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Research Article

The Impact Toughness and Hardness of Treated and Untreated Sisal Fibre-Epoxy Resin Composites

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The effect of the combined chemical treatment of sisal fibres through the subsequent processes of mercerisation (alkali treatment), then silane treatment and eventually acid hydrolysis, on sisal fibre was investigated. The effect of the treated fibres on the impact toughness and hardness of their composites with epoxy resin was also studied. Scanning electron microscopy of the surfaces of the treated and untreated fibres showed that the chemical treatment processes enhanced the removal of surface impurities and therefore increased the roughness of the surfaces of the fibres. This avails an increased surface area for interlocking with matrix and is, therefore, expected to enhance adhesion of the two. The treated fibre reinforced composites were observed to have higher values of impact toughness and hardness than the untreated fibre reinforced composites. These higher values were attributed to better interfacial bonding due to better mechanical interlocking between the treated fibres and epoxy resin arising from the increased roughness of the treated fibres.

1. Introduction

A composite material is a physical mixture of two or more different materials that result in a component with superior properties to those of any individual component [1]. In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties [1, 2]. The main advantages of composite materials are their high specific strength and stiffness, when compared with other materials allowing for a reduction in weight of finished parts [3].

The constituents of a composite are categorized as the reinforcement and the matrix. The reinforcement is the discontinuous phase while the matrix is the continuous phase [1–3]. The reinforcement is usually embedded in the matrix. The reinforcement is usually in the form of fibres, sheets, or particles whereas the matrix is either a polymer, ceramic, or metal [2]. The reinforcement provides strength and stiffness to the composite material [4]. The matrix on the other hand transfers and distributes the applied loads to the fibres and in many cases contributes some needed properties such as ductility, toughness, and electrical insulation [1, 3]. Examples of polymer matrices include epoxy resins, polyester resins, and phenolic resins while metallic matrices include aluminium resin, magnesium resin, and titanium resin [3]. The most common methods used in the manufacture of composite materials are compression moulding, pultrusion, hand layup, resin transfer moulding (RTM), injection moulding, and filament moulding [1].

Composites may be classified as particulate reinforced composites or fibre reinforced composites [3]. The particulate reinforced composites consist of tiny particles having thickness in the micron [5, 6] and nanoscales [7] embedded into a matrix. The particles occur in the form of flakes or powder [8]. Fibre reinforced composites on the other hand are made of continuous or discontinuous fibres that are embedded in a matrix [3].

A reemerging area of fibre reinforced composites is that of natural fibre reinforced composites [9]. Natural fibres are

increasingly being considered as an environmentally friendly substitute for synthetic fibres in the reinforcement of polymer-based composites [2, 9]. The use of these fibres instead of glass and carbon is, for example, under consideration in the automotive industry [10]. Although many different types of natural fibres are available, sisal (*Agave sisalana*) is a particularly attractive option due to its rapid growth over a wide range of climatic conditions [11] and its low cost [10]. Although the use of natural fibres partly satisfies the requirements of regulations that enforce the use of environmentally friendly and sustainable materials [10], the matrix system must also be considered in this regard. Clearly, completely biodegradable matrices such as polylactic acid (PLA) are preferable, but the current high cost of these matrices is a disadvantage in comparison to epoxy resin [10]. Sisal/epoxy composites are therefore of considerable commercial interest.

Even though natural fibres have the potential to supplement glass fibres in polymer composites [12], limitations arise with respect to mechanical performance and moisture absorption when natural fibres are used [9]. These limitations are present irrespective of whether thermoset or thermoplastic polymers are used as the matrix material. Previous studies [13–15] have reported that the main factor that limits the mechanical properties of natural fibre composites is the chemical incompatibility between the hydrophilic lignocellulosic molecules of the natural fibre and the hydrophobic molecule of the resin. This incompatibility leads to difficulties in ensuring effective fibre-matrix interface bonding which, in turn, causes ineffective load transfer between the reinforcing material and the matrix [10, 12, 13]. Various options, including chemical treatments of natural fibres and the use of compatibilisers, have been suggested in order to achieve the necessary compatibility of surface energies between the fibres and the matrix. Li et al. [16] presented a review article on the various chemical treatments used to improve compatibility between natural fibres and polymer matrices. Approaches such as mercerisation (alkali treatment), silane treatment, acetylation, benzoylation, use of maleated coupling agents, peroxide treatment, permanganate treatment, and isocyanate treatment were considered. Amongst the various methods presented, mercerisation and silane treatments have been widely reported on.

Mercerisation involves immersing the fibres in an alkaline solution for a period of time. It works by increasing the surface roughness of the fibre which improves mechanical bonding with matrices [16]. It also exposes more cellulose on the surface of the fibre to potential chemical bonding with matrices [17]. Silane treatment entails soaking the fibres in a weak solution of a silane diluted in water/alcohol or water/ketone mixture. In the presence of water, silane breaks down into silanol and alcohol. The silanol reacts with the OH groups of the cellulose in natural fibres, forming stable covalent bonds on the cell wall that are chemisorbed onto the fibre surface [16]. Use of silane improves the degree of cross-linking in the interface region and increases the fibre surface area, allowing for stronger bonding between the fibre and matrix [18]. Acid hydrolysis involves subjecting natural fibres to harsh acid treatment, which causes the amorphous lignin regions to break up thus releasing the individual crystallites of cellulose. Sulphuric acid and hydrochloric acid are extensively used in performing acid hydrolysis [19].

While most researchers have used either alkali treatment or silane treatment or acid hydrolysis individually, it is necessary to attempt using the three methods of treatment in combination, since the mechanisms by which they affect natural fibres are completely different. Herrera-Franco and Valadez-Gonzalez [20] considered high-density polyethylene [HDPE] reinforced with henequen fibres at a volume fraction of 20%. The effects of alkali and silane treatments on these fibres were studied individually in addition to the effect of the two treatments acting in combination. It was found that alkali treatment resulted into almost no improvement, whereas silane resulted into a 19% improvement. When the combination of the treatment was considered, there was an improvement of 30%.

Impact tests are usually carried out during the earliest stages of the design process in order to determine the integrity of the material under impact loading. Impact tests are usually done in order to determine the maximum impact load that a material can bear at a particular temperature [21]. Impact resistance of fibre-reinforced composites, like that of other materials, is measured by several test methods, namely, Charpy, Izod, drop weight, split Hopkinson bar (SHB), explosive, and ballistic impact [22]. The results of impact tests are presented in the form of fracture energy, damage accumulation, and/or measurement of the number of drops to achieve a determined damage or stress level. The results depend on many variables such as size of specimen, strain rate, type of instrumentation, and test setup [22].

Wang et al. [23] identified two different damage mechanisms for fibre reinforced composites that were loaded on a drop weight impact system. For fibre fractions lower than the critical fibre volume, fibre fracture dominated the failure mechanisms, while for higher values than the critical fibre volume, the fibre pull-out mechanism dominated the response.

Ramires and Frollini [24] used the Izod unnotched impact test to investigate the impact properties of sisal fibre reinforced tannin-phenolic composites. They carried out their investigations according to the ASTM D256 standard. The researchers found that the improvement in the interfacial bond was the main reason for the improvement of the impact strength. The authors reported that the increased acid sites at the surface of the sisal fibres improved interfacial adhesion. The researchers further reported that the Izod impact strength of the composites increased with an increase in the fibre content up to a maximum of 50% fibre content. However, beyond 50% fibre content, the Izod impact strength decreased due to ineffective impregnation of resin in the fibres. The researchers concluded that the use of sisal fibres as reinforcement material in tannin-phenolic resin was useful since it greatly improved the impact properties of the composite.

Han-Seung et al. [25] carried out a study on the effect of different compatibilising agents on the tensile strength and Izod impact strength of lignocellulosic materials. Low- and high-density polyethylene was used as the matrix, while rice husk flour and wood flour were used as reinforcement. Maleated propylene and maleated polyethylene were used as compatibilising agents to improve the fibre-matrix adhesion.

The researchers found that maleated polyethylene improved the Izod impact strength of notched specimens because of the enhancement in the fibre-matrix interfacial adhesion. On the other hand, the Izod impact strengths of composites produced from maleated polypropylene reinforced with rice husk dropped slightly. The researchers concluded that the Izod impact strength of the maleated polyethylene-incorporated composites improved slightly because of a better interfacial bonding between the matrix and the fibre.

Hardness refers to the resistance a solid shows to local deformation. A hard indenter is placed onto the surface of a material and is then pressed into the material. The size of the permanent indentation thus formed is then measured to determine the hardness of the material. The common methods used to measure hardness are the Brinell hardness test, Rockwell hardness test, Vickers hardness test, and the Barcol hardness test. While Brinell, Rockwell, and Vickers hardness test methods are commonly used, the Barcol hardness test is rarely performed.

Kumar et al. [26] studied the hardness of treated and untreated samples reinforced with sisal/glass epoxy-based hybrid composites using Rockwell hardness testing machine. In each case, five samples were tested and the average value was tabulated. Test specimens were made according to the ASTM D 785 test standard. The diameter of the ball indenter used was 0.25 inches, and all the readings were taken 10 seconds after the indenter made firm contact with the specimen. All the sample surfaces were rubbed with smooth emery paper, which facilitates accurate reading. It was observed that 2 cm fibre length composites had a higher hardness than 1 cm and 3 cm fibre length composites.

The effects of three combined chemical treatments, namely, mercerisation, silane treatment and acid hydrolysis, on sisal fibres are investigated in this paper. The effect of these combined treatments on the impact toughness and hardness of their composites with epoxy resin is also looked into. This is in contrast to other studies on impact and hardness that have used these treatments individually. The composites were manufactured using the vacuum infusion method of composite manufacture. This method prevents the entry of air into, and, formation of voids in the composites that are fabricated and is expected to facilitate the attainment of high strength and stiffness of the composites produced. Furthermore, this method differs from the other fabrication techniques by virtue of the fact that the creation of a vacuum in the mould cavity ensures that the resin is driven into the mould and through the laid out fibres [27] by atmospheric pressure and therefore ensures proper wetting of reinforcing fibres. Air bubbles can still be introduced into the system through the mixing process of the resin and hardener prior to charging into the mould, and through mould leaks. These, however, are weaknesses that are ameliorated in the infusion process.

2. Experimental Details

2.1. Materials. Epoxy Epolam 2015 resin and Epolam 2014 hardener were obtained from AMT composites of South Africa. The mix ratio of the resin and the hardener according to the data sheet obtained from the company was 100 : 32. Sisal fibres in a bundle of 10 kgs were obtained from Mogotio farm, Nakuru County, Republic of Kenya. The reagents which were used in this work were: sodium hydroxide, 3-glycidyloxypropyltrimethoxy-silane, methanol, and hydrochloric acid (HCL). Sodium hydroxide was provided by Minema chemicals (Pty) limited while 3-glycidyloxypropyltrimethoxy-silane, methanol, and hydrochloric acid were provided by Sigma Aldrich limited, all from South Africa.

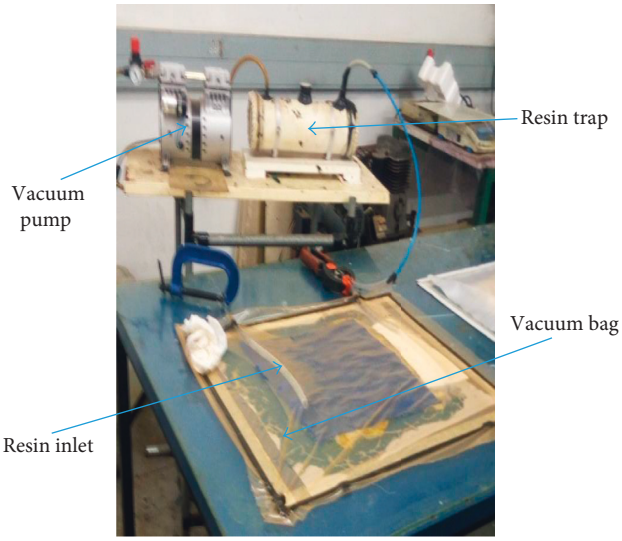


Figure 1: The vacuum infusion process.

2.2. Preparation of Treated Sisal Fibres. The sisal fibres were mercerised by immersion in 5% sodium hydroxide solution for 20 hours. The fibres were then washed with distilled water in order to remove the sodium hydroxide from them and then further immersed in 1% acetic acid in order to neutralise any remaining sodium hydroxide. The fibres were, thereafter, immersed in a silane solution made up of 5% of 3 glycidyloxy-propyl-trimethoxy-silane diluted in a 95% aqueous solution of methanol, the later in order to hydrolyse the silane and make it active [16]. This treatment was then followed by immersion of the fibres in a 67.5% solution of hydrochloric acid for 1 hour [28]. The treated fibres were, thereafter, washed with deionized water and dried in an oven at 45°C for 24 hours.

2.3. Manufacture of Composites. The vacuum infusion method of manufacturing composites was used to fabricate the composites here as shown in Figure 1. This method supports proper wetting of the reinforcing fibres, which gives rise to better and stronger interfacial bonding of the fibre and matrix. Both treated and untreated sisal fibre-epoxy resin composites were manufactured using this method. The sisal fibres were cut using a pair of scissors and straightened using a comb in order to avoid bunching of fibres which would otherwise minimise wetting of the fibres with resin and, therefore, reduce the efficacy of reinforcement. The fibres were then weighed using an electronic balance with an accuracy of ± 0.5 gm and grouped into various masses corresponding to different fibre weight

fractions. A thin layer of wax was smeared onto the base of a square glass mould of 50 cm by 50 cm. The wax ensures that the composite can be easily removed from the glass mould after curing. Predetermined weights of sisal fibres were spread longitudinally in the glass mould. The fibres were then covered with peel ply and infusion mesh simultaneously. The peel ply was made of polyester material and is used to wick away slight excesses of resin. The infusion mesh was made of a plastic material, and it aids the resin to flow efficiently throughout the fibres. A bleeder cloth was then laid near the tube exit to the vacuum so that excess resin could be sucked through the tube to the resin trap. Spiral tubings were then both connected, one to the tube from the resin beaker and one to the vacuum. Thereafter, a vacuum bag was used to cover the entire casting. A tacky tape was then used to secure the vacuum bag onto the mould. The vacuum pump motor was switched on, and the tube leading to the resin storage container was temporarily closed off using a G-clamp in order to avoid suction of air into the fibres before creating a vacuum. A break of one hour was allowed with the vacuum pump running as the resin was being prepared. The resin and the hardener were then measured in their appropriate ratios using an electronic balance of accuracy ±0.5 gm and subsequently mixed using a spatula. Air entrapment in the resin was eliminated through puncturing of air bubbles with a sharp needle. After the break, the resin suction pipe was placed into the resin container and the closing G-clamp on the pipe was removed in order to allow suction of the resin onto the fibres. The sisal fibre reinforced epoxy resin composites were subsequently cured in air for 24 hours. After this air curing, the composite was further cured in an oven at 80°C for four hours as recommended by the supplier in order to produce composites with excellent mechanical properties. The reinforcement was varied from 0 to 50 wt.%, inclusive in the different composites.

2.4. Impact Tests. In order to determine the fracture toughness of the fabricated composites, Charpy impact tests were performed at room temperature using a Hounsfield Balanced Impact Tester (Tensometer Ltd., Croydon, England). The Hounsfield Balanced Impact Tester imposes a three-point impact similar to that created by the Charpy apparatus specified in ASTM D6110-10. Test specimens with a geometry of $50 \times 12 \times 5$ mm in length, width, and thickness, respectively, were cut from the cast composites using a CNC machine. For each composition, a V-notch of $45^\circ \pm 1^\circ$, root radius of 0.25 ± 0.05 mm, and notch width of 2 mm was made. The specimens were, thereafter, sanded off using emery cloth of grade 220 in order to ensure that no out-of-plane notches were introduced onto the specimens. The Charpy impact test, also known as the Charpy V-notch test, is a standardised high-strain rate test which is used to determine the amount of energy absorbed by a material during fracture. The results obtained from Charpy impact test are a measure of a given material's toughness and can also be used to determine temperature-dependent brittle-ductile transition curve of a material [3]. When determining the fracture toughness using the Charpy impact test frame, the sample piece is loaded horizontally onto the apparatus, and the Charpy impact test pendulum hammer is released to strike the notched sample on the back side of the V-notch. The notch is introduced in the test samples to create a known point of stress concentration at which cracks are expected to initiate. After impact, the sample is removed and its failure surfaces examined. If the failure surface is flat and smooth, then failure is classified as brittle. If on the contrary, the failure surface is fibrous, then failure is classified as ductile. The scope of the current study was restricted to the determination of the impact toughness of the composites at room temperature.

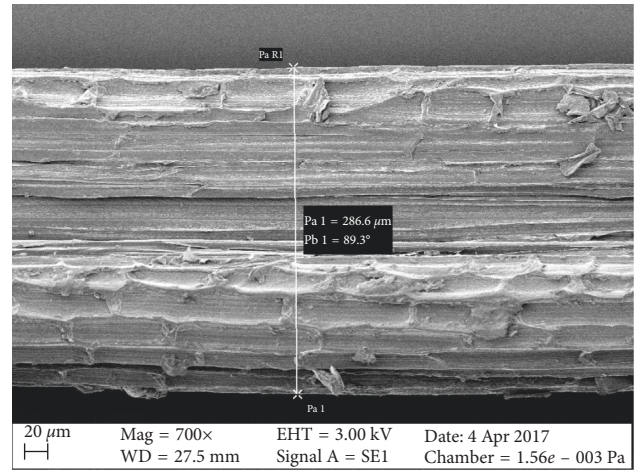


Figure 2: Untreated sisal fibre.

2.5. Hardness. Hardness testing was done in accordance with ASTM D 2583 test standard specifications using the Barber Colman Barcol Impressor. Test specimens with a geometry of $12.7 \times 12.7 \times 3$ mm in length, width, and thickness, respectively, were cut from the cast composites using a CNC machine. The hardness test characterises the indentation hardness of materials by measuring the depth of penetration of the indenter point. The Barcol Impressor, model GYZJ-934-1 consists of a hardened steel truncated cone, with an angle of 26° and a flat tip of 0.157 mm diameter at the spring loading plunger, which is used to make indentation on materials.

2.6. Scanning Electron Microscopy. The surface morphologies of the composites of various fibre weight fractions for both treated and untreated composites were analysed using electron microscopy technique. The composite surfaces were analysed using the Zeiss Environmental SEM (ESEM: model EVO HD 15, operating at 20 kV), where the specimen was gold sputter coated using Quorum 150R ES model thin film coating equipment. The coating was applied in order to enable the specimens to become easily visible. The treated and untreated sisal fibres were scanned as well.

3. Results and Discussion

3.1. SEM Results of Untreated and Treated Sisal Fibres.

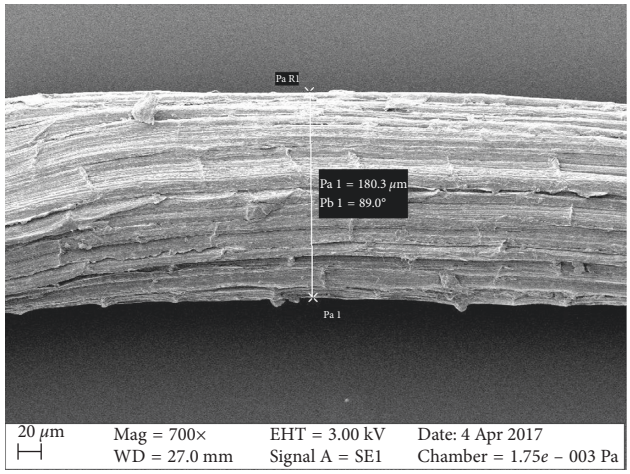


Figure 3: Treated sisal fibres.

The untreated and treated sisal fibres were subjected to scanning electron microscopy with the resulting images shown in Figures 2 and 3.

From the images, it is clear that the cross-sectional dimensions of the treated sisal fibres (180.3 μm) are smaller than that of the untreated sisal fibres (286.6 μm). A reduction in size of the treated sisal fibres leads to better mechanical properties of the resulting composites than those of the untreated sisal fibres due to an increase in number of reinforcing fibres (and therefore reinforcing fibre volume fraction) that can be packed in a cross section of a matrix.

3.2. Impact Test Results. The impact fracture surfaces were observed with a scanning electron microscope. Five scans were conducted for each sample, and representative micrographs are shown in Figures 4(a)–4(j) and 5.

When both the untreated and treated composites were compared at each weight fraction and the number of incidences of fibre pull-out counted in each case, it was found that there were higher incidences of fibre pull-out in the untreated sisal fibre-epoxy resin composites than in the treated sisal fibre-epoxy resin composites. Furthermore, the impact fracture surface of the epoxy resin exhibited a smooth fracture surface. Higher incidence of fibre pull-out is a clear indication of lower fibre-matrix adhesion. Lower interfacial adhesion results in the matrix absorbing higher fractions of the total energy imposed on a composite than would be the case where higher interfacial adhesion exists and, therefore, leads to lower values of impact energy, where the fracture toughness of the matrix is lower.

Average values of impact toughness for both the treated sisal fibre-epoxy resin composites and the untreated sisal fibre-epoxy resin composites which were determined using a Charpy impact test machine are presented in Table 1. The impact toughness of the pure epoxy resin was also determined and is recorded in the table as well.

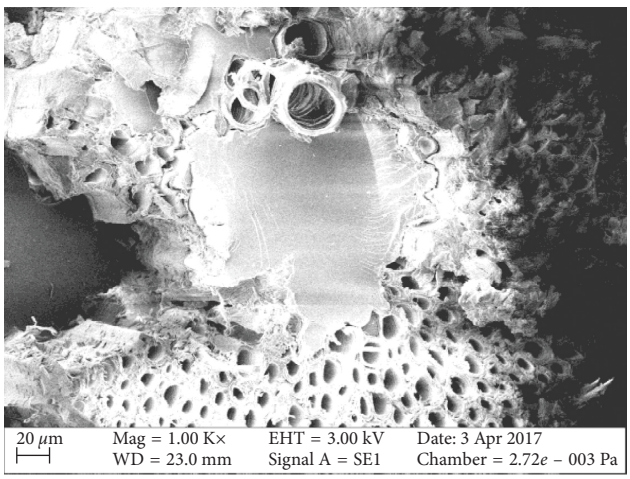
The results in Table 1 clearly show that impact energy of reinforced composites was enhanced by the three combined treatment methods for the reinforcing fibres. Increase of impact energy due to an enhanced fibre-matrix adhesion was also reported by Ramires and Frollini [24]. The average impact energy of the treated sisal fibre-epoxy resin composites is seen in the table to have increased by 28.09%, 20.07%, 14.06%, 15.44%, and 22.34% for composites with 5 wt.%, 10 wt.%, 15 wt.%, 30 wt.%, and 50 wt.%, respectively, over the values obtained for the untreated sisal fibre-epoxy resin composites for the same weight fractions. The standard deviations of the impact energies for both the treated and the untreated composites are small, all falling within the range from 0.12 to 0.93, while the coefficient of variations for both the treated and untreated sisal fibre-epoxy resin composites are also low, ranging from 13.48% to 31.59%. The low values of the standard deviations and coefficient of variations implies that there was not much scatter in the experimental data obtained.

It is evident from the values in the above table that the average values of impact energy of the tested specimens increased from a value of 0.84 joules for pure epoxy resin to a maximum of 10.34 joules and 12.65 joules for a 50 wt.% untreated and treated sisal fibre-epoxy resin composites, respectively. These are 1130.95% and 1405.95% increases in the value of impact energy, respectively, over the values of pure epoxy resin. The increase of the average impact energy for the untreated and treated fibre reinforced composites over the values for the pure epoxy resin for the five percentage weights of 5 wt.%, 10 wt.%, 15 wt.%, 30 wt.%, and 50 wt.% were significant at 35.73%, 197.62%, 313.10%, 678.57%, and 1130.95% and 154.76%, 252.38%, 371.43%, 798.81% and 1405.95%, respectively, for the untreated and treated sisal fibre-epoxy resin composites. The higher values of impact energy for the treated sisal fibre-epoxy resin composites over the untreated sisal fibre-epoxy resin composites can be attributed to the improved mechanical interlocking due to rougher surfaces of the treated sisal fibres and improved interfacial bonding.

The values of impact toughness shown in Table 1 are plotted in Figure 6.

The curve plots in Figure 6, for both the treated and untreated sisal fibre-epoxy resin composites depict a continuous increase of the impact toughness with an increase in fibre loading. The magnitude of the impact energy of the plotted curve for the treated sisal fibre-epoxy resin composites is higher than that for the untreated sisal fibre-epoxy resin composites. This difference in magnitude of the two curves is because of the difference in reinforcing effects of the treated and untreated sisal fibre. In addition, both curves do not have minimum points. The absence of minimum points in both curves is because the range of percentage weights at which tests were done did not include those at or around the minimum point. The correlation coefficient in both graphs is very unity, implying a near perfect curve fit of the curves to the experimental data plotted in both case.

3.3. Hardness Test Results. The results arising from the measurements of hardness are presented in Table 2 for the treated and untreated sisal fibre-epoxy resin composites. The results at 0 wt.% represent pure epoxy resin.



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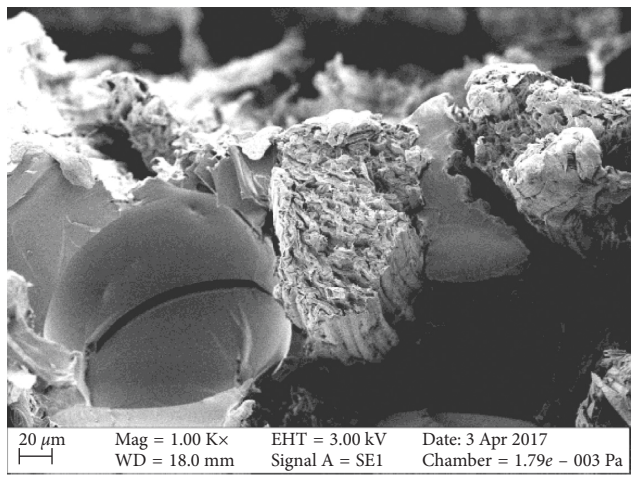

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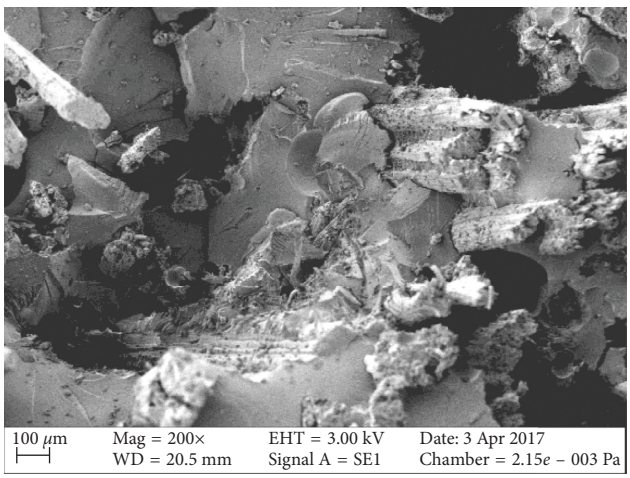

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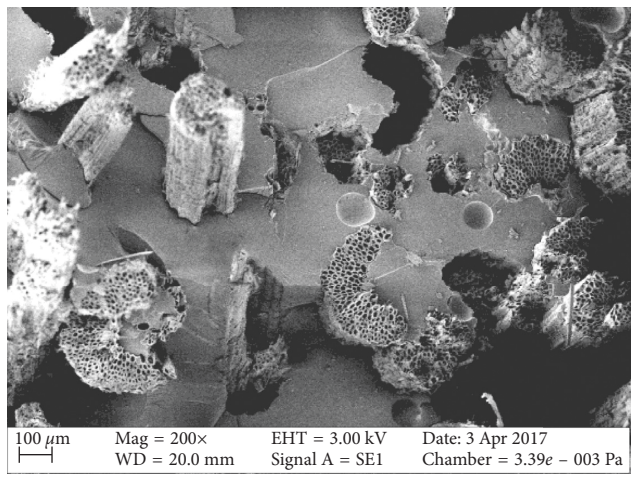

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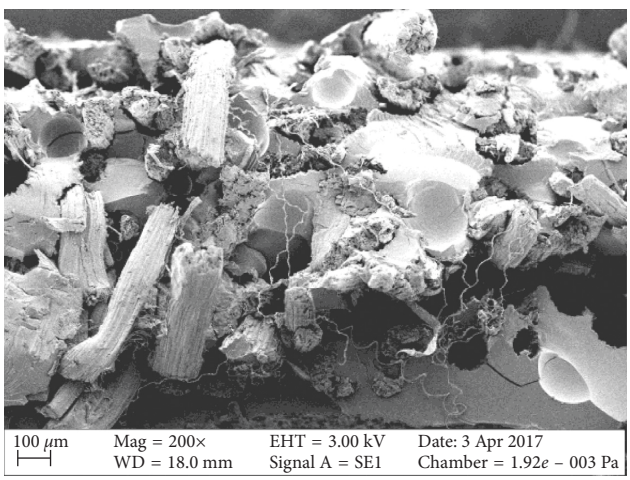

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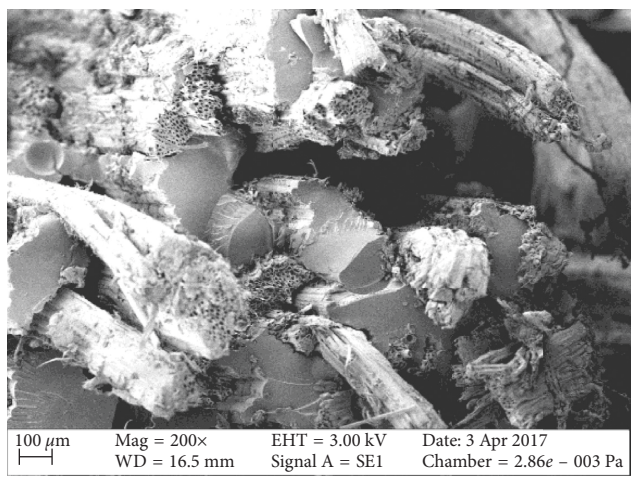

(f)

Figure 4: Continued.

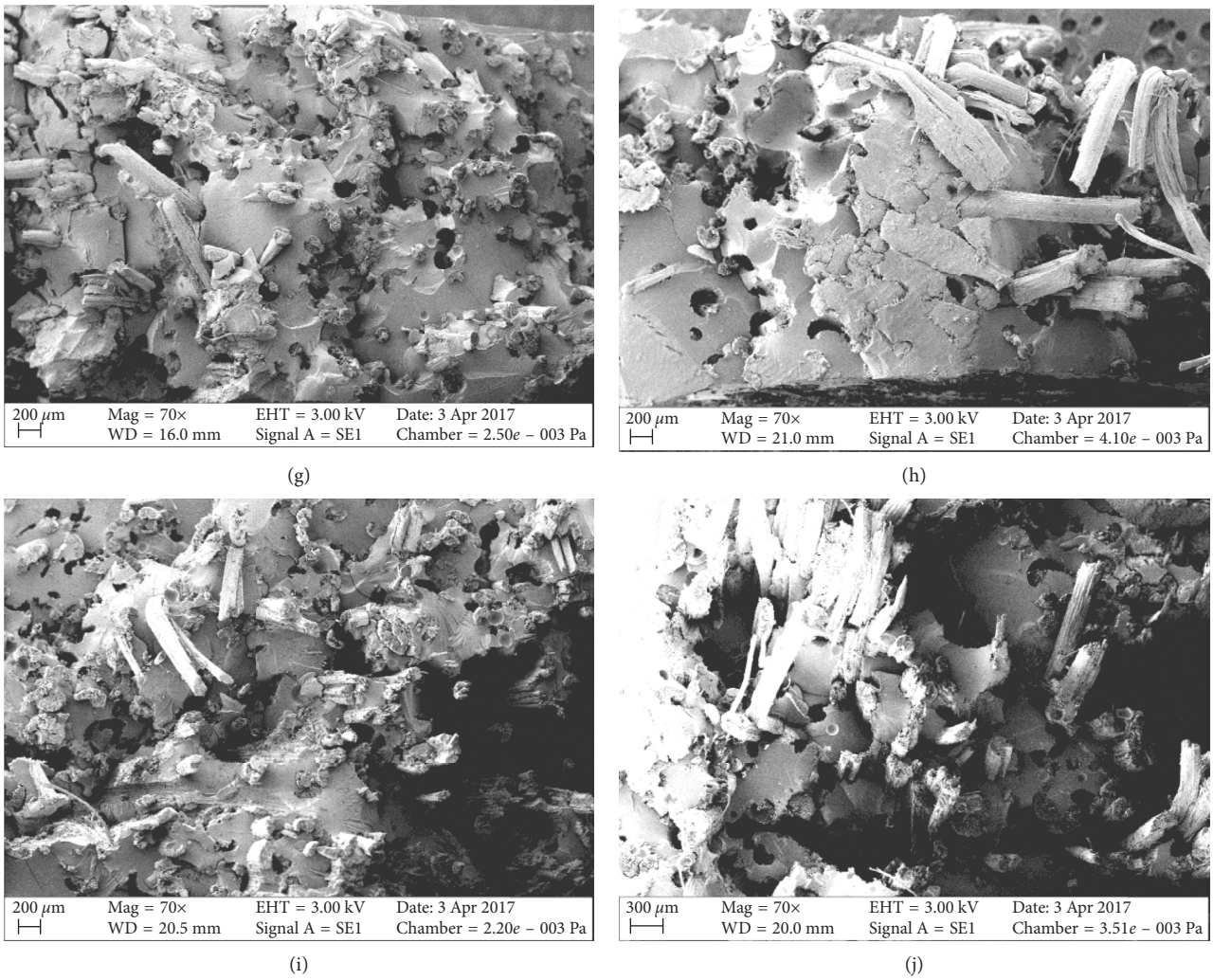

Figure 4: Impact scans of epoxy resin and untreated and treated sisal fibre-epoxy resin composites. (a) 5 wt.% untreated sisal fibre-epoxy resin reinforced composite. (b) 5 wt.% treated sisal fibre-epoxy resin reinforced composite. (c) 10 wt.% untreated sisal fibre-epoxy resin reinforced composite. (d) 10 wt.% treated sisal fibre-epoxy resin reinforced composite. (e) 15 wt.% untreated sisal fibre-epoxy resin reinforced composite. (f) 15 wt.% treated sisal fibre-epoxy resin reinforced composite. (g) 30 wt.% untreated sisal fibre-epoxy resin reinforced composite. (h) 30 wt.% treated sisal fibre-epoxy resin reinforced composite. (i) 50 wt.% untreated sisal fibre-epoxy resin reinforced composite. (j) 50 wt.% treated sisal fibre-epoxy resin reinforced composite.

Pure epoxy at 0 wt.% and treated and untreated sisal fibre-epoxy resin composites were tested at ten different points on their respective surfaces and their average values calculated. All the samples showed statistical similarity as indicated by the small values of coefficient of variation in the table. This similarity indicates the efficiency of the vacuum resin infusion manufacturing process of preparing composites with reference to the presence of pores and distribution of fibres.

The 50 wt.% sisal fibre-epoxy resin composite had the highest value of hardness of 45.00 BU for the untreated sisal fibre-epoxy resin composites and 49.00 BU for the treated sisal fibre-epoxy resin composites with a value of standard deviation of 0.82 for both sets of composites, and coefficients of variation of 2.72 and 2.15, respectively. These low values of standard deviation and coefficients of variation imply that there was no much scatter in the values obtained.

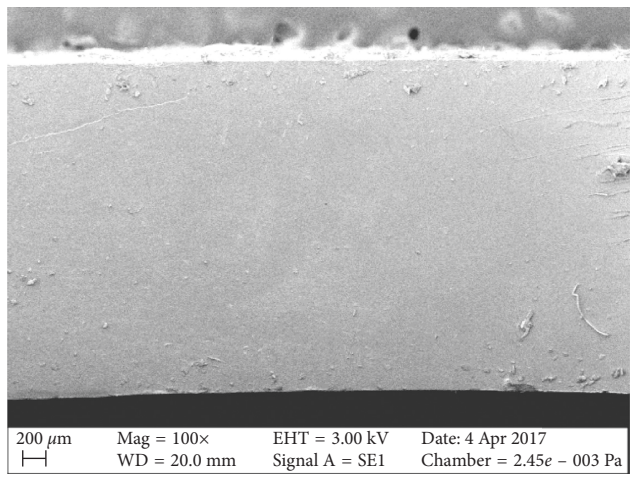

Figure 5: Impact fracture surface of pure epoxy resin.

Table 1: Values of impact toughness for pure epoxy as well as treated and untreated sisal fibre-epoxy resin composites.

Weight % of the reinforcing fibre	Impact energy of untreated sisal fibre-epoxy resin composites			Impact energy of treated sisal fibre-epoxy resin composites			% increase of impact energy
	Range (joules)	Average (joules)	Coefficient of variation (%)	Range (joules)	Average (joules)	Coefficient of variation	
Epoxy (0)	0.54–1.22	0.84 ± 0.24	28.33	0.54–1.22	0.84 ± 0.24	28.33	—
5	0.81–1.89	1.14 ± 0.29	25.47	1.63–2.44	2.14 ± 0.29	13.48	28.09
10	2.30–2.71	2.50 ± 0.12	14.86	1.08–4.75	2.96 ± 0.93	31.59	20.07
15	1.36–4.61	3.47 ± 0.86	24.81	2.03–5.56	3.96 ± 0.84	21.32	14.06
30	5.28–7.86	6.54 ± 0.67	22.45	6.34–8.15	7.55 ± 0.67	25.47	15.44
50	8.76–11.74	10.34 ± 0.74	18.44	10.77–13.15	12.65 ± 0.82	25.22	22.34

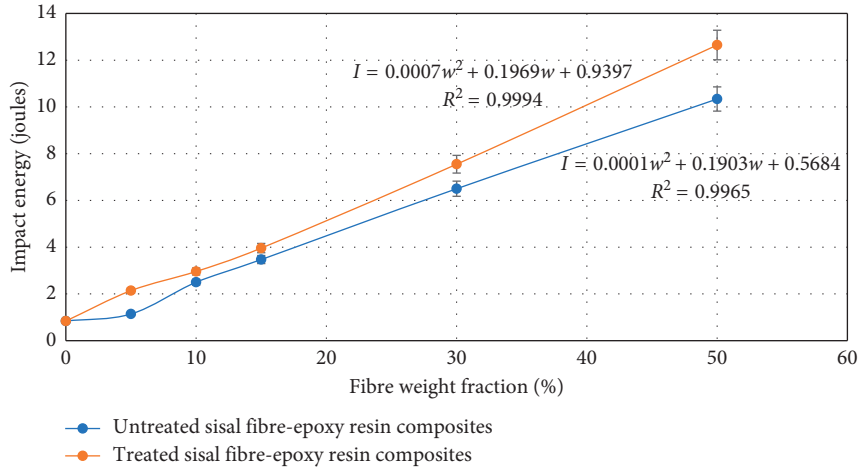

Figure 6: A plot of the average values of impact energy versus fibre weight fraction % for treated and untreated sisal fibre-epoxy resin reinforced composites.

Table 2: Barcol values of hardness for pure epoxy resin and treated and untreated sisal fibre-epoxy resin composites.

Weight % of the reinforcing fibre	Values of hardness for the untreated sisal fibre-epoxy resin composites (Barcol units-BU)			Values of hardness for the treated sisal fibre-epoxy resin composites (Barcol units-BU)		
	Range (BU)	Average (BU)	Coefficient of variation (%)	Range (BU)	Average (BU)	Coefficient of variation (%)
Epoxy (0)	25.00–27.00	26.00 ± 0.94	3.63	25.00–27.00	26.00 ± 0.94	3.63
5	27.00–31.00	29.00 ± 1.41	4.88	29.00–31.00	30.00 ± 0.94	3.14
10	29.00–31.00	30.00 ± 0.82	2.72	37.00–39.00	38.00 ± 0.82	2.15
15	27.00–31.00	29.00 ± 1.49	5.14	27.00–31.00	29.00 ± 1.56	5.39
30	38.00–41.00	39.00 ± 1.77	3.46	42.00–46.00	43.00 ± 1.43	3.54
50	44.00–47.00	45.00 ± 1.65	4.35	48.00–51.00	49.00 ± 1.32	3.26

The values of hardness presented in Table 2 are plotted in Figure 7.

From Figure 7, it is clear that there is an initial increase in the values of hardness of the treated and untreated sisal fibre-epoxy resin composites up to maximum values of 30 and 38 BU respectively, both at a reinforcing fibre weight of 10% fibre. After this, the values of hardness reduce down to a value of 29 BU at a reinforcing fibre weight of 15%, which is higher that the value of 26 BU for pure epoxy resin. Thereafter, the values of hardness increase continuously upto a reinforcing fibre weight of 50%. The reduction in the Barcol hardness after 10 wt.% can be attributed to the poor wettability between the fibres and the matrix leading to agglomeration as the fibre weight percentage increases upto 15 wt.%. From 15 wt.%, the values of hardness increases continuously upto 50 wt.% due to more even distribution of the reinforcing fibres and a corresponding increase in the stiffness of the composites. The correlation coefficient in both graphs is near unity, implying a near perfect curve fit to the experimental data plotted in both cases.

3.4. Comparison to Other Published Works. It is interesting to compare the current results with the previous works. Table 3 summarises the available impact and hardness properties of polymeric composites based on natural fibres.

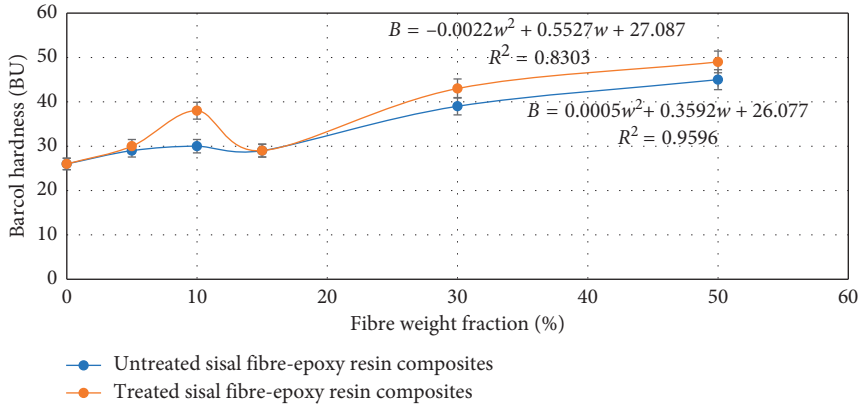

Figure 7: A plot of average values of the Barcol hardness (BU) versus fibre weight fraction % for treated and untreated sisal fibre-epoxy resin composites.

Table 3: A summary of impact strength and hardness of selected natural fibre composites.

Matrix	Fibre (type of orientation)	Fibre content (%)	Type of treatment	Impact strength (joules)	Hardness (Barcol units)	Reference
PLA	Sisal (random)	30.00	None	3.30	—	[29]
PLA/PEG-plasticized	Sisal	30.00	None	4.50	—	[29]
UFR	Sisal (random)	50.00	Alkali, MAPP	9.50	—	[30]
PP	Wood (flour)	30.00	Alkali, MAPP	5.00	—	[30]
PP/EPR/MAPP	Wood (flour)	30.00	Alkali, MAPP	7.00	—	[30]
PP/MAPP	Wood (flour)	30.00	Alkali, MAPP	5.00	—	[30]
Epoxy	Areca fibre	40.00	Alkali	—	45.00	[31]
Epoxy	Sisal (unidirectional)	0.00–50.00	Alkali, silane, acid hydrolysis	0.84–12.65	26.00–49.00	Present study

It is evident from Table 3 that the current results are an improvement of 7%–56% for impact and 9% for hardness on the values obtained from the previous results. Clearly, the combined chemical treatment of mercerisation, silane, and acid hydrolysis, leads to an improvement in the mechanical properties of impact and hardness of the order of 7%–56% for impact and 9% for hardness of sisal fibre reinforced epoxy resin composite.

4. Conclusions

The following conclusions were made:

(1) Chemical treatment of sisal fibre surfaces leads to continuous increases in the impact toughness of the treated sisal fibre-epoxy resin composites with increasing weight fraction of the reinforcing fibres.

(2) Chemical treatment of sisal fibre surfaces leads to an increase in the hardness of the sisal fibre-epoxy resin composites.

(3) The hardness of both the treated and untreated sisal fibre-epoxy resin composites increased gradually with an increase in fibre loading up to a maximum fibre weight fraction of 10% and then decreased beyond here up to fibre weight content of 15% as a result of fibre bunching, thereafter increasing gradually up to fibre weight fraction of 50% due to an increase in the spatial distribution of the reinforcing fibre and increase in the stiffness of the resulting composite.

(4) The combined chemical treatment of mercerisation, silane, and acid hydrolysis leads to an improvement in the mechanical properties of impact and hardness that is higher than in cases where only one treatment process is used on its own.

Conflicts of Interest

The authors have no conflicts of interest to disclose in relation to the current research.

Acknowledgments

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