are fabricated with unidirectional arrangement of the fibres. It is observed that the addition of alkali treated palmyra fibre enhanced the impact strength of the composite more than addition of jute fibre to the composite.

Thiruchitrambalam *et al.* [45] investigated the physical, chemical properties of untreated and chemically treated palmyra palm leaf stalk fibres (PPSF). PPLSF extracted from the leaf stalks of palmyra palm tree were subjected to alkali, benzoylation and permanganate pre – treatments. They analysed the changes in chemical, physical, mechanical and morphology of the untreated and treated fibres and concluded that the diameter of fibres was not found to be uniform throughout the fibre length. Untreated fibres had an average diameter of 320µm. the diameter of fibres were found to reduce due to treatments by 25%, 34% and 41% for alkali, benzoyl and permanganate treated fibre respectively in comparison to untreated fibre. Chemical analysis also indicated the removal of hemicelluloses and partial removal of cellulose, lignin and wax. The densities of fibres were seen to increase due to chemical pre – treatments. Highest density was observed in the case of benzoylchloride treatment compared to other treatments. The chemical constituents of untreated and treated PPLSF and the comparison of both the chemical and physical properties of natural fibres with palmyra fibres are shown in Table 3 and Table 4 respectively.

Table 3. Chemical Contents of Untreated and Treated Palmyra Fibres.

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Wax (%)	Density (g/cc)
Untreated	58.58	22.8	13.48	0.53	0.456
Alkali Treated	52.56	Nil	10.23	0.16	1.152
Benzoyl Chloride Treated	52.55	Nil	10.36	0.15	1.194
Permanganate Treated	51.98	Nil	8.92	0.16	1.186

Source: [45].

Table 4. Comparison of Chemical and Physical Properties of Natural Fibres with Palmyra Fibres.

	Cellulose	Hemicellulose	Lignin	Wax	Density	Diameter
PPLSF	58.58	22.8	13.48	0.35	0.456	320
Jute	58.63	-	12 – 14	-	1.3	10 – 40
Sisal	66 – 78	10 – 14	10 – 14	0.3	1.5	50 – 200
Cotton	82.7	5.7	-	0.6	1.6	-
Flax	64.1	16.7	2	1.5	1.5	-
Ramie	68.6	13.1	0.6	0.3	1.5	-
Coir	-	16.8	32.1	-	1.2	100 – 450

Source: [45].

3. Conclusions

Dynamic mechanical analysis, mechanical properties, thermal property, water absorption property and tribological property of fibre polymer composite are discussed and the following conclusions are reported.

- 1) Mechanical properties like tensile, flexural and impact properties of organic brake pad composite can be improved by increasing fibre content or loading, especially treated fibres.
- 2) Dynamic mechanical properties such as storage modulus, loss modulus, damping, Young's modulus and glass transition temperature are found to improve as a result of various chemical treatments.
- 3) Thermal stability of fibres improved when treated with two types of treatments of both boiling water and alkaline together.
- 4) The interfacial bonding (adhesion) between fibres and matrices is greatly enhanced by chemical treatments which reduces water absorption property and decreases the biodegradation potential of the fibre as well.
- 5) Wear rate and coefficient of friction of fibre reinforced polymer composites are found to decrease as a result of increasing organic fibre content.
- 6) Smaller or minute particle size organic fibre composites have better homogeneity, and good compatibility with binding materials, hence yield better mechanical properties and reduce both water absorption and noise during braking process.

References

- [1] Anon. Automotive Brake Repairs Trends and Safety Issues. *SciElo Analytics Brasil Website*. [Online] May 2, 2004. <http://www.sirim.my/amtec/pm/brake.html>.
- [2] Norton, R. L.,. *Machine Design: An Integrated Approach*. [ed.] Ali Gordon. 4th. s. l.: Pearson, 2010.
- [3] Weintraub, M. *Brake Additives Consultant*. s. l.: Private Communication, 1998.
- [4] Blau, P. J.,. *Compositions, Functions and Testing of Friction Brake Materials and Their Additives*. U.S. Department of Energy, Energy Efficiency and Renewable Energy, Transportation Technologies. Tennessee: Oak Ridge National Laboratory, 2001. pp. 78-80.
- [5] *Performance of Ceramic-Enhanced Phenolic Matrix Brake Lining Materials for Automotive Brake Linings*. Hee, K. W., Filip, S. P. 7-12, 2005, *Wear*, Vol. 259, pp. 1088-1096.
- [6] *Development of Natural Fibre in Non-metallic Brake Friction Material*. Efendy, H., Mochamad, W. M., Yusuf, N. B. M. Palembang: s. n., 2010, Seminar Nasional Tahunan Teknik Mesin (SNTTM), Vols. Ke-9, pp. 13-15.
- [7] Dagwa, I. M. Development of Automobile Disc Brake Pad from Local Materials. Benin: University of Benin, 2005.
- [8] *Bio Fibres and Biocomposites*. John, M. J., Thomas, S. 3, 2008, *Carbohydrate Polymers*, Vol. 71, pp. 343-364.
- [9] *Influence of Chemical Surface Modification on the Properties of Biodegradable Jute Fabrics-Polyester Amide Composite*. Mohanty, A. K., Khan, M. A., Hinrichsen, G. 2, 2000, *Composites Part A: Applied Science and Manufacturing*, Vol. 31, pp. 143-150.
- [10] Biswal, S., Satapathy, A. *Preparation, Properties and Wear Performance Evaluation of Epoxy-Palmyra Fibre Composites*. Mechanical Engineering, National Institute of Technology. Rourkela: Wiley Online Library, 2016.
- [11] *Natural Fibre Reinforced Poly (Vinyl Chloride) Composites: A Review*. Abdul Khalil, H. P. S., Tehrani, M. A., Davoudpour, Y., Bhat, A. H., Jawaid, M., Hassan, A. 5, 2013, *Journal of Reinforced Plastics and Composites*, Vol. 32, pp. 330-356.
- [12] *A Review on the Tensile Properties of Natural Fiber Reinforced Polymer Composites*. Ku, H., Wang, H., Pattarachaiyakoo, N., Trada, M.. 4, 2011, *Composites Part B: Engineering*, Vol. 42, pp. 856-873.
- [13] *Natural Fiber Reinforced Polymer Composites in Industrial Applications: Feasibility of Date Palm Fibers for Sustainable Automotive Industry*. Al-Oqla, F. M., Sapuan, S. M. 2014, *Journal of Cleaner Production*, Vol. 66, pp. 347-354.
- [14] *Mechanical Processing of Bast Fibres: The Occurrence of Damage and its Effect on Fibre Structure*. Hänninen, T., Thygesen, A., Mehmood, S., Madsen, B., Hughes, M.. 1, 2012, *Industrial Crops and Products*, Vol. 39, pp. 7-11.
- [15] *Processing and Characterization of Natural Cellulose Fibers/Thermoset Polymer Composites*. Thakur, V. K. & Thakur, M. K. 2014, *Carbohydrate Polymers*, Vol. 109, pp. 102-117.
- [16] *Biocomposites Reinforced with Natural Fibres*. Faruk, O., Bledzki, A. K., Fink, H. P., Sain, M. 11, 2012, *Progress in Polymer Science: 2000-2010*, Vol. 37, pp. 1552-1596.
- [17] *Influence of Processing and Chemical Treatment of Flax Fibres on their Composites*. Van de Weyenberg, I., Ivens, J., De Coster, A., Kino, B., Baetens, E., Verpoest, I. 9, 2003, *Composites Science and Technology*, Vol. 63, pp. 1241-1246.
- [18] Dai, D. & Fan, M. *Wood fibres as Reinforcements in Natural Fibre Composites: Structure, Properties, Processing and Applications in Natural Fibre Composites: Materials, Processes and Properties*. s. l.: Woodhead Publishing, 2014. pp. 3-65.
- [19] *Chemical Treatments on Plant-Based Natural Fibre Reinforced Polymer Composites: An Overview*. Kabir, M. M., Wang, H., Lau, K. T., Cardona, F. 7, 2012, *Composite Part B-Engineering*, Vol. 43, pp. 2883-2892.
- [20] *Oil Palm Fibre (OPF) and its Composites: A Review*. Shinoj, S., Visvanathan, R., Panigrahi, S., Kochubabu, M. 1, 2011, *Industrial Crops and Products*, Vol. 33, pp. 7-22.
- [21] *Characterization of Chemically and Enzymatically Treated Hemp Fibres Using Atomic Force Microscopy and Spectroscopy*. George, M., Mussone, P. G., Abboud, Z. & Bressler, D. C. 2014, *Applied Surface Science*, Vol. 314, pp. 1019-1025.
- [22] *Possibilities for Improving the Mechanical Properties of Jute/Epoxy Composites by Alkali Treatment of Fibres*. Gassan, J. & Bledzki, A. K.. 9, 1999, *Composites Science and Technology*, Vol. 59, pp. 1303-1309.

- [23] *The Effect of Fiber Treatment on the Mechanical Properties of Unidirectional Sisal-Reinforced Epoxy Composites*. Rong, M. Z., Zhang, M. Q., Liu, Y., Yang, G. C., & Zeng, H. M.. 10, 2001, *Composites Science and Technology*, Vol. 61, pp. 1437-1447.
- [24] *Continuous Natural Fiber Reinforced Thermoplastic Composites by Fiber Surface Modification*. Wongsriraksa, P., Togashi, K., Nakai, A. & Hamada, H. 2013, *Advances in Mechanical Engineering*, Vol. 5, p. Article ID685104.
- [25] *Rice and Einkorn Wheat Husks Reinforced Poly (lactic acid) (PLA) Biocomposites: Effects of Alkaline & Silane Surface Treatments of Husks*. Tran, T. P. T., B'en'ezet, J. C. & Bergeret, A.. 2014, *Industrial Crops and Products*, Vol. 58, pp. 111-124.
- [26] *Effect of Chemical Treatment on Physical, Mechanical and Thermal Properties of Ladies Finger Natural Fiber*. Hossain, S. I., Hasan, M., Hasan, M. N. & Hassan, A.. Article ID 824274, 2013, *Advances in Materials Science and Engineering*, Vol. 2013, p. 6 pages.
- [27] *Natural fiber composites with plant oil-based resin*. O'Donnell, A., Dweib, M. A. & Wool, R. P. 9, 2004, *Composites Science and Technology*, Vol. 64, pp. 1135-1145.
- [28] *Mechanical and Thermomechanical Behaviors of Sizing-Treated Corn Fiber/Polylactide Composites*. Luo, H., Xiong, G., Ma, C. et al. 2014, *Polymer Testing*, Vol. 39, pp. 45-52.
- [29] *Maleated Natural Rubber as a Coupling Agent for Paper Sludge Filled Natural Rubber Composites*. Ismail, H., Rusli, A. & Rashid, A. A.. 7, 2005, *Polymer Testing*, Vol. 24, pp. 856-862.
- [30] *Effect of Surface Treatments on the Electrical Properties of Low-Density Polyethylene Composites Reinforced with Short Sisal Fibers*. Paul, A., Joseph, K. & Thomas, S. I., 1997, *Composites Science and Technology*, Vol. 57, pp. 67-79.
- [31] *Chemical Modification of Jute Fibers for the Production of Green-Composites*. Corrales, F., Vilaseca, F., Llop, M., Giron'es, J., M'endez, J. A. & Mutj', P.. 3, 2007, *Journal of Hazardous Materials*, Vol. 144, pp. 730-735.
- [32] *Study of the Interfacial Properties of Natural Fibre Reinforced Polyethylene*. Torres, F. G. & Cubillas, M. L. 6, 2005, *Polymer Testing*, Vol. 24, pp. 694-698.
- [33] *Characterization of Poly(lactic Acid) (PLA)/Kenaf Composite Degradation by Immobilized Mycelia of *Pleurotus ostreatus**. Hidayat, A. & Tachibana, S.. 2012, *International Biodeterioration & Biodegradation*, Vol. 71, pp. 50-54.
- [34] *A Method for Determining Reactive Hydroxyl Groups in Natural Fibers: Application to Ramie Fiber and its Modification*. He, L., Li, X., Li, W., Yuan, J. & Zhou, H. 2012, *Carbohydrate Research*, Vol. 348, pp. 95-98.
- [35] *Surface Modification of Cellulose with Triazine Derivative to Improve Printability with Reactive Dyes*. Xie, K., Liu, H., & Wang, X. 3, 2009, *Carbohydrate Polymers*, Vol. 78, pp. 538-542.
- [36] *Investigation on the Surface Properties of Chemically Modified Natural Fibers Using Inverse Gas Chromatography*. Cordeiroa, N., Ornelasa, M., Ashorib, A., Sheshmanic, S. & Norouzi, H.. 4, 2012, *Carbohydrate Polymers*, Vol. 87, pp. 2367-2375.
- [37] *Influence of Various Chemical Treatments on the Composition and Structure of Hemp Fibres*. Le Troedec, M., Sedan, D., Peyratout, C., et al.. 3, 2008, *Composites Part A: Applied Science and Manufacturing*, Vol. 39, pp. 514-522.
- [38] *Effect of Fibre Surface Treatments on the Essential work of Fracture of HDPE-Continuous Henequen Fibre-Reinforced Composites*. May-Pat, A., Valadez-Gonzalez, A., Herrera-Franco, P. J. 6, 2013, *Polymer Testing*, Vol. 32, pp. 1114-1122.
- [39] *Fiber Surface Treatment and its Effect on Mechanical and Visco-Elastic behaviour of Banana/Epoxy Composite*. Venkateshwaran, N., Elaya Perumal, A., Arunsundaranayagam, D. 2013, *Materials & Design*, Vol. 47, pp. 151-159.
- [40] *Effect of Chemical Modification on Properties of Hybrid Fiber Biocomposites*. John, M. J., Francis, B. K., Varughese, T. & Thomas, S. 2, 2008, *Composites Part A: Applied Science and Manufacturing*, Vol. 39, pp. 352-363.
- [41] *Fabrication of Medium Density Fibreboard from Enzyme Treated Rubber Wood (*Hevea brasiliensis*) Fibre and Modified Organosolv Lignin*. Nasir, M., Gupta, A., Beg, M. D. H., Chua, G. K. & Kumar, A.. 2013, *International Journal of Adhesion and Adhesives*, Vol. 44, pp. 99-104.
- [42] *Effects of Fiber Treatment on Morphology, Tensile and Thermogravimetric Analysis of Oil Palm Empty Fruit Bunches Fibers*. Norul Izani, M. A., Paridah, M. T., Anwar, U. M. K., Mohd Nor, M. Y., H'Ng, P. S.. 1, 2013, *Composites Part B: Engineering*, Vol. 45, pp. 1251-1257.
- [43] *Effect of Chemical Treatment on Flexural Properties of Natural Fiber Reinforced Polyester Composite*. Rokbi, M., Osmani, H., Imad, A. & Benseddiq, N. 2011, *Procedia Engineering*, Vol. 10, pp. 2092-2097.
- [44] *Performance of Oil Palm Empty Fruit Bunch Fibres Coated with Acrylonitrile Butadiene Styrene*. Bateni, F., Ahmad, F., Yahya, A. S. & Azmi, M. 4, 2011, *Construction and Building Materials*, Vol. 25, pp. 1824 -1829.
- [45] *The Physical, Chemical Properties of Untreated and Chemically Treated Palmyra Palm Leaf Fibres*. Thiruchitrabalam, M., Logesh, M., Shanmugam, D. & Muthukumar, S. 2.24, 2018, *International Journal of Engineering & Technology*, Vol. 7, pp. 582-585.
- [46] Shanmugam, D. *Studies on the Properties of Palmyra Palm Leaf Stalk Fibre (PPLSF) Reinforced Polyester Composite Materials*. Tamil Nadu: Anna University, 2014.