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Influence Of Sodium Hydroxide And Zinc Chloride Treatments On The Mechanical And Physical Properties Of Coconut Fruit Fiber-Vinyl Ester Composites

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Abstract
Natural fiber-reinforced polymer composites are increasingly recognized as sustainable alternatives to synthetic fiber-reinforced polymer composites. This study aimed to evaluate the mechanical, physical and morphological characteristics of chemically-treated coconut fruit fiber (CFF) reinforced vinyl ester composites. The coconut fibers were subjected to the sodium hydroxide (NaOH) and zinc chloride (ZnCl) treatments before being used to manufacture composites. The composites of different fiber contents were tested for tensile strength, flexural strength, flexural modulus, impact strength, water absorption, and fracture morphology by scanning electron microscope (SEM). The results showed that mechanical properties increased with fiber content until about 30 wt.% and then decreased with further increases in fiber content. The tensile strength of NaOH treated composites was always higher than that of ZnCl treated composites, with a maximum tensile strength of 54.45 MPa and 48.93 MPa respectively. Additionally, NaOH treatment resulted in better flexural and impact properties and reduced water absorption in all fiber loading, which showed good fiber-matrix bond and moisture resistance. SEM micrographs showed that the fiber dispersion, the bonding between fibers and matrix and the pull-out and void formation were improved more in the composites treated with NaOH than that of ZnCl . The results showed that the types of chemical treatments and the amount of fiber loading have a significant effect on composite properties, and that the mechanical properties and durability of the composites were most improved by the treatment with NaOH for structural and engineering applications using sustainable materials.

Keywords: *Coconut fruit fiber; Vinyl ester composite; Zinc chloride treatment; Sodium hydroxide treatment; Mechanical properties; Water absorption.*

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I. Introduction

With the growing awareness of global communities on environmental sustainability, conservation of resources and valorization of waste, a great deal of research has been done on the use of natural fiber-reinforced polymer composites as a substitute for conventional synthetic fiber composites [1,2]. The synthetic fibers (glass and carbon) are used to reinforce materials that have very good mechanical properties, but the production of such fibers is accompanied by high energy consumption, high cost, and other difficulties of using the fibers, such as requiring the use of non-renewable resources and being difficult to recycle [3]. As environmental issues and the demand for sustainable material solutions have become more prominent, renewable lignocellulosic fibers from agricultural resources have been increasingly studied [2]. Natural fiber composites have many desirable properties, such as low density, biodegradability, wide availability, and reduced environmental impact, which makes them desirable for use in semi-structural engineering applications, packaging, consumer products, and automotive components [1,4]. In addition, the use of agricultural wastes as reinforcement materials helps reduce waste and promotes the implementation of a circular bio-economy by converting low-value biomass into value-added products [5].

Coconut fruit fiber (CFF) has gained considerable interest among the other natural fibers that were studied for composite applications due to its abundance, renewability and physical properties [6,7,8]. Because of the amount of fibrous material generated while harvesting coconuts, it is usually either discarded or used in very limited quantities as reinforcement materials [9]. Coconut fruit fiber has a relatively low density that helps in the manufacture of low-density composites for weight-sensitive applications [10]. Furthermore, the fiber is tough and has a satisfactory durability, which are desirable features, in addition to the biodegradability property making it an environment-friendly fiber alternative to synthetic reinforcements [11]. Coconut resources are also available in a significant portion of the tropical and subtropical areas, further promoting its sustainability as a reinforcement material. The addition of coconut fruit fiber to polymer matrices not only optimizes the use of the resources but also offers an opportunity to decrease the cost of the materials and to make the manufacturing environmentally friendly [12].

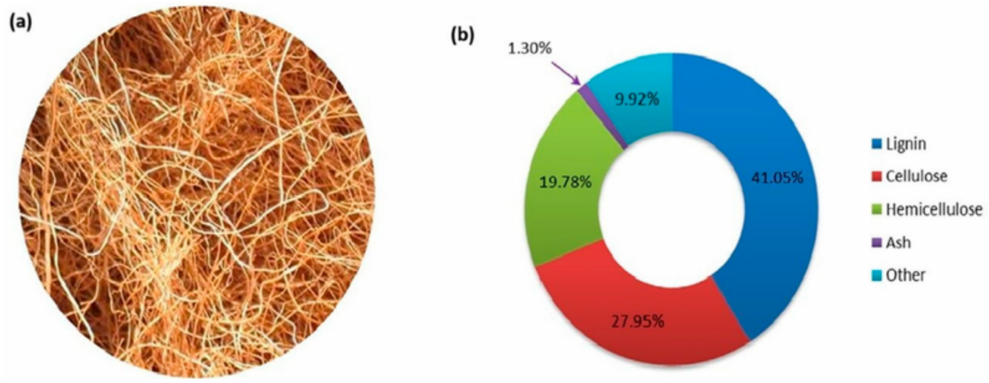


Figure 1: (a) Brown coir and (b) Chemical composition of untreated coir[6]

However, it is still a challenge to produce high performance natural fibre reinforced polymer composites as there are many differences between lignocellulosic fibre and polymer matrices [13,14]. From the earlier studies, it can be noted that all the natural fibers are hydrophilic substances containing hydroxyl in their constituents, while most of the thermosetting and thermoplastic polymers are relatively hydrophobic and have poor interfacial compatibility with the reinforcement [13,15]. This mismatch often leads to low bonding quality at the interface, which affects the transfer of stress during mechanical loading, and can cause fibre pull-out, debonding at the interface, voids and reduced strength of the composite[13,16]. In addition, poor bonding of the components can result in dimensional instability and loss of mechanical properties and long life under service conditions [17,14]. Therefore, surface modification of natural fibers to make them more suitable with polymer matrices is one of the most important research areas, which will enable the creation of natural fiber based composites with durability, mechanical efficiency and moisture repellency properties [15,13].

Various physical, chemical and physicochemical surface modification techniques have been attempted to render the natural fibers compatible with the polymer matrix and to enhance the overall performance of natural fibers based composite[18,19]. Of these, the chemical treatment is one of the most widely used due to its ease, efficiency and versatility for application to various systems of lignocellulosic fiber [19,20]. In case of natural fibres, the surface properties can be modified by chemical treatment, which can influence the interaction of fibres with the surrounding polymer matrix and may result in enhanced fibre-matrix interface properties of natural fibre composites [18,20]. Among the various surface modification techniques, sodium hydroxide (NaOH) treatment has been the most widely studied, and its ability to enhance the mechanical properties and moisture resistance of natural fiber-reinforced polymer composites[21,22] has been documented. Another popular chemical modification process is the treatment with zinc chloride (ZnCl), which can be used to enhance the surface properties of fiber and affect the performance of the composites, and depends mainly on the processing conditions and fiber-matrix systems used[19,20]. Although there are reported improvement with chemically treated natural fiber composites, the effectiveness of a specific treatment is influenced by the type of fibers used, the treatment conditions, type of matrix, fiber loading and processing technique. Hence, there is a need for comparative testing between surface modification techniques of different chemical treatments for different natural fiber/polymer composite systems [18,21].

Vinyl ester resin one of the available matrices with excellent mechanical property and chemical and environmental resistance, it can be used as a good matrix material in the manufacturing of natural fibre composites [23,24]. The use of vinyl ester resins in marine structures, chemical processing equipment, transportation and civil infrastructure applications is widespread due to their many attractive properties, which are superior to many conventional thermosetting polymer systems, such as corrosion resistance, moisture resistance, and resistance to aggressive chemical environments [13,25]. Moreover, vinyl ester matrices possess other significant properties, including a good tensile strength, flexural strength, dimensional stability and thermal properties, and are suitable for producing lightweight composites for structural and semi-structural engineering applications [24,26]. The use of natural fibers in vinyl ester matrices presents a chance to combine the sustainability benefits of renewable lignocellulosic reinforcements with the durability and high performance of advanced thermosetting polymers [24]. The durability and performance of the natural fiber/vinyl ester composites, however, is largely influenced by the quality of fiber-matrix interface, where moisture may penetrate the internal of the natural fiber composite, limit the stress transfer, and affect the service performance of the composite[25,27].

Although extensive research has been carried out for coconut fiber-reinforced polymer composites, the few recent works published have focused on polyester, epoxy and thermoplastic matrices, and there are few studies in the literature that have evaluated the properties of coconut fiber composites with vinyl ester matrices[13,22]. In comparison to other natural fibers, mechanical and physical properties of the CNFC have received less attention, while the influence of different chemical processes on the mechanical and physical properties under similar processing conditions has not been mentioned. Likewise, there are limited published data for comparing the properties of the coconut fruit fibre/vinyl ester composite (tensile properties, flexural properties, impact properties, water absorption and fracture morphology) after the surface modification using NaOH and $ZnCl_2$ [23,28]. These chemical treatment approaches, therefore, need to be critically evaluated in terms of their relative effectiveness and the surface modification/composites performance correlation needs to be better understood. The information will assist in the development of natural fiber vinyl ester composites with improved mechanical, moisture and structural reliability which can be used in engineering applications [13,29].

Hence, the aim of this study is to look into the effect of NaOH and $ZnCl_2$ treatment on mechanical property, water absorption behavior and morphological study of coconut fruit fibre filled vinyl ester composites. Based on the literature, it was determined that the tensile, flexural and impact properties are the major ones that represent the structural performance of natural fiber-reinforced polymer composites (NFRPC) and hence, these were chosen for the composite specimens fabricated and tested with different fiber loadings [30,31]. The water absorption behaviour was also examined to understand how moisture uptake affects the performance of the composites as exposure to water is one of the key factors contributing to the long-term durability of natural fiber composites [26,32]. Additionally, scanning electron microscopy (SEM) was used to analyze the fracture features of the composites and to gain an understanding of the interaction between the fibres and matrix, which is crucial for assessing the efficiency of stress transfer and the consequent mechanical behaviour of composite materials[30,33]. Based on the results of this study it is hoped that the understanding of how chemical surface modification affects the relationship between fiber treatment, microstructure, moisture resistance and mechanical characteristics will contribute to the development of sustainable natural fiber reinforced vinyl ester composites and promote the further use of natural fiber composites in engineering applications [31,34].

II. Materials And Methods

Materials

The coconut fruit fiber (CFF) used for reinforcement was sourced from Agbani community in Nkanu West local government area of Enugu State, Nigeria and processed before being used for the fabrication of composite. Vinyl ester resin, used as the polymer matrix, had a density of 1.12 g/cm³ at 25 °C and a viscosity of 450-600 cP. The resin was purchased from a reputable local supplier (ResinTech Industries, Nigeria). The properties of vinyl ester resins, such as good mechanical properties, chemical resistance, and durability in aggressive environments, [23,26] makes them attractive matrix materials for fiber-reinforced composites. The reagents NaOH and $ZnCl_2$ used for treating fibers were of analytical grade. In particular, NaOH (98% purity) and $ZnCl_2$ (99% purity) were purchased from BDH Chemicals (UK) and used without further purification. The materials chosen for the reinforcement and matrix were coconut fruit fiber as the main material for reinforcement and vinyl ester as the main material for the matrix, as natural lignocellulosic fibers can be used as a source of sustainable reinforcement material for polymer composites, while vinyl ester is selected as the main matrix material because it has the appropriate mechanical strength and environmental resistance for engineering applications [29,34].

Fiber Treatment

To enhance the surface properties of the extracted fibers, they were chemically treated with sodium hydroxide (NaOH) and zinc chloride ($ZnCl_2$), methods that have been extensively used to make natural fibers more compatible with polymer matrices[7,18,19]. Equal amounts of each type of fiber were prepared, one of which was used as a control and the rest were chemically treated. In the case of $ZnCl_2$ treatments, the fibers were first soaked in distilled water for 1 h, filtered and then soaked in $ZnCl_2$ solutions with different concentrations (1-9 wt.%) and different solution-to-fiber ratios (2-6 $g\ L^{-1}$) for different durations (8-12 h). The treated fibers were then transferred to the acetic anhydride solution, washed many times with distilled water, drained and air dried for 48 h. For NaOH treatment, the fibers were dipped in alkali solutions of concentration between 1 and 9 wt.% and ratio between the alkali solution and the fibers 2-6 $g\ L^{-1}$ for 8-12 h. After the treatment, the fibres were neutralized with acetic acid, washed with distilled water to remove excess alkali and subsequently air-dried for 48 h prior to further processing. The treatment procedures and the processing conditions selected are in line with the surface modification process commonly used for the surface modification of lignocellulosic fibers to be used in the production of polymer composite materials [20,22].

Composite Fabrication

Fibers for the composites were prepared by physically mixing chemically treated coconut fruit fibers, chemically cured vinyl ester resin, and vinyltriethoxysilane (VTES) coupling agent in a mixing bowl before composite fabrication. The concentration of the VTES coupling agent used was fixed at 2 wt%, as reported concentrations for natural fiber-reinforced polymer composites (NFRPCs) are commonly used for improving the compatibility of fiber-matrix interface [13,33]. The fiber loading was manipulated based on the experimental design, and the optimum loading of fiber in the composites was found to be about 30-35 wt.%. The amount of treated fibre was weighed and added to the vinyl ester resin matrix, and the mixture was thoroughly stirred to obtain uniform dispersion of the fibre in the matrix. This composite mixture was then fed into the injection molding machine, mixing and molding was finished and then placed into the CNC manufactured moulds of 150 mm × 150 mm × 5 mm. The moulded composites were subjected to compression moulding under a pressure range of 5-10MPa and they were primarily cured at room temperature (25 ± 2 °C) for 24 hours. The composites were post-cured by hot-air oven at 80 °C for 2 h, which is similar to the post-curing temperature and time used in vinyl ester composite systems [23,27]. After which, the composite laminates were demoulded, left at room temperature and pre-conditioned for 48 hours before specimen preparation and mechanical testing.

Mechanical Testing

Tensile Test

Tensile test is conducted as per ASTM D638, which is the standard procedure for testing the tensile behavior of polymer composites and natural fiber-reinforced composite materials [19,33]. The crosshead speed of 50 mm min ^{1} was applied to a Universal Testing Machine (Testometric, 2500 kgf, Rochdale, England; Serial No. 52978) with a dog-bone shaped specimen. All specimens were mounted vertically between the machine grips and loaded to failure. Each composite formulation was tested on five specimens and the average values reported. Stress–strain curves were plotted for each sample and the tensile strength, tensile modulus, yield strength and elongation at break were calculated.

Flexural Test

The flexural properties were measured following ASTM D790, which is a standard test method for determining flexural properties of fiber reinforced polymer composites [32,33]. The same Universal Testing Machine was used for testing at a crosshead speed of 50 mm min ^{1}. The specimen size was 127 × 12.7 × 3.5 mm and was tested on a suitable span, and the flexural strength was obtained from the load-deflection curve using equation (1) below. Five specimens were tested for each composite formulation and an average taken.

(1)

Impact Test

The energy absorbed by the material under sudden loading was determined by using a Charpy impact testing method in accordance with ASTM A370, which is a standard method for measuring impact resistance of materials [19,33]. The V-notch of size 45° measured 2 mm while specimens were prepared of 100 × 10 × 10 mm. All specimens were hit by a pendulum dropped from a fixed height, while they were placed horizontally. The energy absorbed in fracture was recorded directly from the testing machine and thereby impact strength of the composites were found using equation (2) below. Five specimens were tested for each composite formulation and the average value was reported for the reproducibility of the experimental results.

(2)

Water Absorption

The water absorption properties of the composites were evaluated following ASTM D570 by applying equation (3). The dry weight of each sample (W) was initially obtained before it was immersed. Specimens were floated in water for set times and then were withdrawn at intervals. The surface moisture was removed from it and wet weight (W) taken. Water absorption (WA) was calculated using:

(3)

where:

- W_0 = initial dry weight of specimen (g)
- W_t = specimen weight after immersion time t (g)

Scanning Electron Microscopy (SEM) Analysis

The surface morphology of the fabricated composites was studied using Scanning Electron Microscopy (SEM), a commonly used technique for characterizing the microstructural features of natural fiber reinforced polymer composites such as aspect ratio of fibers, bonding between fiber and matrix and fracture characteristics [33,35]. The specimens were mechanically tested and then fractured, for subsequent examination and evaluation of fiber dispersion, fiber-matrix interface interaction and fracture morphology. The samples were cleaned before imaging and transferred to aluminum stubs before mounting on the grid, and SEM micrographs were obtained under low-vacuum conditions. Imaging was done on a Thermo Fisher Scanning electron microscope (SEM) Prisma, with an accelerating voltage of 20.0 kV, an electron beam current of 200 mA, and a working distance of 13.5 mm, using a CBS detector and a 200 µm scale bar at a magnification of 250×. These acquired images were then evaluated for the distribution of the coconut fruit fibers in the matrix (vinyl ester), quality of fiber-matrix interface, and fracture features evaluation of ZnCl and NaOH treated composites. Either of SEM-based analyses are extensively used to correlate fracture shape to mechanical property data of natural fiber-reinforced composites [29,32].

III. Results And Discussion

Effect of Fiber Loading on the Mechanical Properties of CFF/Vinyl Ester Composites

Figures 2 and 3 depict the effect of fiber loading for the mechanical properties of (CFF) reinforced vinyl ester composites using both ZnCl -treated CFF and NaOH-treated CFF respectively. The properties of tensile modulus, flexural strength, flexural modulus and impact strength of both compositions were higher in the range of fiber loading 20-30 wt.%, but then decreased at higher levels of fiber loading (35-40 wt.%). This trend suggests that the fiber loading is an important factor in the reinforcibility of NFPMC and corroborates the findings of other classes of composite materials [7,29,33].

The tensile modulus showed an increasing aspect of 1.44 Gpa, increasing at 20 wt.%, and 2.52 Gpa at 30 wt.% for the ZnCl -treated composites compared with the tensile modulus at 20 wt.% and 2.51 Gpa at 30 wt.% respectively, for the neat composites. Similarly, the flexural strength increased by 2.44 Mpa and 2.58 Mpa for 20 wt.%, 30 wt. % respectively for the ZnCl -treated composites compared to 20 wt.%, 2.57 Mpa respectively, for the neat composites. Likewise, the flexural modulus went up from 1.52 GPa to 2.45 GPa and the impact strength was enhanced from 33.14 Joules per m² to 58.31 joules per m². All of the measured properties decreased beyond 30 wt.% fiber loading with tensile modulus, flexural strength, flexural modulus, and impact strength reaching 2.00 GPa, 44.73 MPa, 2.07 GPa, and 48.47 J/m² at 40 wt.% fiber loading, respectively.

Similar results were found in the composites treated with NaOH. The tensile modulus increased from 1.64 GPa at 20 wt. % to 2.73 GPa at 30 wt. %, while the flexural strength and flexural modulus attained maximum values of 54.42 MPa and 2.51 GPa, respectively. In a similar fashion, the impact strength rose from 34.57 J/m^2 at 20 wt.% fiber loading to 61.27 J/m^2 at 30 wt.% fiber loading and then slightly decreased with increasing fiber loadings.

The higher mechanical characteristics obtained at up to 30 wt.% fiber loading indicate that this content was able to maintain a good amount of matrix continuity while offering good fiber reinforcement, leading to effective transfer of the stress from the fiber to the matrix. Reducing the clustering of fibers and increasing the distribution of fibers in the matrix improves the ability to evenly distribute the load when physically loaded in the matrix at moderate contents of fiber. When the fiber content was above 30 wt.%, there were a gradual decrease in the mechanical properties. This decrease could be related to formation of localized defects compromising the transfer efficiency, lack of wetting of the reinforcement by the polymer matrix, and fiber agglomeration. In the case of natural fiber-reinforced polymer composites, excessive loading of an amount of fiber than can cause the matrix continuity to break and create stress concentration sites that will end up reducing the performance of the material [36,37,38].

In all the fiber loadings tested, the composites with NaOH treated fibers performed better than the composites with ZnCl treated as expected. The tensile modulus of 2.73 GPa, flexural strength of 54.42 MPa, flexural modulus of 2.51 GPa and impact strength of 61.27 J/m² were observed for the NaOH treated composite at 30 wt. % loading of fiber, while the ZnCl treated composite had 2.67 GPa, 49.48 MPa, 2.45 GPa, and 58.31 J/m², respectively. The properties of mechanical performance of the NaOH treated composites indicated it is more effective and efficient in transferring stress to the composite, which leads to better stiffness, bending and energy absorption capacity. In other LC-FRP composite materials, similar improvement after the alkali treatment was observed, which led to the superior mechanical properties due to the increased interactions among the matrix and fibre [39]. Thus, it can be concluded that, in comparison with the ZnCl treated fibers, the NaOH processing was more effective in improving the reinforcing efficiency of coconut fruit fibers and the best mechanical property was obtained in 30 wt% loading of fibers under the conditions used for the treatments [40,41,42].

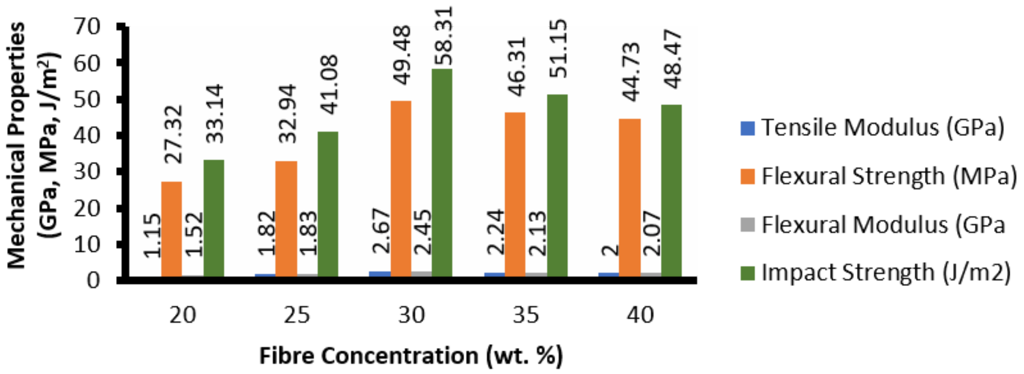


Figure 2: Effect of fiber conc. on the mechanical properties of ZnCl-treated CFF reinforced vinyl ester composite

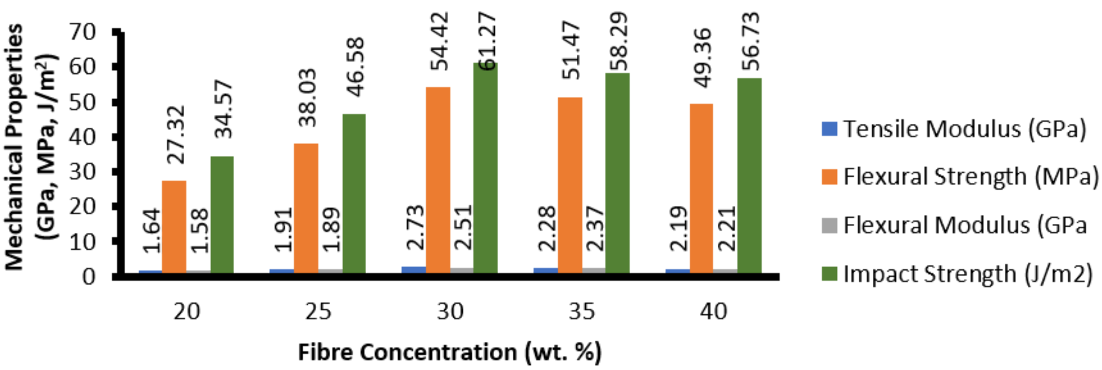


Figure 3: Effect of fiber conc. on the mechanical properties of NaOH-treated CFF reinforced vinyl ester composite

Water Absorption Behaviour

Figures 3 and 4 present the water absorption behaviour of chemically treated coconut fruit fibre (CFF)/vinyl ester composites as a function of fibre loading and immersion time, respectively, for the composites. The effect of chemically treating the coconut fruit fibre (CFF) compared with the untreated fibre is shown in Figure 5. The water absorption capacity of all the fibres has significantly decreased after chemical treatment with moisture absorption of 0.47 for untreated fibre, 0.17 for ZnCl treated fibres and 0.15 for NaOH treated fibre. The increase in water absorption was a progressive process in both composite systems as the fiber loading (20-40 wt.%) and immersion time (24-120 h) increased, thus showing that higher fiber contents and immersion times increased water absorption [43,44]. This is also true for natural fiber reinforced polymer composites where the higher the percentage of fiber content, the more moisture pathways are available to transport moisture within the composite material, thereby increasing the chances of water diffusion [32,34,45,46].

In all experimental cases, composites that were pre-treated with NaOH always had lower water absorbent than the composites that were pre-treated by ZnCl [13,29]. Of the composites, the lower moisture uptake for the NaOH treated composites might be attributed to better fiber-matrix interaction and to lesser path of moisture in the composite. In similar treatments of water absorption, various lignocellulosic fiber-reinforced polymer composites showed interfaces with a higher degree of compatibility, and moisture did not penetrate the composites but didn't eliminate the natural hydrophilic nature of the fibers, either [47,48,49].

Overall, it could be concluded that the moisture absorption of the coconut fruit fibre/vinyl ester composites increased by increasing the amount of fibre used and the time of immersion[50], but NaOH treated samples absorbed less moisture than that treated with ZnCl [51]. The results indicated that the chemical modification has improved the environmental durability and dimensional stability of the natural fibre-VESCs to increase their potential to serve in a humid and/or moisture steeping environment [26,32,52]

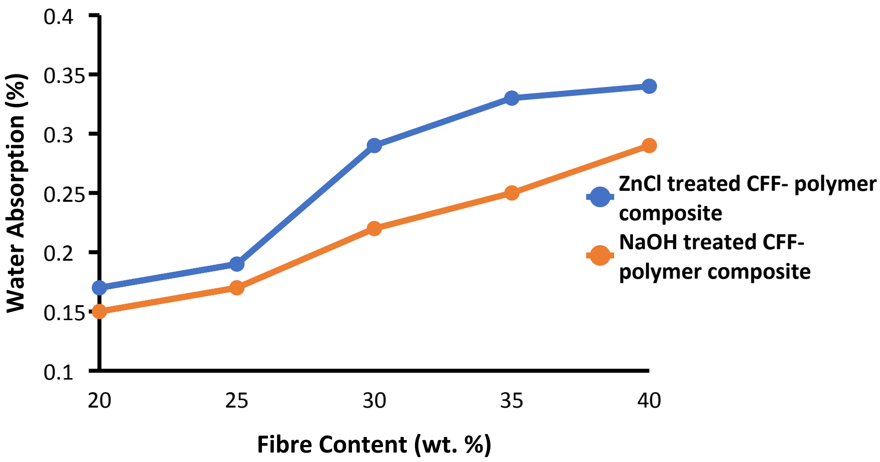


Figure 4: Effect of fiber content on water absorption for chemically treated fiber-polymer composites.

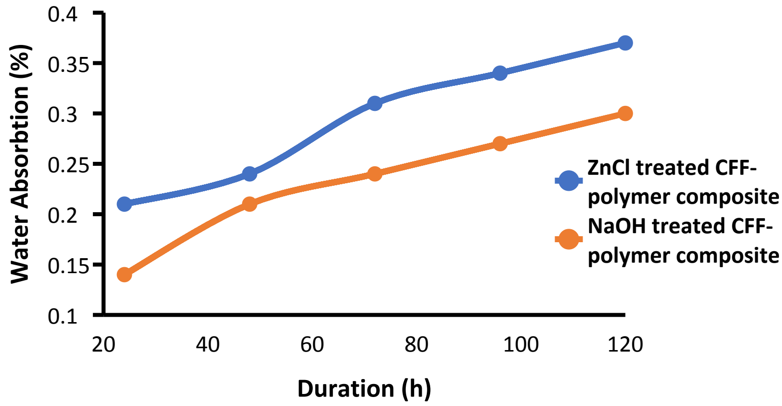


Figure 5: Effect of duration on water absorption for chemically treated fiber-polymer composites.

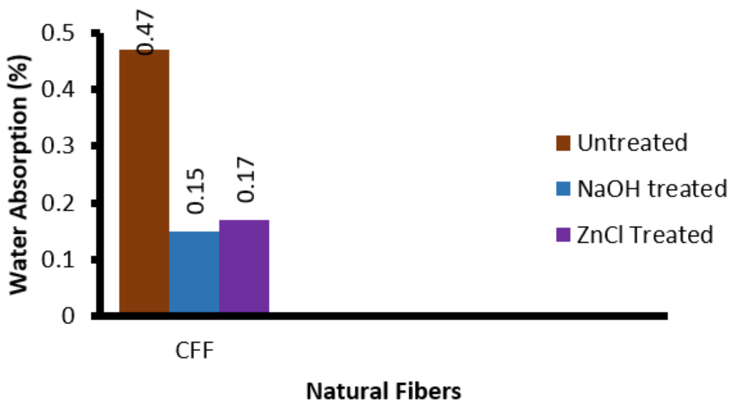


Figure 6: Effect of chemical treatment on untreated and treated fibers

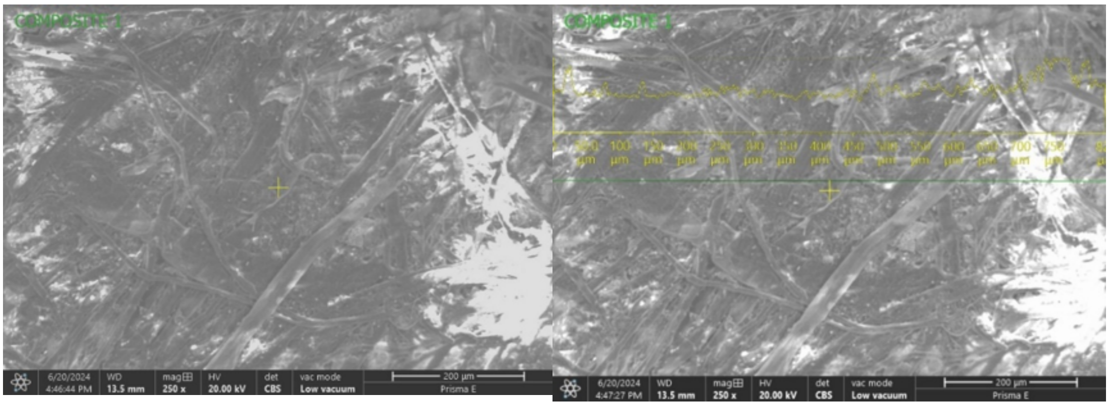
Morphological Analysis

Surface morphologies of the two types of composites, namely, the ZnCl treated coconut fruit fiber (CFF)/vinyl ester composite and NaOH treated coconut fruit fiber (CFF)/vinyl ester composite, are shown in Figure 7. Distinct fracture behaviour differences between the two composites were observed using scanning electron microscope (SEM) images, due to the chemical treatment effect on the interface between the fibre and the matrix [53,54]. SEM was chosen to elucidate the failure mechanism and to give qualitative evidence on fibre dispersion, fibre/matrix pullout, or fibre fracture of the natural fibre reinforcements in polymer composites, and to analyse the characteristics of the interfaces [29,33,55]

For the CFF composite composite in Plate 1a processed by ZnCl , the fracture surface is relatively rough and has regions with discontinuities along the interface between fibers and matrix [56]. The fracture surface of the ZnCl -treated CFF composite (Figure 7a) shows signs of fiber pull-out, isolated voids, and localized discontinuities at the fiber-matrix interface. These are characteristics which suggest that a fairly poor bond was obtained between the fiber and surrounding matrix, under the circumstances of loading for fracture [57]. Further, localized differences in surface topography are observed in the measured surface profile (Figure 7b), which is consistent with the large variation in fracture morphology observed in the SEM image. The fibers seem to be fairly evenly distributed in the vinyl ester, but; some gaps and pull out features at the interfaces imply incompletely uniform load transfer between fibers and vinyl ester matrix over fractured surface area. Of note, localized interfacial debonding and decreased reinforcement effectiveness have been linked to similar fracture characteristics in natural fiber-reinforced polymer composites (NFRCs)[34].

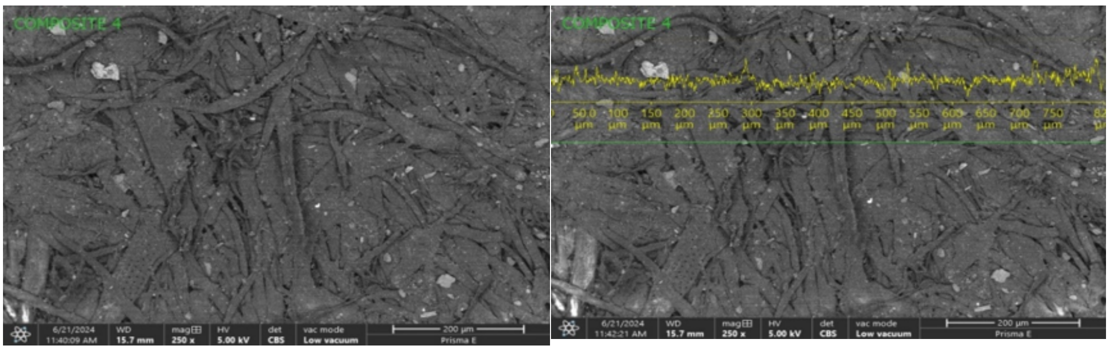
On the contrary, the fracture surface of the NaOH treated CFF composite (Figure 8) demonstrates a more compact fracture surface of the composite, where the fibers look well integrated in the vinyl ester matrix. Less gaps and fiber pull-out features can be observed and the fracture surface morphology is more coherent than that of the ZnCl treated composite [58]. These observations indicate better fiber-matrix interaction and the more efficient transfer of the applied load to the fibers before failure. The lower occurrence of voids and fiber debonding could have been another reason for getting higher tensile, flexural and impact values for NaOH-treated composite [59,60]. The same SEM observations were reported by Ramachandran [13] and Aravindh [21] for alkali treated natural fiber composites in which it was observed that enhanced fiber embedding and reduced defects at the fiber-matrix interface under alkali treatment resulted in better mechanical properties.

The overall SEM observation results are consistent with the results of mechanical testing. Due to the relatively good fiber embedding and the rareness of pull-out observed in the NaOH-treated composite, it may be concluded that it has a relatively strong load transfer capability in the interface, while it has comparatively weak load transfer capability in the interface in the ZnCl -treated composite because of the rougher fracture surface and the gaps in the interface [61]. The NaOH-treated coconut fruit fiber/vinyl ester composite showed more improvement in these morphological features, agreeing with the previously mentioned tests carried out by Kumar [33] and Feng [34] for the chemically modified natural fiber/natural polymer composite.



(a) (b)

Figure 7: Surface morphology of the $ZnCl_2$ treated CFF-polymer composite (a) Plane surface (b) Measured textural surface



(a) (b)

Plate 4.4: Surface morphology of NaOH treated CFF-polymer composite. (a) Plane surface (b) Measured textural surface.

IV. Conclusion

Chemical surface treatment significantly influenced the performance of coconut fruit fibre (CFF)-reinforced vinyl ester composites. NaOH-treated composites, particularly at 30 wt.% fibre loading, exhibited the highest tensile, flexural, and impact strengths, together with the lowest water absorption, owing to improved fibre–matrix adhesion confirmed by SEM analysis. In contrast, ZnCl -treated composites showed comparatively lower performance due to weaker interfacial bonding. The findings demonstrate the potential of NaOH-treated CFF composites as sustainable, lightweight materials for automotive, construction, marine, and general engineering applications. Future studies should investigate their long-term durability, thermal stability, weathering behaviour, and scale-up for industrial production.

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Conflicts of Interest

The authors declare that there is no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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