Vol. 46, No. 2 (2024) 283-297, DOI: 10.24874/ti.1537.08.23.11

Tribology in Industry

www.tribology.rs

RESEARCH

Mechanical and Wear Properties of Developed Cellulosic Fiber-Particles Hybrid Reinforced Epoxy-Based Composites for Automotive Application

Isiaka Oluwole Oladele[a,b,*], Samuel Olumide Falana[a], Linus Nnabuike Onuh[a,c], Olajesu Favour Olanrenwaju[d], Samson Oluwagbenga Adelani[a,e], Precious Ebube Nnodu[a], Oluwatosin Johnson Ajala[a]

[a]*Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, PMB 704, Nigeria,*
[b]*Centre for Nanomechanics and Tribocorrosion, School of Metallurgy, Chemical and Mining Engineering, University of Johannesburg, Johannesburg, South Africa,*
[c]*Faculty of Materials and Chemical Engineering, University of Miskolc, Miskolc, Egyetem ut 1, 3515 Hungary*
[d]*Department of Materials Science and Engineering, Iowa State University, Ames, IA, USA,*
[e]*Materials Science and Engineering Program, University of Colorado Boulder, 80303, Colorado, USA.*

Keywords:

Sisal fiber
Waste paper
Hybrid composite
Polymer
Epox
Automotive
Mechanical and wear properties

* Corresponding author:

Isiaka Oluwole Oladele
Email: iooladele@futa.edu.ng

Received: 31 August 2023
Revised: 8 October 2023
Accepted: 29 November 2023

A B S T R A C T

Studies are presently ongoing to advance the development of bio-composite materials through the exploration of the potential use of reinforcements of natural origin in polymer matrixes. In this particular investigation, hybrid reinforced composite was formulated for automotive application by utilizing epoxy as the matrix and sisal fiber-paper particles as the reinforcements. The sisal fiber was extracted employing soil retting method, subjected to surface treatment, and combined with paper particles. Following preparation of the reinforcements, predetermined compositions (3, 6, 9, 12 and 15 wt %) were mixed with epoxy resin before being poured into the moulds using hand layup process and were allow to cure. The study focused on the mechanical, wear, and water absorption properties, as well as the surface morphologies of the developed composites. The results of the study revealed that the optimal properties were achieved with the utilization of 9 wt. % and 12 wt. % sisal fiber-paper particles reinforced composite. Particulate paper was discovered to be a suitably surface compatibilizer in thermosets when used as fillers with fiber reinforcement. Thus, the epoxy based composite reinforced with hybrid sisal fiber-paper particles is suitable for automobile application in the fabrication of bumper and other epoxy based body parts.

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1. INTRODUCTION

In recent years, composites have been found to meet optimal criteria for a variety of materials of interest to designers. Over the past half-century, significant advances have been made in the design and manufacturing of lightweight as well as high strength materials which is largely attributable to the proliferation of polymer composite materials [1]. Polymer matrix composites reign as the most

prevalent form of advanced composites. The versatility of these materials is notable because they can be fashioned into an array of shapes and sizes [2]. Furthermore, they offer exceptional strength and stiffness, coupled with resistance against the corrosive effects of the environment [3]. Among the various categories of polymeric composites, one notable type is epoxy. This thermosetting polymer boasts a distinctive set of mechanical, chemical, and thermal properties, making it a popular option for use as impregnating materials, adhesives, or matrices in composite materials. Epoxy-matrix composites, in particular, are widely recognized for their strong adhesion, lightweight nature, excellent mechanical and tribological characteristics, sufficient chemical and corrosion resistance, minimal shrinkage upon curing (resulting in good dimensional stability), and relatively simple processing requirements. Given these favorable attributes, the demand for epoxy-based composite materials remains consistently high for a range of applications, including in structural components, electrical and electronic systems, automobile parts, and industrial tooling [4]. However, the mechanical properties of epoxy-based matrix composites are limited on average in comparison to those of metal matrix composites, hence, to address this challenge; fillers are employed to reinforce the matrix. It is important to note that considerable advancements have been made in this regard. Particles, fibers, and whiskers have all been utilized for the reinforcement of PMCs and it has been reported that the properties of the epoxy based matrix has been enhanced with the addition of reinforcements [5-7]. However, despite several works on epoxy based composites using sisal fiber with improved properties, sisal fiber-paper particles have not been investigated, hence, one of the reasons for this research. Aside this, after the generation, distribution, and conservation of energy, one of the most pressing issues facing the world is the protection of the environment. As a result, there is a constant effort to develop environmentally friendly materials that do not pose a threat to human health or the environment as a whole. To this end, researchers have turned to natural fibers as a substitute for synthetic fibers that were previously used in various applications. These fibers are incorporated as additives in polymer resins for various advanced applications in automobile, aeronautics, and other areas due to their lightweight, sustainable, renewable, high modulus, and non-toxic nature. Furthermore, they have the ability to absorb carbon dioxide (CO_2) from the atmosphere, thus improving the quality of oxygen available to humans. Although there is much appeal in replacing synthetic fiber-based composite materials with natural fiber-based composites, the mechanical performance of the latter is still inadequate. This is due to the fact that the mechanical performance of composite materials is contingent upon a number of factors, including fiber loading, the type of fibers and matrix, as well as the bonding between fibers and the matrix, with fiber hybridization playing a critical role. Hybridization, which involves combining two or more reinforcements in a polymer matrix, can take the form of artificial-artificial, natural-artificial, or natural-natural types [2,8]. This method has the potential to address the drawbacks of a composite of a single reinforcement type while retaining the benefits of the others. The mechanical properties of hybrid composites are primarily influenced by the volume percentages fraction, stacking sequence of the layers, treatment, and external variables. As of late, research has focused on hybridizing two or more different polymers or reinforcements to enhance the mechanical properties of composites [6]. For example the effects of hybridization on the mechanical properties of bagasse/sisal/coir reinforced epoxy hybrid composite was investigated by Oluwatoyin [9] and it was revealed that hybridization resulted in an augmentation of both the tensile strength and flexural modulus of the composites. In contrast, the hardness of the composites decreased with the hybridization of the fibres. Also experimental investigation of suitable car bumper material using glass fiber reinforced polymer (GFRP), kenaf, sisal and kapok fiber was investigated by Mahesh [10]. In the research GFRP with kenaf, kapok and sisal fiber-synthetic based hybrid composites and another composition with kenaf, kapok and sisal fiber composites were prepared and, from the results it was concluded that the synthetic-based hybrid composites are suggested as the bumper material compared to the natural fiber-based hybrid composites.

The automotive industry faces two major challenges: high costs and heavy components. These issues lead to increased consumption of fossil fuels, resulting in significant CO_2 emissions and contributing to climate change. To mitigate vehicle fuel consumption and exhaust emissions, it is essential to manufacture vehicles using lighter materials, which can help reduce CO_2 emissions and promote a healthier and more environmentally friendly approach to sustainable development. As

reported by Davoodi et al [11], a 25% reduction in vehicle weight could potentially save 250 million barrels of fossil fuel. Epoxy-based composite materials reinforced with natural reinforcements (fibers or particles) offer a promising solution, capable of reducing car weight by about 10-30% [12]. Natural reinforced composites offer several advantages, including low density, high specific strength, cost-effectiveness, and ease of production. These reinforcements can be sourced from plants, animals, or minerals. Extensive research has demonstrated the effectiveness of polymer composites reinforced with natural fibers. This approach not only reduces reliance on synthetic fibers, which contribute to environmental degradation, but also promotes sustainability [13, 14]. In addition, studies on natural reinforced composites have demonstrated that composites in their hybrid form exhibit better properties over single reinforced composite. When it is subjected to loading conditions, each individual reinforcements offers its best possible resistance. Marichelvam's research on the fabrication of a new hybrid composite from palm sheath and sugarcane bagasse fibers with epoxy resin indicates the suitability of these materials for automobile dashboard applications by emphasizing their outstanding mechanical qualities [15]. An exploratory study was carried out to evaluate the efficacy of integrating milkweed, kusha grass, sisal, banana, and hay fibers with polypropylene, resulting in a unique composite material suited for automotive applications [16]. Another hybrid composite (HC), was developed for lightweight car applications using sisal/kenaf fibers reinforced with an epoxy matrix. The water absorption capacity of HC material was discovered to be superior to that of individual fiber composites in a study of water absorption. The automotive industry is promoting eco-friendly technology in automobile manufacturing by using natural fibers. Concurrently, the sustainability movement is creating new commercial prospects in the automotive industry, making these fibers ideal for usage as biofibers in environmentally sustainable products [17].

Paper is widely recognized as one of the most widely used materials for packaging primarily due to its low cost and availability. Also, it is usually considered as a sustainable material owing to its derivation from renewable sources, namely plants, and its remarkable recyclability at a rate as high as 100%. Waste papers are readily obtainable in homes, schools, and offices where paper usage is extensive. Unfortunately, in numerous developing nations, waste papers are frequently incinerated or disposed of indiscriminately which showed that the potentials in these waste materials is currently underutilized and this causes environmental problems [18,19]. Therefore, successful application of waste papers in addition to other reinforcements can aid the actualization of the advancement in the materials potentials such as light weight and adequate filling and wetting agent in polymer composite development due to it cellulose content [19].

Several studies have looked into alternatives to encourage the reuse and recycling of waste paper. Among these options are the manufacturing of useful substances like bioethanol [20,21] and activated carbon [22], as well as the use of waste paper as a filler in polymeric composites [23]. Natural fiber-reinforced polymeric composites are increasingly being used to create sustainable, durable, and lightweight materials with advantageous qualities for a variety of applications [24]. Waste paper from plant sources has emerged as a viable substitute for or supplement to synthetic fibers, inorganic solid waste fillers like fly ash and slag ultrafine powder due to its low cost, reduced weight, recyclability, high performance, and environmentally friendly nature [25]. Waste paper can be used as a filler in polymeric composites in a variety of forms, including paper sheets for laminated composites [26], paper particles for injection molding [27] treated paper with coupling agents and cellulose recovered from paper [28]. Its integration improves polymer physicomechanical characteristics, which aligns with the environmental principles of the 2030 Agenda for Sustainable Development goals, which aim to promote the well-being of present and future generations through global collaboration.

The use of paper particles in conjunction with other natural fibers or particulates, in polymer matrix composites is yet to undergo extensive examination by researchers. Specifically, the addition of particulate waste papers into epoxy has not been thoroughly investigated. Consequently, this research aims to develop a lightweight hybrid epoxy-based composite for automotive applications by incorporating sisal fibers and paper particles in varying proportions (3-15 wt. %). The

microstructure of the fracture surface of the hybrid reinforced epoxy composites was examined. Additionally, the mechanical properties, wear behavior, density, and water absorption properties of the hybrid composites were evaluated. The material is expected to be used in the fabrication of bumpers, dashboards, door panels, and other upper body components, where polymers such as polypropylene, polyamide, polyvinyl chloride, and polyethylene are currently employed. Aside from the reasons indicated above, the use of paper particles would improve waste management within our settings, which is one of the most significant difficulties confronting people all over the world. Reusing garbage is a waste management technique that includes reclaiming operations [29].

2. MATERIALS AND METHODS

2.1 Materials

The present study utilized commercially available Bisphenol A diglycidyl ether epoxy resin and diethylene triamine curative, commonly known as hardener, sodium hydroxide and distilled water that was procured from Pascal Scientific Akure in Ondo State, Nigeria. The Agave sisalana leaves were sourced from a farmland located at longitude 5.159440 and latitude 7.296990 in Akure, Ondo State, while the waste paper was obtained from the University environment.

2.2 Extraction and treatment of sisal-fiber

The process of obtaining sisal fiber involved extracting it from the plant's leaves using the soil retting method. This method consists of burying the leaves underground for 15 days to allow fermentation to occur followed by washing and sun drying within 5 days. This method, as previously demonstrated in Oladele et al [29], is chosen for several reasons. It is cost-efficient and sustainable since it does not require the use of chemicals; instead, it relies on microbial action, specifically the activity of bacteria and fungi. These microorganisms break down the pectin that binds the fibers, allowing for their extraction and removing non-fiber components and impurities from the plant material. Soil retting also accelerates the breakdown of plant cell walls, reducing overall processing time. Unlike decorticated fibers, which are beaten, thereby weakening the fiber, this method is favored by researchers for its ability to produce high-quality fibers that are strong, durable, and flexible, as confirmed in the results of studies by Oladele et al [30], Daramola et al. [31], and Balogun et al [32]. The resulting fibers were chemically treated in a shaking water bath at 50°C for four hours with a 1 M sodium hydroxide solution (Uniscope Surgifriend Medicals, England; Model No.: XMTD-8222). After that, the item was thoroughly cleaned with tap water and then rinsed with distilled water until the digital pH meter indicated that it was neutral. This was done to make sure that any sodium hydroxide that was inside the fibers was completely removed. The mercerized fibers were then chopped into little pieces of 10 mm in length and dried for five days in the sun during the dry season. After that, they were oven dried for 4 hours at 60°C to remove moisture content and were kept in a desiccator for later use. The surface treatment of fibers can modify their chemical composition and surface roughness, enhancing adhesion between the fibers and the matrix material. This strengthens the interfacial bond, reducing the risk of fiber-matrix debonding and improving the overall mechanical properties of the composite. Additionally, this treatment can increase the hydrophilicity of sisal fibers, promoting better wetting by the matrix material. Improved wetting leads to enhanced fiber dispersion, resin impregnation, and, consequently, improved mechanical properties while reducing the potential for voids or defects in the composite. This surface treatment method has been observed to yield robust fibers due to the elimination of stress induction from beating, a factor commonly associated with decorticated fiber. This method of surface treatment was done in accordance with Oladele et al [30].

2.3 Production of paper particles

Waste papers were first reduced in size using a paper cutter and subsequently soaked in water within a plastic bucket for a period of 3 days. The soaked paper was later pulverized with paper pulp machine and pressed to remove excess water before sun drying for 7 days. The dried paper was further processed by grinding with laboratory grinder to obtain the fine particles of <100 μm used. Chemical treatment was not carried out on paper particles because they have good adhesion with epoxy and are been used as fillers in this work.

2.4 Fabrication of composites

The composite materials were produced using the open mold hand lay-up technique. This method is cost-effective due to its minimal tooling and equipment requirements, making it suitable for small-scale production and prototypes. It is highly versatile and adaptable, accommodating various part sizes and shapes, including both simple and complex geometries. Hand lay-up can be executed with basic tools and equipment that are readily available and easy to operate, unlike some other composite manufacturing methods that require specialized machinery. Additionally, this technique allows for the use of a variety of reinforcement materials, such as woven or chopped fibers, fabrics, mats, and unidirectional rovings, providing flexibility to tailor the composite properties to specific requirements. In this research, both particles and fibers were incorporated into the epoxy matrix, with weight percentages ranging from 3% to 15% for sisal fiber and paper particles, as presented in Table 1.

Table 1. Design of the composites.

Weight (%)	Epoxy (g)	Hardener (g)	Sisal (g)	Paper pulp (g)
Control	133.3	66.6	-	-
3	116.4	58.2	2.7	2.7
6	112.8	56.4	5.4	5.4
9	109.2	54.6	8.1	8.1
12	105.6	52.8	10.8	10.8
15	102.0	51.0	13.5	13.5

The sisal fibers and paper particles were reinforced in 1:1 ratio. This was to ensure uniformity in the weight fraction of the reinforcement materials and to investigate the effect of the blend of short fiber and particulate cellulosic reinforcements on the composites. The epoxy resin and hardener were added in a 2:1 ratio which was in accordance with Oladele et al [33]. A homogeneous mixture of the reinforcements, epoxy resin and hardener was achieved by manual mixing with a glass rod stirrer for 5 minutes within a polymeric container. The resulting homogeneous mixtures were then introduced into mould specifically designed for each property to be investigated which was already prepared by applying a release agent to prevent the composite from adhering to the mold surface. The composites were allowed to cure at ambient temperature of about 28±4°C for 24 hours before extraction from the moulds. After extraction the composites were allowed to cure at the same ambient condition for about 21 days. The cured samples were then subjected to testing in accordance with the ASTM standards. This technique was adopted by Bekele et al [6] and Atmakuri et al [8]. Figure 1 showed part of the representative fabricated samples.

Fig. 1. Representative samples of de-molded fabricated composite samples before trimming.

2.5 Evaluation and characterization of the developed composites

Flexural Test

Flexural properties of the samples was evaluated by means of the 3-Points Bending Test, in accordance with the standards established by ASTM D790 [34]. The tests were conducted through the utilization of a universal tensile testing machine of the Instron Series 3369 model. The dimensions of the specimens used were 120 mm, 15 mm, and 3 mm, for length, width, and thickness, respectively. The execution of the test was carried out under a displacement control rate of 10 mm/min. The test speed was set at 5 mm/min over a span measuring 65 mm. The representative values were calculated from the average of the results obtained from 3 samples tested for each composition.

Tensile Test

The examination of tensile properties of the fabricated samples was carried out in accordance with the ASTM D638-14 [35]. The procedure was carried out utilizing a Universal Testing Machine (Model: Instron series 3369). Dumbbell-shaped specimens measuring 90 × 10 × 3 mm were used for the experimentation where the test was carried with a crosshead speed of 5 mm/min utilizing a 10 kg load cell.

Impact test

An impact test was carried out on the sample using a Charpy impact testing machine per ISO 179. Samples were cut into the impact test dimension of 80 mm x 10 mm x 3 mm. Samples were placed horizontally on the machine, maintaining a distance of 60 mm between lines of support. The initial reading of the gauge was taken and then a suspended handle that swings and fractures the sample was released. The final reading was taken after the sample has fractured. For each sample, three test pieces were tested. The average value was taken as the representative value.

Hardness test

Hardness test was carried out on the sample using Shore D hardness tester following ASTM D2240-00 [36]. In order to accomplish this, the samples were cut to 25x25mm and placed on the flat surface of the tester stand and indented with a force of 15 kgf on each composite sample with a 15 second pause. Five values were obtained and the average value was used for analysis.

Wear test

The wear procedure follows the standard CS-10 Calibrase. The wear test was carried out with Taber abraser, Model ISE AO16. The standard load used was 500 g and a revolution of 200 RPM. A Centre hole of 10 mm was made on the sample to fix the test piece on the machine. The sample was secured to the instrument platform which is a motor driven at a fixed speed and the values were recorded. Each specimen was a flat and round disc of approximately 100 mm^2 and a standard thickness of approximately 6.35 mm. Wear resistance was measured using the weight difference before and after abrasion (weight loss technique). During testing, loose particles adhering to specimens were carefully removed, especially before weighing. Similar process was done by Oladele et al., [30]. The wear index of each of the samples was determined using Equation 1.

$$Wear\ Index = \frac{W_1 - W_0}{C} * 1000 \quad (1)$$

Where W_1 is the initial weight, W_0 is the final weight after surface abrasion and C is revolutions per minute. RPM used is 200.

Water absorption

Water absorption tests were conducted in accordance with the guidelines set by ASTM D5229M-12 [37]. To execute the test, 250 cm^3 of water medium was dispensed into uncontaminated plastic containers. The original weight of each sample was measured via chemical weighing, and readings were noted every day for a duration of four days. The specimens were taken out, cleansed with a fresh cloth before each weighing session. The data collected during the experiment were employed to determine the weight gained through utilization of Equation 2. Where W (g) is weight gain per hour, Wo and Wt are the oven-dry weight, and the weight of the sample after time t, respectively.

$$W\ (g) = W_t - W_O \quad (2)$$

Density measurement

The densities of the samples were obtained by cutting the samples into 4mm diameter. The density was determined using Quarrz, Rock Density Tester AU-300R. The weight and volume of each specimen was determined by the machine.

Microstructural examination

The fractured surfaces of the samples were examined using Scanning Electron Microscope (Model: JEOL JSM-6480LV). The samples were securely affixed to stubs with the aid of silver paste. The samples were gold sputtered to improve electrical conductivity before the characterization at a voltage of 15 kV.

3. RESULTS AND DISCUSSION

3.1 Flexural properties

The results for maximum flexural strengths are presented in Figure 2, which delineates the correlation between maximum flexural strength at various sisal-paper particles loadings and the control. A notable elevation in the flexural strength of composites was observed within the range of 6 to 15 wt. %, with an optimal strength of 57.30 MPa at 12 wt. %, which signifies a 76.20 % increase as compared to the control's 32.52 MPa from epoxy material. It is plausible that the alkaline treatment of the sisal fiber contributed to the enhancement of

flexural properties of the epoxy based composites [33,38]. Moreover, it was observed that the flexural strength exhibited an upward trend upon the inclusion of reinforcements within the range of 3-12wt%. This occurrence could potentially be ascribed to the homogeneous distribution of stress and the interlocking configuration of the fibers in the matrix, which served as influential factors in the refinement of the material's attributes. Addition of paper particles might have aided this proper transfer of load from epoxy to sisal fibers due to adequate filling of pores/voids that would have resulted into weakness. Hence, suitable blend of paper particles in epoxy matrix played a pivotal role in augmenting the material's characteristics. At a weight percentage of 15%, a reduction in the flexural strength of the reinforced composite samples was detected. This decline could be ascribed to improper blending of paper particles and sisal fiber in the matrix or fiber clustering which can cause weak interfacial connections between fiber and matrix material [8] Nevertheless, when compared to the values at low weight fractions (3-9%), the flexural strength presented a higher value. Similar results were observed in Oladele et al. [30] when sisal fiber and eggshell were reinforced in epoxy matrix.

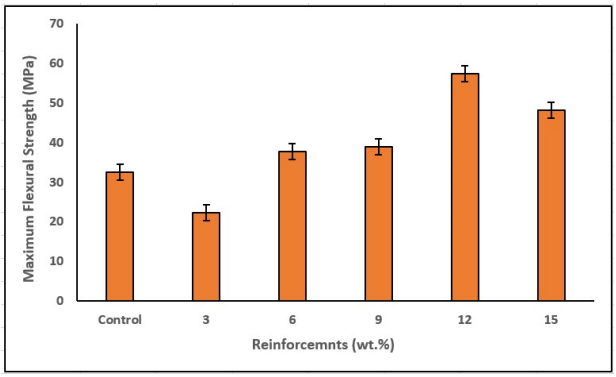


Fig. 2. Maximum flexural strength of reinforced sisal fiber–paper particles hybrid reinforced composites and unreinforced epoxy matrix.

Similarly, Figure 3 displays the correlation between flexural modulus at various sisal-paper particles loadings and the control. It exhibits a comparable trend with Figure 2 except with a shift in the optimal value from 12-wt% of reinforced epoxy composites for flexural strengths to 9 wt% reinforcements in flexural modulus. Thus, the optimal values from the sisal fiber-paper particles hybrid-based composites were 721 MPa compared to the unreinforced epoxy with a value of 626 MPa. This impressive achievement can be attributed to the robust interconnectivity between sisal fiber/paper particles and epoxy matrix. Further increase in reinforcements subsequently led to a marginal decrease in the flexural modulus at 12 and 15-wt%. This occurrence can also be ascribed to what was stated in Figure2 for the reduction in value at 15-wt%. Flexural properties evaluate the magnitude of force necessary to flex a beam under specific three-point loading conditions. Frequently, these results are employed to determine the most suitable materials for manufacturing components that can endure loads without yielding to flexure [39]. Similar to these findings was the work of Kolawole et al. [40] and Panneerdhassa et al [41]. In general for the flexural properties it was observed that composite reinforced with 3wt. % SF-PP had lower flexural properties compared to the unreinforced composite (control) and this can be attributed to inadequate uniform distribution of reinforcement used or there was no proper adhesion between the matrix and the reinforcements when fabricating the composite for flexural test in the metallic mould used.

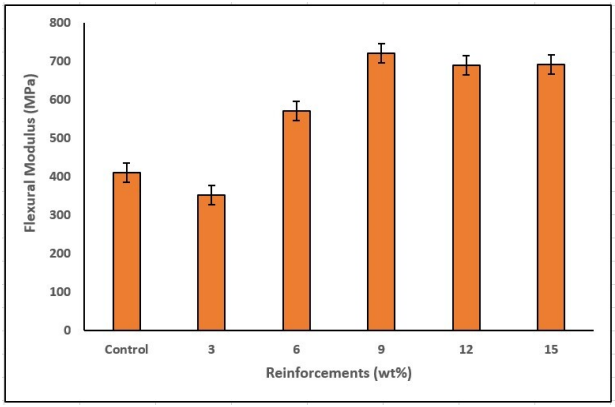


Fig. 3. Flexural modulus of reinforced sisal fiber–paper particles hybrid reinforced composites and unreinforced epoxy matrix.

3.2 Tensile properties

The result in Figure 4 revealed an uptrend in the maximum tensile strength of the composite materials from 3 wt. % to 9 wt. % for reinforced composites followed by gradual reduction. This enhancement in strength with an increase in reinforcement content followed by a decrease was reported in composite development by Oladele et al. [33]. The outcomes of the study reveal that the composite that incorporated 9 wt% reinforcements manifested a tensile strength of 32.94MPa which is significantly higher in comparison to the 17.64MPa observed in the control. These results imply that the

amalgamation of hybrid reinforcements and epoxy matrix was successful in achieving proficient adhesion and stress distribution. Nevertheless, the inclusion of sisal fiber and paper particles beyond the above-mentioned reinforcement loadings was found to cause a gradual decrease in tensile strength. This decrease could be ascribed to inadequate bonding at the fiber/filler/matrix interface, ultimately leading to a reduction in the bonding strength of the composites. Although 15 wt% reinforced composite had 32.82MPa which is quite higher than the control sample and also 3-6wt% reinforced composite, this same trend was observed in Figure 3.

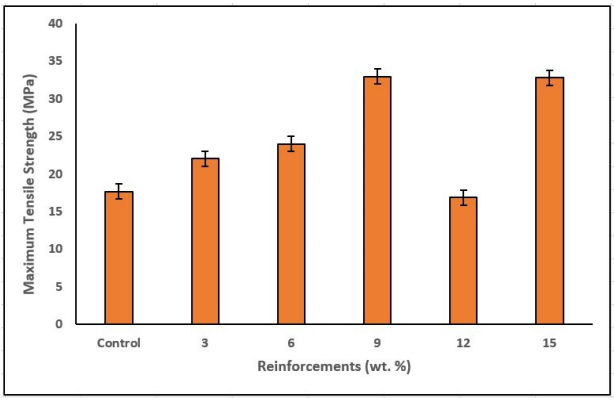


Fig. 4. Maximum tensile strength of reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

The effect of utilizing hybrid reinforcement consisting of sisal fiber-paper particles on epoxy matrix was demonstrated by analyzing the tensile modulus as presented in Figure 5. The results indicated that the tensile modulus of the composite samples, which were fabricated using various reinforcement ratios ranging from 3-12 wt%, exhibited an overall improvement. Only the composite sample reinforced with 15 wt% displayed a lower tensile modulus than the control sample. Conversely, all other composite samples that were reinforced exhibited a higher tensile modulus than the control sample. Nonetheless, the optimal content of the reinforced sisal fiber-paper particle hybrid composite was found to be from 12 wt%, yielding a tensile modulus of 428.21MPa. It can be inferred that the significant increase in the tensile modulus from 3-12wt% was due to the excellent bonding between the sisal fiber/paper particles reinforcements and the epoxy matrix [30]. The reduction in tensile modulus as the content reaches 15 wt% can be ascribed to clustering of fibers and fillers within the matrix or wetting of the filler at high concentration [40,42]. This observation emphasizes the concept that the integration of fillers in the polymer matrix amplifies the stiffness of the composites within a specific range with optima value [30]. A similar trend was observed in Figure 2.

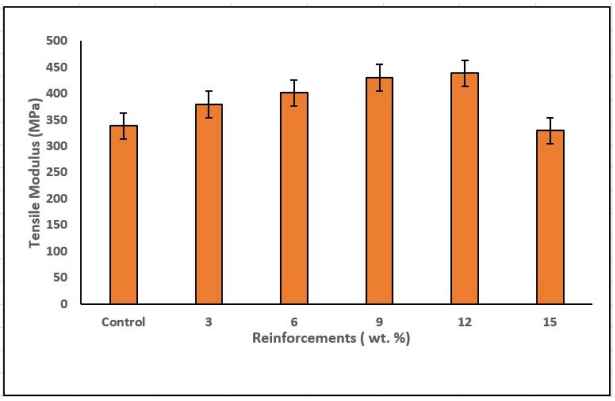


Fig. 5. Tensile modulus of reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

3.3 Impact strength

The impact of hybrid reinforcement employing sisal fiber-paper particles on the epoxy matrix was demonstrated by means of Figure 6, and a congruent tendency was noted much like the mechanical properties indicated in Figures 2-5. The composites that were produced possess significantly enhanced impact strengths when compared to the control, with the optimal value being 9 wt. % and exhibiting an impact strength of 46.24 kJ/m^2, a 235% increment compared to the control, which had an impact strength of 13.82 kJ/m^2. The impact strengths of the fabricated composites were highly enhanced within 9-15 wt% with a slight decrease from 12-15 wt% compared to what was achieved within 3-6 wt%. Nevertheless, within 9-15 wt%, the range gave a better results than the lower ones (3-6 wt %). The observed decline observed with the addition of sisal-paper particles reinforcement from 12-15 wt% could be attributed to the accumulation of particles/higher fiber loading in the composites, thereby reducing their energy-absorbing capacity in agreement with Oladele et al. [30], Owuamanam [43]. Additionally, a significant 158% enhancement was observed when increasing the weight percentage from 6% SF-PP to 9% SF-PP. This enhancement may be attributed to the proper dispersion of reinforcements within the matrix during composite production. However, in

comparison to the control, the reinforced samples exhibited adequate interfacial adhesion between the bio fibers and the epoxy matrix. This improvement can be attributed to the surface modification of the sisal fibers [33,44,49] and the adequate wetting, soaking and proper bonding of the particulate paper and sisal fiber within the epoxy matrix. The particulate paper might have serves as an agent for interfacial adhesion between the sisal fiber and the epoxy, thus, supporting adequate transfer of load from matrix to the fiber.

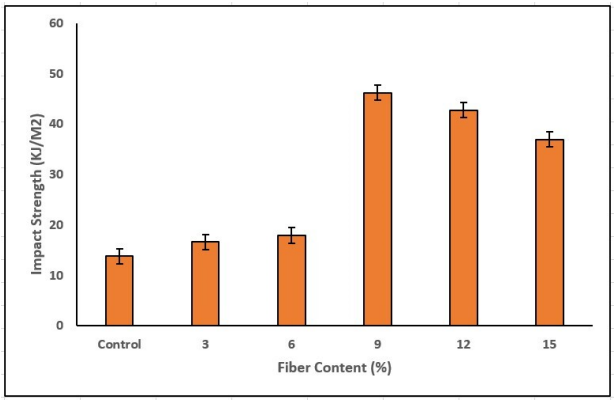


Fig. 6. Impact strength of reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

3.4 Hardness

Figure 7 illustrates the hardness of the composites and the control (unreinforced epoxy matrix). It was observed that with the exception of 6, 9 and 12 wt% based samples; the hardness of all other composite samples was lower than that of the control sample. The reduction in hardness at 3wt% reinforcement which was also observed for its flexural properties may be attributed to factors such as the volume fraction of reinforcement, poor interfacial bonding between the reinforcement and the matrix, reinforcement orientation, or the presence of porosity during composite fabrication. At 15wt%, the reduction in hardness can be attributed to overloading of the matrix with sisal fiber-paper particles, which can adversely affect composite properties. An initial increase in hardness, observed from 3wt% to 9wt% with the highest value recorded at 9wt% (a 16% increment), may be attributed to effective interfacial adhesion between the reinforcing agents and the matrix. This improved interfacial bonding enhances hardness and may also be linked to increased stiffness and the interlocking of fibers [45]. This trend was similarly observed in the research by Oladele et al. [30] where poultry eggshell-sisal fiber hybrid reinforced epoxy composites was investigated. Moreover, the enhancement in rigidity could potentially be attributed to the effective interfacial adhesion between the reinforcing agents and the matrix, which fosters the property of hardness. Additionally, this phenomenon may also be linked to an increase in stiffness and the interlocking of fibers [33,45].

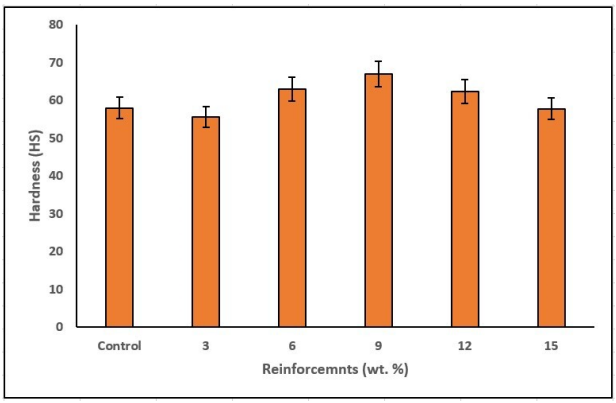


Fig. 7. Hardness of reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

3.5 Wear resistance

The investigation was conducted to compare the wear behavior of various materials with the control, which is illustrated in Figure 8. An abrasion wear test was executed to examine the impact of reinforcements on the wear loss at material surfaces. The findings revealed that these reinforcements led to variations in the abrasive properties of the produced composites when compared to the epoxy resin, which served as the control. These variations in the wear behavior of the reinforced composite may be attributed to the non-uniform distribution and orientation of the sisal fiber-paper particles in the epoxy matrix, or the entrapment of air bubbles during the fabrication of the composite using the hand layup technique. However, all the generated composites exhibited a lower wear index, indicating a higher level of wear resistance than the control sample (0.76mg), this can be attributed to good bonding between the reinforcements and the epoxy matrix as well as the stiff nature of the fiber [7]. Thus, it can be inferred that the addition of these reinforcements can enhance the wear resistance of epoxy materials in all areas of application where surface

abrasion is prevalent. The findings from Figure 8 indicate that the composites containing 9 and 12 wt% reinforcements exhibited the least wear index of 0.49 and 0.46 mg, respectively among the remaining reinforced composites. This implies that composite with 3, 6 and 15 wt% reinforcement will exhibit low wear resistance suggesting that the composite reinforced with 9-12 wt% sisal fiber-paper particles possess superior wear resistance. This finding can be supported by the similar results observed in the findings of Ramesh et al [46] and Oladele et al. [7].

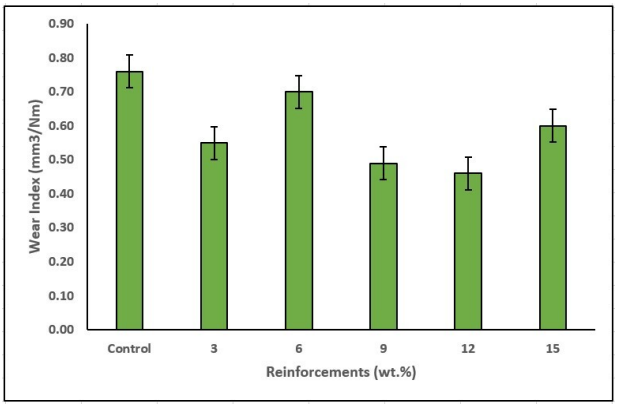


Fig. 8. Wear Index reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

3.6 Water absorption

The water absorption characteristics of all the composites under study, as influenced by the immersion time of 96 hours, have been graphically presented in Figure 9 and the values are given in Table 2. The data depicted in the plots clearly indicate that a rise in the content of reinforcements is directly proportional to an increase in the percentage of water absorption. This observation could be attributed to the inherent hydrophilic properties of the natural fiber and filler [33,47]. It was discovered that the reinforced composite exhibited rapid and linear water absorption during the initial phase, specifically within the first 24 hours, until it reached a saturation point at around 80-84 hours. This saturation denotes an equilibrium state in which the composite can no longer absorb any more water. On the other hand, the control sample did not display rapid water absorption and attained a saturation level of approximately 48-72 hours. Similar trend was observed for composites reinforced with other natural fibers in epoxy matrix for plantain fiber and stem [33] and, Cockle Shell Particles (CSP) with Oil Palm Fibre (OPF) [47]. In addition, it was observed that composites reinforced with 9-15 wt. % SF-PP exhibited an initial high rate of absorption, followed by a decrease at 48 hours. This behavior can be attributed to the proportion of sisal fiber-paper particles within that range to show the effect of reinforcement content on water absorption potentials. It showed that below this threshold, the absorption potential of the ensuing composites could be low compared to what will be obtainable above this value. Sisal fiber and paper particles are natural materials with inherent hydrophilic characteristic, allowing water molecules to readily bind to the sisal fiber-paper particles. As the composite absorbs more water, these particles may swell and close, reducing the water absorption rate as observed at 48hr. While the epoxy matrix is hydrophobic and as water continues to diffuse into the composite, it eventually reaches the epoxy matrix and since sisal fiber-paper particles has less resistance, there will be absorption. Therefore, the water absorption rate increases again as it interacts with the epoxy matrix as observed at 72hr. The water absorption rate will continue to increase until the composite reaches its saturation point. The saturation point is the point at which the composite cannot absorb any more water.

Table 2. Water absorption rate of composite for 96hrs.

Weight fraction %	Time (Hr)				
	0	24	48	72	96
	0	0.012	0.024	0.034	0.039
3	0	0.066	0.101	0.162	0.312
6	0	0.265	0.247	0.329	0.438
9	0	0.761	0.467	0.551	0.664
12	0	0.613	0.465	0.617	0.744
15	0	0.791	0.602	1.000	1.193

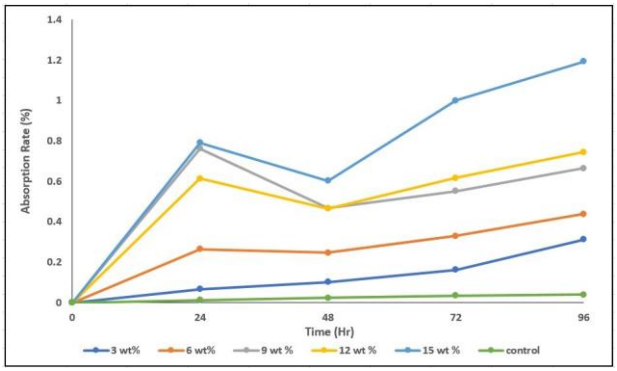


Fig. 9. Water absorption rate of reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

3.7 Density

Figure 10 displays the response of an epoxy composite reinforced with sisal fiber-paper particles as a function of density.

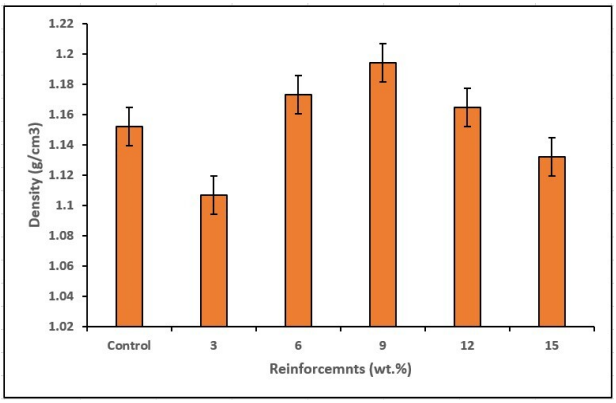
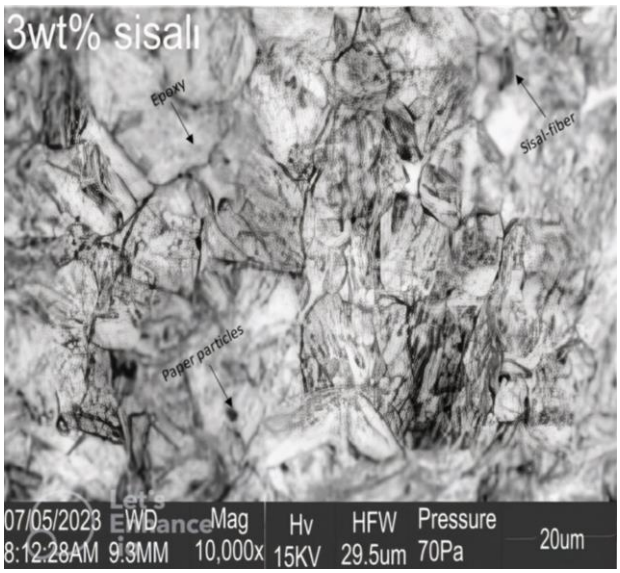


Fig. 10. Density of reinforced sisal fiber-paper particles hybrid reinforced composite and unreinforced epoxy matrix.

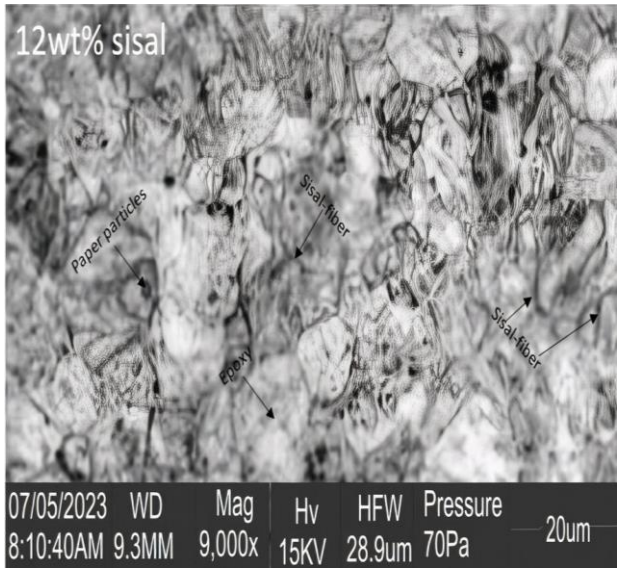
A similar pattern was also observed in Figure 7 for the composite's hardness which implies that dense and hardness is linearly proportional. In Figure 9 it was observed that the first increase in density with no wt% reinforcement, followed by a decrease in density with a further increase in 3wt% of reinforcement, this indicates the formation of voids in the composite which occurred during production of the composite. However it was noted that an upward trend was evident from 3-9 wt% when reinforcing agents were added to the epoxy matrix, with 9 wt% exhibiting the highest density of 1.194 gcm-^{3}. This may be attributed to the appropriate dispersion of the reinforcement throughout the matrix during the developmental phase. However, a decrease was noted from 12-15 wt% reinforcement and the density of control was greater than some of the reinforced composites (3 and 15 wt %). This result is actually in correlation with Figure 7 because according to Oladele et al [30] high density enhances high material hardness. Asokan et al [48] reported a variation in natural fibre density of 1.2 – 1.6 g/cm^{3}. From the results presented in Figure 9, it can be observed that the reinforced composite fell below this range, except for the composite reinforced with 9wt% sisal fiber-paper particles, which was in close proximity. This finding is significant as it suggests that the use of such low density composites could potentially lead to fuel savings in automotive applications, while also promoting the development of fully biodegradable composites for environmentally friendly and sustainable growth. Voids in the composites produced using open mould hand lay-up technique can be minimized through proper fabrication techniques such as compression molding, hot pressing, and vacuum bagging to produce void-free composites.

3.8 Microstructural analysis

The utilization of scanning electron microscope (SEM) enabled the examination of the surface morphology of the developed composites. Hence, in Figure 11 (a-b), the image depicts the features at 3 wt. % for low weight and 12 wt. % for higher weight sisal fiber-paper particles in epoxy matrix.



(a)



(b)

Fig. 11. Scanning Electron Micrograph (SEM) of epoxy composites reinforced with (a) 3 wt. % (b) 12wt % sisal fiber- paper particles.

The microstructure reveals the intrinsic coalescence and adhesion of the epoxy polymer to the reinforcements utilized. The surface pattern further indicates the creation of a homogeneous matrix in the host resin by the reinforcements, with both the paper particles and sisal fiber being embedded in the epoxy matrix, as depicted in Figure 11(a). No observation of fiber debonding was observed due to the chemical treatment given to the fiber used, likewise at 12 wt. % in (b). Also, it was observed that the paper particles were properly bonded with the epoxy matrix as seen in Figure 11(b). This may contribute to the reasons why there is an improvement in the mechanical properties.

4. CONCLUSION

Sisal fiber-paper particles hybrid reinforced epoxy composites for automotive application was investigated and the following conclusions were achieved.

1. All the mechanical properties evaluated and wear resistance were enhanced within 9-12 wt% sisal fiber-paper particles addition with increase and decrease at both ends to reveal optimum reinforcement content for the fabricated composites.
2. Addition of paper particles as filler was noticed to assist the interfacial bonding and adhesion thereby aiding proper load transfer to the sisal fiber. Both alkaline fiber treatment for surface modification and proper wetting and soaking of paper particles contributed to enhanced mechanical and wear properties of the composites. Thus, particulate waste paper can be used as surface compatibilizer in epoxy matrix and other thermosetting polymers.
3. Based on the improved properties at 9-12 wt% sisal fiber-paper particles, these content can be considered for mass production of parts for automotive applications in the area of armrest, dashboards, bumper, door panels and other body parts components. This work has shown the usefulness of sisal fiber and waste paper particles as reinforcements in thermoplastic materials.

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