

**Effect of Chemicals Treatment and Fiber Loading on Mechanical Properties of Borassus
(Toddy palm) Fiber/Epoxy Composites**

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ABSTRACT

The aim of the present study was to investigate and compare the mechanical properties of untreated and chemically modified Borassus fiber reinforced epoxy composites. Composites were prepared by hand lay-up process by reinforcing Borassus fibers with epoxy matrix. To improve the fiber-matrix adhesion properties, alkali (NaOH), and alkali combined with silane (3-aminopropyltriethoxysilane) treatments on the fibers surface were carried out. Examinations through Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM) were conducted to investigate the structural and physical properties of the Borassus fibers. Tensile properties such as modulus and strength of the composites made by chemically modified and untreated Borassus fibers were studied using a Universal Testing Machine (UTM). Based on the experimental results, it was found that the tensile properties of the Borassus reinforced epoxy composites were significantly improved, as compared with the neat epoxy. It was also found that the fiber treated with combination of alkali and silane exhibited superior mechanical properties as compared with alkali and untreated fiber composites. The nature of fiber/matrix interface was examined through SEM of cryo-fractured samples. Chemical resistance of composites was also found to be improved with chemically modified fiber composites.

Keywords: Borassus fruit fiber, Chemical treatments, Spectroscopy, Composites, Tensile testing, Morphology

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INTRODUCTION

This century has witnessed escalating demands for the consumption of polymer plastics as important raw materials [1-2]. In particular, polymer plastic composites are gaining more and more acceptance in various industrial sector applications such as automotive, construction, marine, aerospace and sports [3]. Synthetic fiber-reinforced polymer plastic composites are widely used in many industries as a light weight alternative to non-ferrous structures [4]. However, synthetic fiber-reinforced plastic composites have recently come under serious criticism due to their non renewable feedstock and pollution problems [5]. An emergent environmental consciousness and public concern, the indefensible utilization of petroleum and new environmental regulations have resulted in increasing demand for environmentally friendly materials [6, 7]. This in revolve, has fashioned the need for new materials and processes that are attuned with the environment. Recent consideration has focused on natural fiber composites, which are composed of natural cellulosic fibers embedded in a polymer matrix [8, 9].

In the recent years, natural fiber reinforced composites have acknowledged increasing attention in radiance of the increasing environmental consciousness [8-10]. Compared with synthetic fibers especially conventional glass fibers, natural fibers have numerous advantages like being renewable and environmentally friendly, having low cost, light weight, and high specific mechanical performance [10]. However, some drawbacks of natural fibers such as higher polarity and hydrophilicity compel natural fibers to exhibit poor compatibility with polymers and result in the deterioration of mechanical properties upon atmospheric moisture adsorption [11]. Moreover, the natural fibers show inferior mechanical properties, easily degradable by UV radiation and flammable than compared with glass fibers. In order to improve the mechanical

properties and the interfacial property of the natural fibers, various modifications such as physical modification and chemical modification on the natural fibers have been investigated [11-14]. All these methods have demonstrated successful in improving the fiber-matrix interactions, which have resulted in polymer composites with significantly improved mechanical properties.

In the present work the authors prepared a new composite system using Borassus fruit fibers as reinforcement and epoxy as resin matrix. Epoxy resins are used widely in industry because of their strong adhesive properties, popular thermoset, excellent chemical resistance and better mechanical properties [15]. *Borassus* (Toddy or Palmyra Palm) (Fig. 1a), is a member of palm tree family, normally found in the tropical regions of Africa, Asia and New Guinea. The Palmyra palm has been one of the most important trees, economically useful and widely cultivated in Cambodia and India, where it is used over 800 different ways. These fruits contain cellulosic semisolid flush, which is armored by the fibers. A detailed study of alkali treatment effect on morphology, mechanical and thermal properties of these fibers was reported in the literature [16] and suggested that these fibers could be utilized as reinforcement component in composite manufacturing. Borassus fruit fibers are inexpensive, abundantly available, eco-friendly and hence it is essential to explore the potential utility of these fibers to the technical world. In an endeavor, we recently developed natural fiber reinforced polymer matrix composites, using Borassus fruit fiber as reinforcement [17-19]. In this work, we treated Borassus fruit fibers by alkali, silane (3-aminopropyltriethoxysilane) and alkali combined with silane to improve tensile properties of composites. From a literature review it is clear that no work has been reported on mechanical performance of alkali and silane treated Borassus fiber/epoxy composites. The treatment effects on the fibers were characterized by scanning electron microscopy and infrared spectroscopy. Thus, the aim of this study was to prepare composites by chemically modified Borassus fibers with epoxy matrix and subsequently to characterize their structural, tensile, morphological and chemical resistance properties.

MATERIALS AND METHODS

Materials

Borassus fruit fibers were extracted from dried ripened fruits as described elsewhere [16]. Epoxy (Araldite LY-556) and hardener (HY-951) were obtained from CIBA Pvt. Ltd., India. Chemicals

like sodium hydroxide (NaOH), acetic acid and 3-aminopropyltriethoxysilane were obtained from Merck, India.

Extraction of Fibers

The Borassus fruits (Fig. 1b) were collected from Anantapur district in Andhra Pradesh state of India. The Borassus fruit fibers were extracted from dried ripened fruits. The fruits were dipped in water for 2 weeks and the black skin was separated. The separated fibers (Fig. 1c) were thoroughly washed with tap water, followed by distilled water and sun dried for a week. The fibers were then kept in a hot air oven for 24 h at 105 °C to remove the captured moisture.

Alkali Treatment

Borassus fine fibers were treated with 5% sodium hydroxide solution at 30 °C, maintaining a liquor ratio of 30:1 and dipping in the alkali solution for 8 h. The fibers were then washed with tap water repeatedly, neutralized with dilute acetic acid, again washed with distilled water, and dried in a hot air oven at 105 °C for a period of 24 h.

Silane Treatment

A silane (3-aminopropyltriethoxysilane) solution of 1 wt.% was prepared in acetone. The pH of the solution was adjusted to 4 with acetic acid and stirred continuously for 5 min and allowed to stand for 15 min. Alkali treated Borassus fibers was then immersed in the solution for 6 h. After treatment, the fibers were separated from the solution and then dried in an oven at 60 °C for 12 h. Finally, the fibers were thoroughly washed with water to remove excess of acetic acid residue until a pH of 7 was reached and then dried in an oven at 80 °C for 24 h.

Fourier Transform-Infrared Spectroscopy

Fourier transform-infrared (FT-IR) spectroscopy studies on untreated and chemically modified Borassus fibers were carried out using a Smart iTR ATR Nicolet iS 10 FT-IR spectrophotometer. All samples spectra were recorded in the 4000–500 cm^{-1} region with 32 scans in each case, at a resolution of 4 cm^{-1} .

Formulation of composites

For making the composite laminates by the hand lay-up process, a glass mould covered with Teflon® sheet and having dimensions of 160X160X3mm was used. Laminates were made from epoxy resin and hardener taken in the ratio of 100 and 15 parts by weight, respectively. The mould was filled with a mixture of matrix and chopped Borassus fibers (diameter and length in the range of 0.10 to 0.15 mm and 2 to 3 cm, respectively) in random orientation with varying fiber content (4, 8, 12, 16, 20 and 24% by weight) and allowed to cure at room temperature for 24 h. The cured laminates were demolded and post cured in a hot air oven at 100 °C for 3h. After that, the same process was followed with the chemically modified fibers to produce laminates.

Tensile Testing

Tensile tests were carried out according to ASTM D3039-78 standard using a Universal testing machine (INSTRON 3369) with a load cell of 10 kN. The gauge length was 100 mm and a crosshead speed of 5 mm/min was maintained. Tensile strength and modulus were considered for the analysis. Five specimens were used for each test and the average values reported.

Morphology

Surface morphology of untreated and chemically modified fibers as well as corresponding epoxy reinforced Borassus fiber composites was observed by an Oxford X-Max scanning electron microscope. However, the composite samples were submerged in liquid nitrogen and then broken (cryogenic fracture). All samples were coated with carbon by electrodeposition to impart electrical conduction before recording the micrographs.

Chemical Resistance

The chemical resistance of Borassus fiber-epoxy composites was studied using ASTM D543-87 (specimen dimensions: 20 x 20 x 3 mm) method. The effects of some solvents (water, benzene, carbon tetrachloride and toluene), acids (hydrochloric acid and nitric acid), alkalis (sodium hydroxide and ammonium hydroxide) and salt (sodium carbonate) was studied on the matrix and composites. In each case, 10 pre-weighed samples were suspended in the respective chemical reagents for 24 h. The samples were removed and immediately washed with distilled water and dried by pressing them on both sides with a filter paper. The samples were then weighed, and the percentage weight gain/loss was determined using the following equation:

$$\%Weight\ gain\ or\ loss = \frac{Final\ weight - Original\ Weight}{Original\ weight} \times 100$$

RESULTS AND DISCUSSION

Preliminary Study

The foremost work involved in the present research was to extract fibers from ripened fruits and study their physical and tensile properties and chemical composition. Figure 1 presents photographs of a Borassus tree with fruits, fruit bunch, extracted fibers, and the prepared Borassus/epoxy composite laminate. The average length, diameter, aspect ratio; tensile modulus, tensile strength, and elongation at break; α -cellulose, hemicellulose, and lignin content of the Borassus fibers are found to be 120 mm, 0.13 mm, 923; 4918 MPa, 65.2 MPa, 47.2%; 53.4%, 29.6%, 17.0% respectively [16]. Based on the above values, it was established that Borassus fruit fiber can be a promising future alternative natural reinforcement in composites. In the present work, Borassus fruit fiber was used in the preparation of composites based on epoxy.

Surface Topography of Fibers

The effect of surface treatment on the fiber surface topography was studied using scanning electron microscopy. Figure 2 shows surface of the untreated and chemically modified fibers. The untreated fiber [Fig. 2a] revealed no fibrillation but compact surface as the fibrils are bound together by chemical constituents i.e., hemicellulose, lignin and surface impurities. It is usual that sodium hydroxide is the most commonly used chemical for leaching or cleaning the surface of natural fibers. Further, the surface of the alkali treated fiber (Fig. 2b) was rather rough and cleaner, due to the dissolution of surface impurities in the alkali solution [16]. Also binding materials were partially removed and as a result the individual cellular part was exposed on the surface [20]. The rough surface topography of the fibers is preferable to assist better fiber-matrix adhesion. Silane coupling agents are widely used to enhance the adhesion between polymeric matrices and natural fibers. However, the surface topography of alkali combined with silane treated fiber (Fig. 2c) becomes more rougher (with scratches) than untreated and alkali treated fibers. Due to the initial treatment of alkali, the hemicellulose and impurities from the fiber

surface were removed and then silane predominately removed the remaining surface impurities by the action of solvent. This might escort to high interlock and adhesion between the fibers and the matrix. To further confirm the changes on alkali and alkali combined with silane treatment of the fiber, FTIR spectra were recorded.

FTIR Spectroscopy Analysis

Figure 3 shows the FT-IR spectra of untreated, alkali-treated, and alkali combined with silane treated Borassus fibers. It can be observed that untreated fiber spectra had a most representative broad absorption band at 3346 cm^{-1} that belonged to the strong hydrogen-bonded OH stretching present in aliphatic or aromatic alcohols in the fiber components [16]. The two peaks at about 2931 and 2847 cm^{-1} were due to the C-H stretching from aliphatic saturated compounds, i.e. aliphatic moieties in cellulose and hemicellulose [16]. The small shoulder band at 1743 cm^{-1} was assigned to the carbonyl groups (C=O) due to the presence of acetyl ester and carbonyl aldehyde groups of hemicellulose [16, 20]. The band at 1651 cm^{-1} was due to the bending mode of the absorbed water [21]. The bands at 1589 , 1511 and 1458 cm^{-1} belonged to the aromatic C=C ring stretching and C-H deformation in methyl, methylene and methoxyl groups of lignin [21]. The bands at 1423 , 1370 , and 1317 cm^{-1} were assigned to the $-\text{CH}_2$ scissoring, $-\text{OH}$ bending vibration and C-H asymmetric deformation of cellulose, respectively [21]. An intense band at 1234 cm^{-1} was attributed to the $-\text{COO}$ vibration of acetyl groups in hemicellulose [16, 20]. The bands at 1152 , 1103 and 1036 cm^{-1} were assigned to the C-O-C, C-O, C-C stretching of cellulose [16, 21]. The sharp absorption band at 894 cm^{-1} was due to the ring valence vibration was characteristic of β -glycosidic linkages between the sugars units [16].

It can be observed that the spectrum of alkali treated fiber is similar to that of untreated fiber. However, the intensity of absorption bands at 1743 and 1234 cm^{-1} significantly decreased in the alkali treated fiber indicating the removal of hemicellulose component in the Borassus fibers to the maximum extent by alkali treatment [16]. Also, the intensity of peak at 1651 cm^{-1} assigned to absorbed water was reduced compared to untreated fiber. This may be due to reduction in polar nature of Borassus fiber provoked by alkali treatment. For other vibrations, i.e., 3346 , 2931 , 2847 , 1589 , 1511 , 1458 , 1423 , 1370 , 1317 , 1152 , 1103 , 1036 and 894 cm^{-1} no considerable change was noticed. Thus, the FTIR studies suggested the reduction of the hemicellulose content on alkali treatment of the fibers. This consequence was also reported

earlier in the literature and discussed as characteristic of the alkaline treatment of natural fibers [20, 22, 23].

The spectrum of Borassus fiber with alkali and silane treatment is shown in same figure (Fig. 3). Figure 3 reveals new absorption bands in the region from 1800 to 800 cm^{-1} which were specific to the silane coupling agent [24, 25]. Further, new peaks appeared at 1681, 1555, 1483, 1471 and 1394 cm^{-1} , which were due to the deformation vibrations of NH_2 groups hydrogen bonded to the hydroxyl groups of both siloxane and the fiber surface [24, 25]. Whereas Si-O-Si and Si-O-C peak is in the fingerprint region of 600-1200 cm^{-1} , it is difficult to completely assign the Si-O-Si and Si-O-C. The intensity of the peak at 1029 cm^{-1} , which is an overlap of Si-O-Si band and the C-O stretching of cellulose was increased after silylation giving further evidence of reaction. This is in agreement with the results reported by Rajan et al. [26]. These modifications are favorable for fibers used as reinforcing agents when incorporated into matrix materials. The polysiloxane network has a larger number of active functional groups than the fiber surface has, and these active functional groups easily undergo chemical reactions with the matrix materials to establish stable bonds. It can be concluded from the FTIR analysis that the silane coupling agent was chemically grafted on the fiber surface.

Tensile Properties of Composites

The tensile strength and modulus of untreated, alkali treated, and alkali combined with silane treated Borassus fiber/epoxy composites as a function of fiber loading the corresponding values graphs are shown in Figure 4. It can be observed from Figure 4 that tensile modulus and strength of Borassus fiber/epoxy composite increased with fiber loading up to 16 wt.% in all cases and then after decreased. This increase in tensile properties indicated that the fibers were able to act as a stress transfer representatives for the epoxy matrix, particularly at 16 wt.% and lower. When the fiber loading exceed 16 wt.%, the amount of epoxy was insufficient to disperse scrupulously into the Borassus fiber and, as a result, the tensile properties decreased. This might have produced the falling fashion in the mechanical properties of the composites at the higher levels of Borassus fiber loadings. However, in all the cases, the tensile properties of the composites were found to be higher than those of the matrix. At the composition of 16 wt.% Borassus fiber by weight, the tensile strength and modulus of both untreated and various types of chemically modified fibers composites were found to be as follows: untreated, 2926 and 47.6 MPa; alkali

treated, 3349 and 52.9 MPa; and alkali combined with silane treated, 4182 and 61.8 MPa. The percent increase in tensile modulus and strength of different types of composites, respectively (presented in parentheses), over the matrix was: untreated (33.8 and 17.2%), alkali treated (53.2 and 30.2%), and alkali combined with silane treated (91.3 and 52.2%).

Borassus fiber/epoxy composites revealed higher tensile properties containing alkali treated fiber than the untreated fiber. Thus, alkali treatment provided a rough surface topography (due to the removal of hemicellulose and surface impurities) which in turn increased the effective surface area available for contact with the wet matrix. It is implicit that the alkali treatment enhanced tensile properties due to mechanical interlocking. In this study, alkali combined with silane-treated fiber composite exhibited the maximum increase of tensile properties compared to those of untreated and alkali treated fiber composites. It could be explained by the fact that, after the alkaline treatment, the hydrogen bonding network within the cellulose structure was broken and the hydroxyl groups of cellulose became more active and therefore improved the hydrophilic nature of the fiber as well as their compatibility with the silane agent [25]. Silane agent might have reduced the number of cellulose hydroxyl groups in the fiber-matrix interface. Therefore, the hydrocarbon chains provided by the application of silane restrained the swelling of the fiber by creating a cross-linked network because of covalent bonding between the matrix and the fiber [25]. Fiber surface modification through varied chemical treatments using such as alkali combined with silane improved the adhesion between fiber and matrix as well as interfacial bonding as a consequence of improved tensile properties.

Composite Morphology

In order to investigate the effect of the chemical treatment on the interfacial bonding in the composites, their fractographs were recorded using a scanning electron microscope (SEM). The SEM micrographs of a cryo-fractured surface of the composites with untreated and chemically modified (alkali treated, and alkali combined with silane treated) Borassus fibers are shown in Figure 5. From Figure 5(a), it is clear that the fibers were extensively pulled out as evidenced by the holes on the matrix surface as shown in case of untreated Borassus fiber/epoxy composites which indicated poor interfacial bonding between epoxy matrix and the untreated fiber which in turn decreased the tensile properties of the composite. However, in the case of alkali treated Borassus fiber composites (Fig. 5b), few fibers were pulled out connecting with the epoxy matrix

as indicated by lesser fiber pull-out holes when compared to the untreated fiber composites. In addition, at some places, fibers were even found to break without any pull-out. These observation indicates faintly improved interfacial bonding between the alkali treated fibers and epoxy matrix. As alkali removes the hemicellulose and impurities from the fiber surface and creates a rougher topography that facilitates mechanical interlocking, they resulted increased tensile properties. Alkali treated Borassus fiber had better interaction with epoxy resin due to the decrease of hemicellulose and surface impurities on the fiber surface by alkali treatment and it also formed inter molecular hydrogen bonding between fiber and epoxy resin.

However, in the case of alkali combined with silane treated fiber composites, the corresponding SEM micrograph is shown in Fig. 5(c). The micrographs exhibited no fiber pull-out, but absence of holes on the fracture surface, i.e., refusal debonding became obvious, and the break of fibers during fracture. On the other hand, the region surrounding the fibers seems to be incessant with the matrix phase. This suggests the strongest interfacial interaction between fiber and matrix. Hence, the hydroxyl groups on the cellulose fiber could interact better with silane coupling agent due to the increase of total reaction sites, thus replicating chemical interaction between the fiber and the matrix that enabled good fiber-matrix adhesion. As a result better stress transfer could be possible by using alkali and combined with silane treated Borassus fiber/epoxy resin composites instead of untreated and alkali treated Borassus fiber/epoxy resin composites. These arguments are also supported by the increase in all the tensile properties. In addition to the tensile properties, the chemical resistance of both untreated and chemically modified Borassus fiber/epoxy composites was investigated.

Chemical Resistance

Chemical resistance tests were used to find the ability of a matrix and composite to resist exposure to solvents, acids, alkalis, and salt and the corresponding values are given in Table 1. From this table, it is clearly evident that for the matrix and composites, weight gain was observed after immersion in chemical reagents. It can be observed that the neat matrix had better resistance for chemical reagents than the Borassus fiber-reinforced composites. The untreated fiber reinforced composites were found to possess lower chemical resistance than that of chemically modified fiber reinforced composites due to poor interfacial bonding between untreated fiber and matrix. The presence of Alkali combined with silane treated fiber composites

was found to conquer this to some extent though the values were found to be higher than neat matrix. This improved interfacial interaction constructs the matrix part around the fiber inert. This reason offers higher resistance to the penetration of chemical reagents into the composites [25].

Comparative Study

The present findings are reasonably comparable to the most recent published works which are mined and listed in Table 2. This Table summarizes the most recent works studying the influence of the fiber orientation of the fibers, influence of chemical treatment on the fibers and the weight or volume fraction of the fibers to the composites. In those works, the woven chemically modified fiber/epoxy composites have shown the higher tensile behavior than the chopped random oriented with untreated fiber/epoxy composites. Woven fiber provides a continuous load transfer throughout the composite area. However, random fiber orientation in the matrix generates a discontinuous load transfer throughout its composites and due to this, complex load distribution and non-uniform stress concentration take place in the matrix which may develop matrix cracking, debonding and failure of the composites. For the present work, it seems the tensile results of the Borassus fibers-epoxy composites in terms of strength is higher to banana, coir, Napier grass, oil palm EFB, pine apple leaf, sisal and sugar palm but lower than the glass and jute fibers-epoxy composites. The tensile modulus of the Borassus-epoxy composites also showed a similar trend to other natural composites as tensile strength of the composites. From this table, it can be seen that the Borassus fiber-epoxy composite is also very competitive candidate with some other natural fibers in reinforcing polymer matrices.

CONCLUSIONS

This study presented an analysis of Borassus fiber reinforced epoxy composites. Surface treatments of Borassus fibers by alkali and alkali combined with silane aqueous solutions were carried. Noticeable changes such as surface roughening structure were observed for chemically modified fibers. The results derived from the FTIR analyses confirmed that hemicellulose was removed during alkali treatment process and then silane reacted with the hydroxyl groups on the Borassus fiber surface. The tensile results of present study showed that tensile strength and modulus of alkali combined with silane treated fiber reinforced composites were higher than the neat matrix, untreated and alkali treated fiber reinforced composites. The fiber-matrix interfacial

bonding for untreated and chemically modified fiber-reinforced composites could be clearly evident in the SEM images. The chemical resistance of composites were found to be improved when chemically modified fibers were used. During comparative study, we found that the tensile properties of Borassus fiber composites were higher comparable to other natural fiber composites, but not better than those of glass fiber composites. Borassus fibers showed promising results as reinforcements for production of polymer composites, which could encourage its application in light weight materials industry.

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Caption for Figures

Fig. 1. Photographs of (a) Borassus tree (b) fruit bunch (c) extracted fibers and (d) composite laminate

Fig. 2. Scanning electron micrographs of (a) untreated (b) alkali treated and (c) alkali combined with silane treated Borassus fibers

Fig. 3. FTIR spectra of untreated and chemically modified Borassus fibers.

Fig 4. Tensile (modulus and strength) properties of untreated and chemically modified Borassus fiber-epoxy composites

Fig 5. SEM micrographs of fractured surface of (a) untreated (b) alkali treated and (c) alkali combined with silane treated Borassus fiber-epoxy composite

Caption for Tables

Table 1. Chemical resistance properties of untreated and chemically modified Borassus fiber-epoxy reinforced composites

Table 2. Comparison of the tensile properties of Borassus–epoxy composites with some other fibers- epoxy composites found in literature.

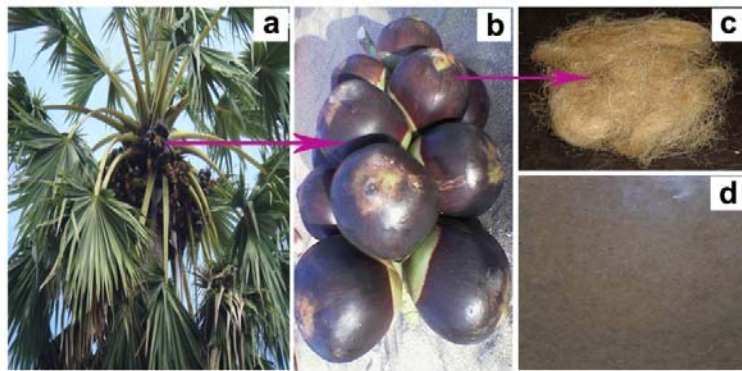


Fig. 1. Photographs of (a) Borassus tree (b) fruit bunch (c) extracted fibers and (d) composite laminate

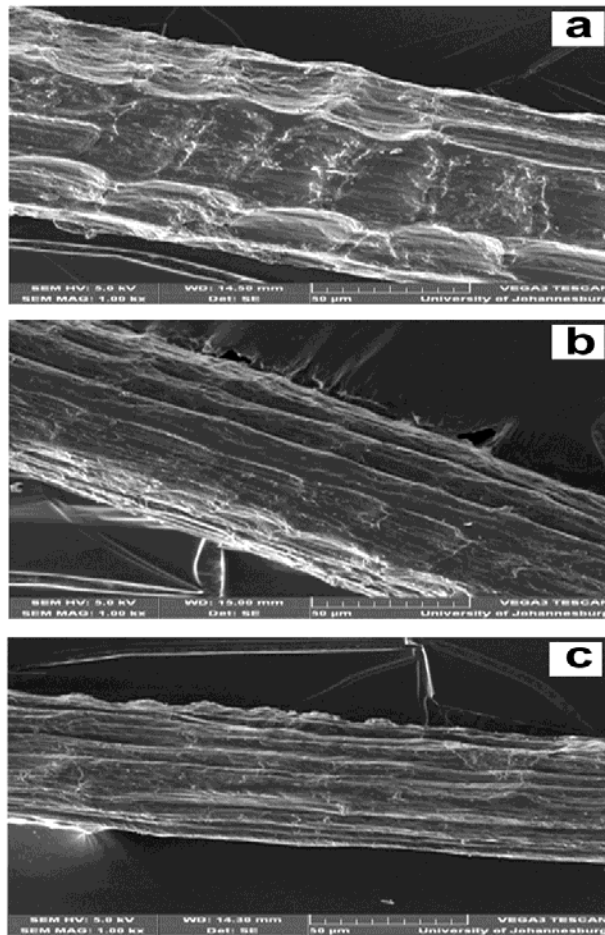


Fig. 2. Scanning electron micrographs of (a) untreated (b) alkali treated and (c) alkali combined with silane treated Borassus fibers

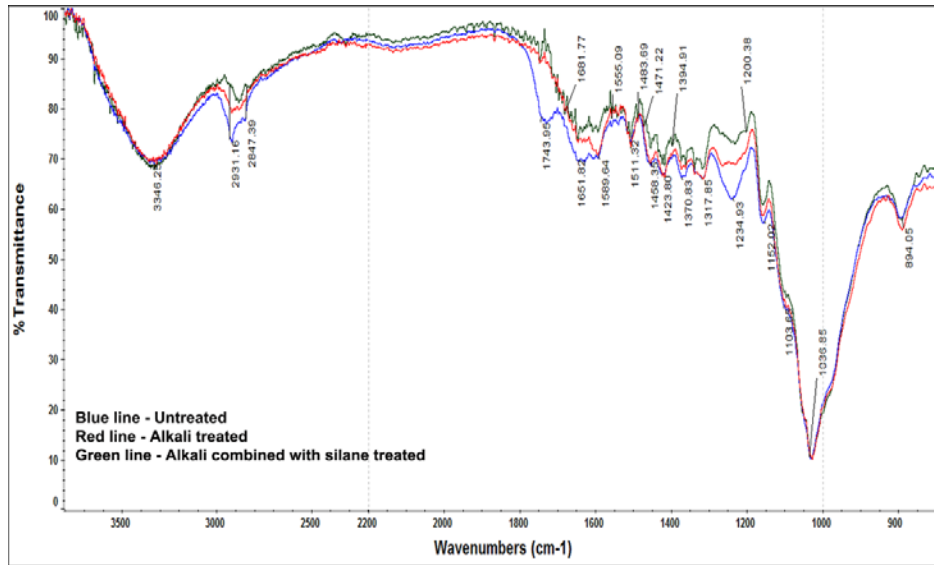


Fig. 3. FTIR spectra of untreated and chemically modified Borassus fibers

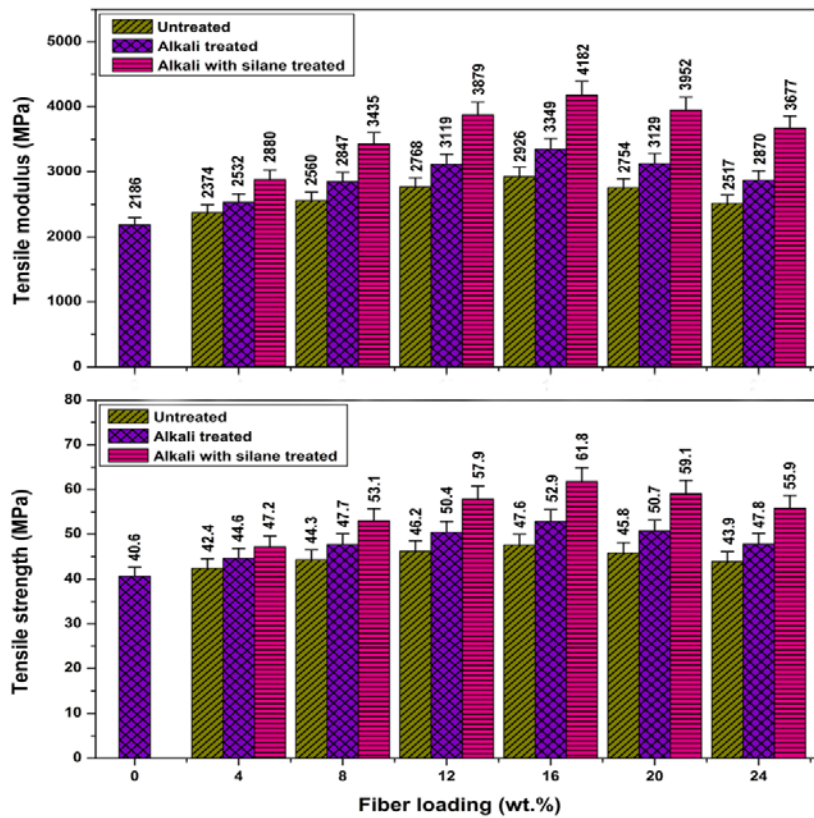


Fig 4. Tensile (modulus and strength) properties of untreated and chemically modified Borassus fiber-epoxy composites

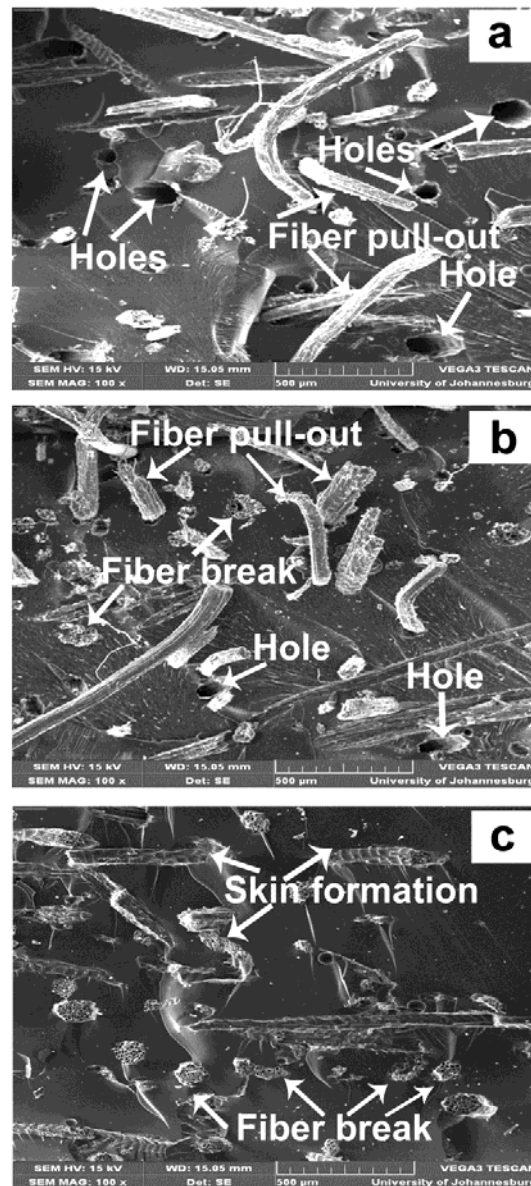


Fig 5. SEM micrographs of fractured surface of (a) untreated (b) alkali treated and (c) alkali combined with silane treated Borassus fiber-epoxy composite

Table 1. Chemical resistance properties of untreated and chemically modified Borassus fiber-epoxy reinforced composites

Chemicals	Epoxy	Borassus fiber-epoxy composites		
		Untreated	Alkali treated	Alkali with silane treated
40% HNO ₃	0.312	2.162	1.983	1.076
10% HCl	0.151	2.917	2.535	1.371
8% CH ₃ COOH	0.228	3.295	2.891	1.594
10% NaOH	0.149	6.781	4.427	2.126
20% Na ₂ CO ₃	0.193	3.735	3.189	2.469
10% NH ₄ OH	0.328	4.916	4.637	1.621
Benzene	0.225	1.738	1.428	0.823
Toluene	0.276	1.316	1.095	0.512
Carbon tetra chloride	0.283	1.371	1.181	0.585
Water	0.125	2.841	2.403	1.237

Table 2. Comparison of the tensile properties of Borassus–epoxy composites with some other fibers- epoxy composites found in literature

Fiber	Fiber Wt.% (or) Vol.%	Fiber orientation	Chemical treatment	Tensile strength (MPa)	Tensile modulus (GPa)	Reference
Banana	20 wt.%	-----	Untreated	26.1	----	[27]
			Silane treated	39.3	----	
Coir	-----	Chopped random	Untreated	17.86	----	[28]
Jute	35 vol.%	Woven mat	Untreated	61.41	5.46	[29]
			Alkali treated	66.49	6.39	
Napier grass	20 wt%	Chopped random	Untreated	28.45	2.72	[30]
			Alkali treated	39.53	2.95	
Oil palm EFB	40 wt.%	Fiber mat	Untreated	22.6	2.23	[31]
Pineapple leaf	20 wt.%	Chopped random	Untreated	23.8	----	[27]
			Silane treated	39.9	----	
Sisal	-----	Chopped random	Untreated	23	0.67	[32]
Sugar-palm	20 wt.%	Chopped random	Untreated	30.49	1.06	[33]
Glass	15–45 vol.%	Nonwoven	----	123–241	10.2–16.7	[34]
Borassus	16 wt.%	Chopped random	Untreated	47.6	2.92	This work
			Alkali treated	52.9	3.34	
			Alkali with silane treated	61.8	4.18	