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Effect of Chemical Treatments and PVA Coating of Fiber on the Properties of Kenaf Fiber Reinforced Epoxy Composites

Md. Abdul Kader[1,*], Mahmudul Islam Hridoy[1], Md. Tanvir Khan Somrat[1], Md. Abdul Wares[1], Syed Mamun R Rasid[1], Muhammad Toufiq Imrose Khaledi[1]

[1] *Department of Mechanical Engineering, Rajshahi University of Engineering and Technology, Bangladesh*

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ABSTRACT

In this study, kenaf fiber-based bio-composites were manufactured using a combination of hand lay-up and compression molding techniques to develop sustainable engineering materials. The fibers were treated with NaOH, acetic anhydride and PVA coating. The effects of these treatments on the surface morphology of fibers were investigated using scanning electron microscopy (SEM). A series of mechanical tests and water resistance capacity were performed to explore the influences of fiber treatments on the properties of composites. The results revealed that the NaOH treated fibers improve moisture resistance, strength and ductility. Acetic anhydride treated fibers enhance moisture resistance, flexibility, and impact strength. PVA coating increases flexibility and impact strength while reducing moisture resistance and other mechanical properties. The combination of all the studied treatments enhances flexibility and impact strength by sacrificing stiffness and moisture resistance. These findings highlight the potential of chemical treatments in optimizing the properties of bio-composite for advanced applications.

1. Introduction

The increasing demand for superior combinations of properties of materials has driven scientists and engineers to develop mechanically robust and multifunctional materials [1]. The most common materials are polymers, ceramics, composites, and metals [2]. Amongst all, composites have been exhibiting promising mechanical properties including higher strength, stiffness, hardness, wear resistance and damping properties [3-6]. Consequently, composites have become the preferred engineering materials in multiple fields such as automotive, aerospace, defense, marine, biomedical and other transportation industries [7-9]. The special advantage of composite materials is that their composition and constituent materials can be tailored to achieve most of the specific set of properties. However, the increasing use of conventional composites that contain non-biodegradable ingredients is becoming a major concern [10]. Detrimental environmental impact of conventional composites has led the foundation to manufacture eco-friendly composites. The matrix and fibers can be taken from bio-based sources to manufacture composites as an alternative of conventional composites with almost no environmental impact [8]. Bio-based composites attract more attention because of their sustainability, excellent degradability, and low toxicity [11-13]. Additionally, the recent developments in bio-composites have introduced multi-functional properties such as conductivity,

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* Corresponding author: Department of Mechanical Engineering, Rajshahi University of Engineering and Technology, Bangladesh
E-mail address: makader@me.ruet.ac.bd (Md. Abdul Kader)

biocompatibility, barrier functionality, and antimicrobial activity. These features of bio-composites lead to the development of advanced materials for biomedical, biosensor and packaging technologies [14].

A variety of natural fibers such as jute, kenaf, sisal, flax and hemp have been used as reinforcement in bio-based composites not only because they are renewable and biodegradable but also offer attractive set of properties including stiffness, strength and flexibility [15, 16]. Among these fibers, kenaf is an excellent source of bio-fibers because of its rapid growth in different climate conditions and ability to accumulate carbon dioxide quickly. Kenaf fiber also exhibits some valuable properties including biodegradability, non-abrasiveness, low density, and high specific mechanical strength. It has been extensively utilized as reinforcement in thermoplastic and thermoset polymers [17]. Additionally, kenaf fibers are used in various industries, including fiberboard, automotive, construction, textiles, and electronics, where they serve as non-woven mats [18].

Though kenaf fiber-based composites hold the potential to serve as an alternative of glass or carbon fiber-based composites in different applications, they have several limitations like other bio-based composites. Some of the key limitations are high moisture absorption, poor thermal resistance, less durability, weak fiber-matrix interfacial adhesion, low mechanical properties, variation of fiber quality, and anisotropic properties [19, 20]. A few studies investigated the bonding between fibers and matrices of bio-composites and reported that the fiber-matrix bonding significantly influences the overall performance of composites [19].

Surface treatments are frequently employed to enhance the performance of natural fiber-reinforced composites by addressing the incompatibility between hydrophilic fibers and hydrophobic matrices. A number of physical and chemical surface treatment procedures for bio-fibers were proposed by earlier research groups to enhance the properties of bio-composites [21]. Physical treatments modify the structural and surface characteristics of fibers, enhancing their mechanical adhesion to polymers. On the other hand, chemical treatments involve in changing both external and internal structures of fibers and can control the overall functionalities of the composites [17].

Different types of fiber treatment techniques such as alkaline treatment, silane treatment and combination of treatments (alkaline-silane, alkaline-bleaching, alkaline-heat, alkaline-beam irradiation) have been conducted by researchers on kenaf fiber [22]. Among these treatments, the alkaline treatment is mostly studied because of its potentiality to improve the performance of composite. Alkaline treatment strengthens the interfacial bond between lignocellulosic fibers and thermoset resins. It decreases fiber diameter and eliminates surface impurities like wax, oil, hemicellulose, and lignin. Additionally, alkaline treatment enhances the adhesion at the fiber-matrix interface by roughening the surface. It also exposes more cellulose on the fiber surface to increase the possibility of bonding with the polymer [22, 23]. Notably, the optimal results are typically achieved when the fiber is treated with an appropriate concentration of NaOH. In most cases, pre-treatment of kenaf fibers with 6% NaOH yields an excellent combination of mechanical properties [22, 24-26]. Alkaline treatment in combination with other types of treatments exhibits excellent improvement in mechanical and moisture resistance properties of kenaf fiber based composites [22]. However, there is a notable gap in literature on the combined effects of alkaline treatment with acetylation or PVA coating.

Acetylation treatment, a form of esterification, is commonly employed to plasticize natural fibers. During this process, acetyl group (-CH3CO) interacts with the hydrophilic hydroxyl groups (-OH) present in the bio-fibers and effectively removes the existing moisture. Consequently, the fibers become less hydrophilic, leading to enhanced dimensional stability of the composites [27, 28]. Additionally, acetylation creates a rougher surface topography to the fibers and reduces the presence of voids [29]. Consequently, mechanical interlocking between the polymer matrix and fiber gets improved, which contributes to enhancing the overall mechanical properties of the composite. Previous studies [23] have highlighted that acetylation enhances various properties of bio-composites, including mechanical strength, dimensional stability, moisture resistance, and thermal stability. Particularly, Chung et al. [30] examined the effects of acetylation on PLA/kenaf composite. Their findings confirmed that a sufficient degree of acetylation significantly reduces the hydrophilicity of kenaf fibers and thereby improves the compatibility of fiber with PLA for stronger interfacial bonding. As a result, the acetylation process significantly enhances the properties of PLA/kenaf composite. Although the acetylation of fibers significantly influences the properties of kenaf fiber-based composites, the existing literature on this topic remains relatively limited. Moreover, there is a lack of studies that specifically examine the correlation between the morphology of acetylated kenaf fiber and the resulting properties of the composite.

Hu et al. [31] pointed out that traditional methods like coupling, esterification, and grafting for modifying natural fibers have drawbacks such as environmental concerns and high cost. They suggested polyvinyl alcohol (PVA) coating treatment as a more eco-friendly, simple, and cost-effective modification process. PVA is a safe, water-soluble, and environmentally friendly polymer. Partially alcoholised PVA molecules possess both hydrophobic chains and hydrophilic hydroxyl groups which make them highly compatible with hydrophilic cellulose. Its hydroxyl groups can form cross-links with compounds like formaldehyde or borax, which allows PVA to effectively modify natural fibers and enhance the interfacial adhesion between the fibers and the polymer matrix. Hu et al. [31] specifically investigated the impact of an alkali/PVA coating on sisal fiber and high-density polyethylene (HDPE) composites. Their findings demonstrated that this treatment significantly improved the interfacial bonding between the fibers and the matrix, resulting in enhanced mechanical strength and better moisture resistance. Despite these promising results, to the best of the author's knowledge, no research to date has investigated the effects of PVA coating on kenaf fiber-based composites.

In this study, the kenaf fibers were treated with NaOH, Acetic Anhydride and PVA coating. Hand layup method with compression molding was used to manufacture the bio-composites. Scanning electron microscopy (SEM) images of the treated fibers were extensively investigated to explore the effects of different treatments and their consequences on the properties of the composite. A suite of mechanical experiments (tension, charpy impact, hardness test) and water absorption test were conducted to investigate the properties of the developed bio-composites.

2. Materials and Methods

Materials

In this study, Kenaf fiber was used as a reinforcement material and epoxy resin was used as matrix material for manufacturing bio-composites. The fiber-to-resin ratio was maintained at 60:40 for all the manufactured composite samples, as it offers the optimal properties in terms of enhanced mechanical strength [32]. Sodium hydroxide (NaOH), acetic anhydride, and polyvinyl alcohol (PVA) were used as reagents for chemical treatments of the fibers.

Pretreatment of Fibers

The ultimate performance of fabricated bio-composites significantly depends on the processing and pretreatment of fibers. Thus, it is essential to follow a proper fiber preparation procedure to achieve the highest quality composite. For this purpose, the fibers were handled with proper care before manufacturing composites. Pretreatment of fiber removes dirt and moisture from the fiber surface which is necessary to achieve maximum advantages of chemical treatments. The pretreatment process also ensures better alignment and minimum wastage of fibers. The following pretreatment processes were performed in the presented study.

(i) Washing: Fibers were submerged in detergent added water for at least 30 minutes to wash them properly. Firstly, the fiber surface became slightly softer and then the dirt and dust attached to the fibers were removed. After that the fibers were sun dried for 24 hours.

(ii) Dehumidification: The presence of moisture on the fiber surfaces may produce porosity in the manufactured composite. It may lead to reducing the mechanical strength and structural stability of the composites. Thus, to remove any excess moisture contents, the prepared fibers were heated in an oven for at least 30 minutes at a temperature range of 60~70° C prior to manufacturing composite.

(iii) Combing: Proper fiber dispersion can result in higher contact between the fibers and the matrix, which leads to improve the overall mechanical characteristics of composites. The fibers were combed to increase the dissolution of the mesh structure inherent in the fiber bundles. This process facilitates the separation of the individual fibers and their proximity to one another. The combing process also helped to align the fibers properly and remove any dirt that was still adhered to the fiber surface.

(iv) Cutting and Weighing: After completing the pretreatments, the fibers were cut to the exact size of the composite manufacturing die. Then, they were weighed to ensure the appropriate ratio necessary for the manufacturing of composites.

Chemical Modification of Fibers

Properties of natural fiber-based composites significantly depend on the chemical modification process of fibers [23]. Mechanical properties and moisture resistance capacity of composites can be improved by chemical modifications of fibers. The following chemical treatments were conducted in this research.

(i) Alkaline Treatment: The studied bio-fibers were soaked in a 6% NaOH solution for 3 hours for surface treatment. Then, the fibers were washed thoroughly using fresh water to remove any excess amount of chemicals left on the surface. After that, the treated fibers were kept in room temperature for 24 hours and then placed in an oven at 80 ℃ for 8 hours.

(ii) Acetic Anhydride Treatment: The fibers were treated with 10% acetic anhydride solution (with 2% sulfuric acid as a catalyst) for 4 hours. Then, the fibers were washed properly under flowing water to remove any access amount of chemicals left on the fiber surface. After that, the treated fibers were kept in room

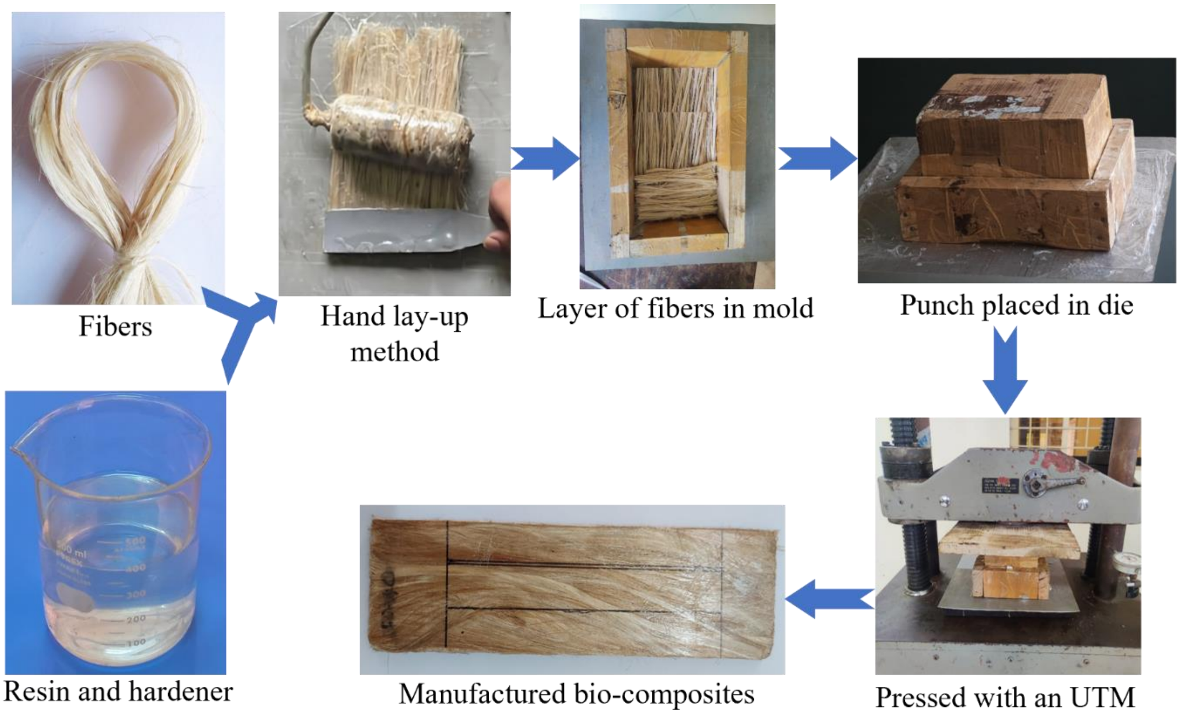


Figure 1. Manufacturing process of bio-composite (hand lay-up and compression molding).

temperature for 24 hours and then placed in an oven at 80 ℃ for 8 hours.

(iii) Polyvinyl Alcohol (PVA) Treatment: PVA of 5% concentration was taken in a beaker at room temperature and stirred for 30 mins. Then it was heated for 1 hour and then stirred intermittently to form a completely dissolved solution of PVA. After that, the solution was sprayed carefully over the fibers. Then the PVA coated fibers were heated in an oven at 50° C for 6 hours to allow the PVA to solidify on the fiber surface. The PVA coating strongly adhered to the celluloses due to solidification. All the manufactured samples with their compositions and treatment are presented in **Table 1**.

Table 1. Details of the fiber treatment processes and compositions of the manufactured bio-composites.

Fiber Treatment	Details of treatments with composition of bio-composites
Untreated	Untreated Fiber (60% Fiber, 40% Resin)
NaOH	6% NaOH treated (3h) (60% Fiber, 40% Resin)
Acetic Anhydride	10% Acetic Anhydride + 2% H2SO4 treated (4h) (60% Fiber, 40% Resin)
PVA	5% Poly Vinyl Alcohol coated (60% Fiber, 40% Resin)
Combined	6% NaOH treated (3h) + 10% Acetic Anhydride and 2% H2SO4 treated (4h) + 5% Poly Vinyl Alcohol coated (60% Fiber, 40% Resin)

Manufacturing Process

A combination of hand lay-up method and compression molding was used for manufacturing bio-composites. The detailed manufacturing process is shown using a flow chart in **Figure 1**. Initially, the surface treated kenaf fibers were evenly placed inside a stainless-steel mold. Then, the mixture of epoxy resin and hardener was spread on the fibers using a brush. Subsequently, using a hand roller, the wet fibers were rolled to obtain a more effective interaction between fibers and the matrix, and to ensure uniform distribution of resin. Following this, a second layer of fibers was then carefully added on top of the resin-coated fibers in a bi-directional arrangement. In this way, total five layers of fibers were added inside the mold. After that, a punch was placed over the mold die. Then, the die-punch assembly was positioned between the platens of a universal testing machine and applied steady pressure of 50 kPa for 24 h to consolidate the composite. Finally, the mold was taken out of the UTM, and the composite was carefully removed from the mold. The produced composite panel was cut into the required size specimen for further testing.

Mechanical Experiments

A series of mechanical experiments including quasi-static tension, Charpy impact, Rockwell hardness using customized setup were conducted to assess the mechanical performance of the developed bio-composites. Additionally, water absorption tests were conducted to investigate the moisture resistance of the composites. Three tests were performed for each composite specimens to ensure repeatability of the test results. The effective properties are presented as the mean of the measured values and the standard deviation shown as error bars to illustrate the uncertainty and variability of the test results.

(i) Tensile Test: Quasi-static tensile tests of the manufactured composites were conducted to investigate their in-plane tensile characteristics. The specimens were prepared and examined with a gauge length of 125 mm according to ASTM D 3039–14 standard. A 20 kN universal testing machine (Model: HST, China) was used to conduct the tensile tests. The tensile test setup is shown in **Figure 2**. `

(ii) Impact Test: The impact strength was measured using a Charpy impact tester according to ASTM D 6110 standard. The specimen dimensions were 127 mm × 12.7 mm × 5 mm. The test was performed by striking the specimens with a striker, mounted at the end of a pendulum. The test assessed the amount of energy absorbed by the specimen during fracture.

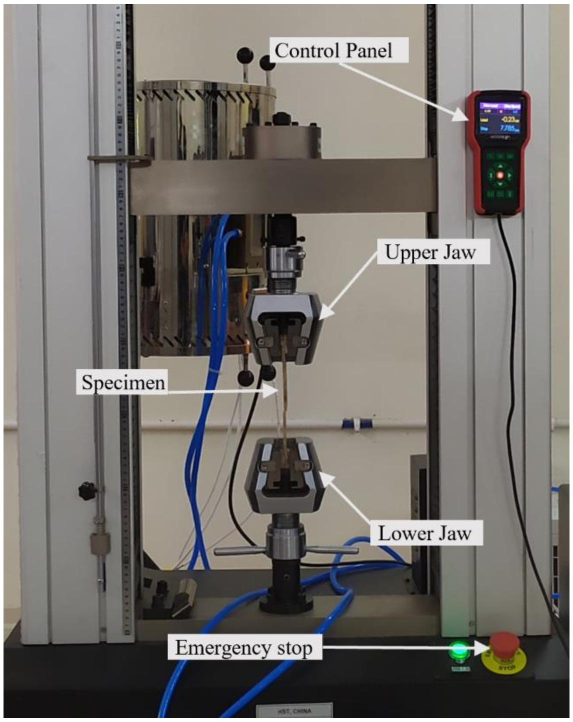


Figure 2. Universal testing machine (Tensile test setup).

(iii) Rockwell Hardness Test: A GEMCO Rockwell hardness tester was used to measure the hardness of the composite specimens. The test was carried out according to ASTM D785 on S scale with a ½ inch ball shape indenter. The specimen dimensions were 50 mm × 50 mm × 6.6 mm. Initially, the datum position was established by applying a minor load of 10 N. A major load of 100 kgf was applied for 10 seconds and then removed, while the minor load was maintained. Finally, the Rockwell hardness number was determined from the digital output which is inversely associated to the depth resulted from the major load [33].

(vi) Water Absorption Test: The water absorption behavior of the bio-composites was studied according to ASTM D570 standard. The specimen dimensions were 25 mm × 25 mm × 3 mm. Initially, the specimens were placed in oven at 90°C and dried until they achieved a consistent weight. Then, the weight of the dried specimens was measured. After that, they were immersed inside water in a glass beaker for 24 hours, and then removed and weighed. The increase in weight percentage provides the water absorption capacity of the composites.

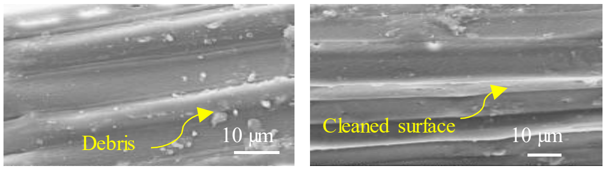
Optical Microscopy

A scanning electron microscope (JCM-7000 NeoScope™ Benchtop SEM, Jeol Ltd., Tokyo, Japan) was used to observe and analyse the changes in microstructural features of fiber surface due to chemical treatments. This analysis allows us to find out the reasons behind a specific property exhibited by a composite specimen.

3. Results and Discussions

Surface morphology of fibers

The surface morphology of the raw and detergent washed kenaf fibers are presented in **Figure 3**(a-b). Impurities and external debris are visible on the fiber surface from the SEM image of the raw fiber. The presence of these contaminants is a sign of the raw and unprocessed state of the fiber. Washing the fibers with detergent effectively removes the surface impurities, as observed in **Figure 3**(b), resulting in a cleaner, smoother surface. It only removes loosely adhered contaminants but does not significantly alter the surface structure of fiber. It also improves the appearance of fibers and prepares them for further chemical treatments by exposing a cleaner surface for subsequent reactions.

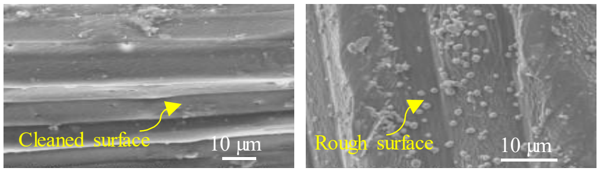


(a) Raw Kenaf Fiber

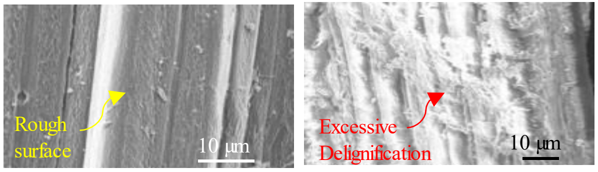
(b) Detergent Washed Kenaf Fiber

Figure 3. SEM images of (a) raw and (b) detergent washed Kenaf fiber.

Figure 4 shows SEM images of kenaf fiber treated with varying amounts of NaOH. A detergent wash image is shown beside the NaOH-treated photographs for comparison. It is observed that the surface of 6% NaOH treated kenaf fiber is rougher and cleaner than that of the detergent washed fiber. The roughness becomes more prominent with the treatment of 10% NaOH solution (**Figure 4**(c)). Excessive removal of lignin can be observed on the surface of 15% NaOH treated fiber (**Figure 4**(d)) which is an indication of fiber damage.



(a) Detergent Wash (b) 6% NaOH

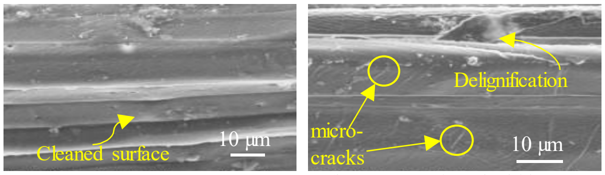


(c) 10% NaOH (d) 15% NaOH

Figure 4. SEM images of Kenaf fiber (a) washed with detergent, (b) treated with 6% NaOH, (c) treated with 10% NaOH and (d) treated with 15% NaOH.

The observed surface changes suggest that the NaOH treatment initially facilitates the removal of surface impurities, including residual organic and inorganic contaminants. As the concentration of NaOH increases, there is progressive interaction with non-cellulosic components such as lignin, pectin, waxes, and oils. This interaction leads to the effective removal of the components from the fiber surface. The elimination of these components enhances the surface roughness and exposes the cellulosic contents [34]. The rough surface topology promotes stronger mechanical interlocking at the fiber-matrix interface, whilst the increased exposure of cellulose offers more potential reaction sites for chemical bonding. However, higher concentration of NaOH makes the fiber almost damaged or significantly weak as observed from **Figure 4**(d) due to excessive delignification [22].Thus, the higher concentration of NaOH should be avoided to achieve optimum quality. Based on our observations and supporting evidence from previous research [22, 24-26], it can be concluded that the 6% NaOH treatment moderately roughens the fiber surface and is expected to provide the optimum combination of mechanical properties. Thus, fibers treated with 6% NaOH are considered the most suitable for manufacturing bio-composites.

The SEM image of Kenaf fiber after treatment with 10% acetic anhydride is presented in **Figure 5**(b). Similar to NaOH treatment, acetic anhydride treatment results in a rough surface of the fiber due to the elimination of non-cellulosic components. However, signs of excessive delignification and presence of micro-cracks are observed in few areas of the micrograph, indicating the degradation of fiber structure and integrity. Therefore, this treatment possibly reduces the strength of fibers and weakens the fiber-matrix adhesion. Acetic anhydride treatment of bio-fiber replaces the hydrophilic –OH groups with hydrophobic acetyl groups (-CH3CO). This replacement reduces the tendency of the fibers to react with water molecules and to form hydrogen bond with them. Thus, acetic anhydride makes the fiber hydrophobic and consequently enhances the moisture resistance property.



(a) Detergent wash (b) 10% Acetic Anhydride + 2% H2SO4

Figure 5. SEM images of Kenaf fiber (a) washed with detergent, and (b) treated with 10% Acetic Anhydride.

Tensile Properties

One of the major reasons behind the dominance of synthetic fiber-based composites over natural fiber-based bio-composites is the lack of enough tensile strength of the latter. If the tensile strength of bio-composites can be improved up to a certain level, synthetic fibers will be easily and effectively replaced while saving the environment. Tensile properties of the composites can be enhanced by several techniques including changing the direction of the fiber alignment, altering the percentage of fiber loading and modifying the surface morphology of fibers [22, 35, 36].

Figure 6 shows the variation of tensile strength, percentage of elongation, and stiffness of the composites manufactured with various treated fibers. In comparison to the untreated fiber-based composite, NaOH treatment increases tensile strength by 6% and elongation by 64%, suggesting increased strength, ductility, and flexibility. The enhancement of tensile strength is attributed to better fiber-matrix adhesion due to the increased surface roughness caused by NaOH treatment [17, 22]. However, this treatment leads to a 26% reduction in stiffness, as the increased flexibility of the fibers compromises the overall rigidity of the composite. On the other hand, acetic anhydride treatment reduces tensile strength by 33% and stiffness by 64%. The reduction in strength and stiffness can be linked to fiber weakening caused by the micro-cracks and delignification as a result of this fiber treatment (**Figure 5**(b)). However, the flexibility of the composite increases significantly, which is evident by a 118% increase in elongation. Similarly, PVA coating reduces the tensile strength by 23% and stiffness by 67%, while increasing the elongation of the composite by 152%. The reduction in stiffness can be explained by the hydrophilic nature of PVA, which readily absorbs moisture due to the presence of many hydroxyl groups [37]. The absorbed moisture softens the composite and consequently reduces the stiffness [38]. The marked increase in percentage of elongation is possibly because of the inherent flexibility of the PVA [39]. For the composite subjected to combined treatments, there is no significant change in tensile strength. However, the stiffness decreases by 56%, and elongation increases by 102% as observed from **Figure 6**. This is understandable, as all the treatments primarily contribute to enhancing the flexibility of composites. In summary, the reduction in the elastic properties of the composites due to the fiber treatments may compromise their suitability for structural applications requiring high strength and rigidity.

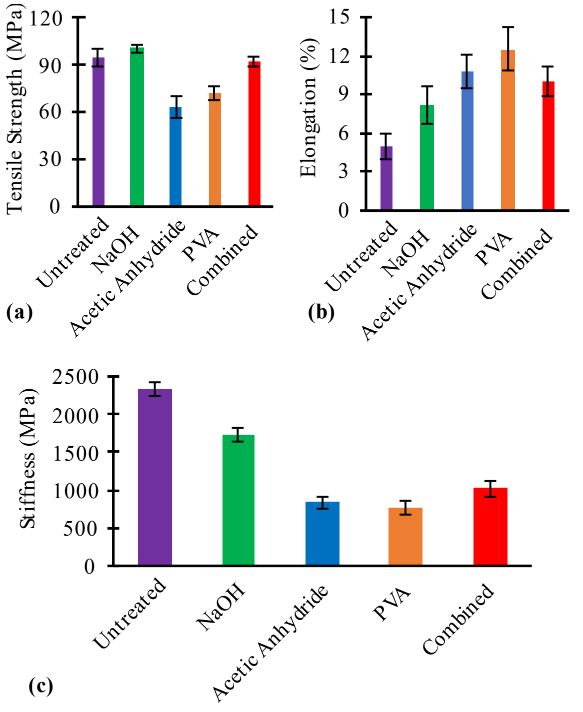


Figure 6. Variation of (a) tensile strength, (b) percentage of elongation and (c) stiffness of the studied composites manufactured with various treated fibers.

Impact Properties

The impact strength of bio-composites is influenced by several key factors such as toughness of the reinforcement material, the characteristics of fiber-matrix interfacial region, and the amount of frictional work required to pull-out fiber from the matrix. Of these factors, the nature of the interfacial region play a crucial role in determining the overall toughness of composites [40].

Figure 7(a) illustrates the effects of different chemical treatments on the impact strength of the manufactured composites. It can be observed that the NaOH treated composite exhibits approximately 17% higher impact strength than untreated composite. The improved impact strength of the treated kenaf fiber-based composites is attributed to the more effective distribution of kenaf fibers within the matrix. The surface treatment enhances the interaction between the fibers and the matrix, resulting in improved fiber dispersion. Additionally, the treated fibers exhibit a rougher surface, which contributes to increase mechanical friction during failure, thereby enhancing impact toughness. Furthermore, surface treatment significantly improves fiber wetting, which reduces the occurrence of voids and fiber agglomeration within the composite. The reduction of voids is particularly important as their presence can lower the energy required for fracture and thereby diminishing the impact toughness of material [41].

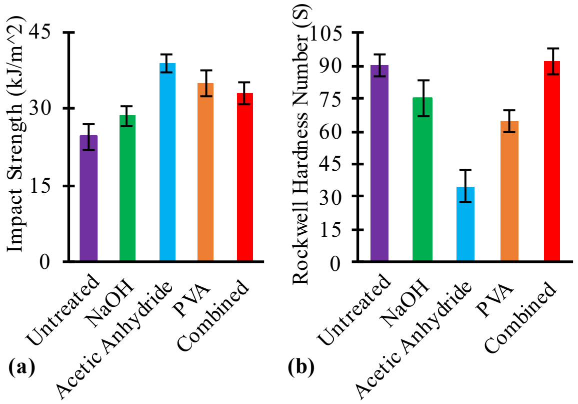


Figure 7. Variation of (a) impact strength, and (b) Rockwell hardness of the studied composites manufactured with various treated fibers.

Among all the treatments, the acetic anhydride-treated composite exhibits the highest impact strength, showing a 59% increase over the untreated fiber-based composite. This improvement may be attributed to the relatively weak interfacial bonding between the fiber and the matrix. The weaker bonding possibly creates cracks that propagate along the fiber-matrix interface, resulting in debonding between the fiber and matrix. This debonding produces a larger surface area and necessitates more frictional work to counteract the differential displacement between the fiber and matrix. These factors enable the acetic anhydride-treated composite to absorb more energy during impact [40]. Additionally, the improved flexibility of the fiber due to acetic anhydride treatment contributes to enhance the impact strength of composite [42]. Similarly, the PVA coating and combination of all treatment also significantly improve the impact strength of the composite, showing a 43.5% and 25% increase respectively compared to the untreated sample as a result of improved flexibility of the composite (**Figure 6**). Thus, the improved flexibility and impact strength resulted from these treatments make the composites well-suited for real-world applications that require the ability to sustain deformation and absorb energy up to large strains.

Hardness Properties

The Rockwell hardness of the composites manufactured with treated kenaf fibers is presented in **Figure 7**(b). All the chemical treatments, except combined treatment, impart detrimental effects on the hardness of the composites. NaOH-treated, acetic anhydride-treated and PVA-coated composite shows a decrease in the hardness of about 17%, 61% and 28% respectively. In contrast, the combined treated composite does not exhibit any significant change in hardness. NaOH treatment increases the composite flexibility (**Figure 6**), hence reducing its hardness. As for the acetic anhydride treatment, there is formation of micro-cracks and delignification of the fiber (**Figure 5**) that weakened the fibers and drastically reduced the overall hardness. The flexibility added by PVA coating on the fiber surface (**Figure 6**) is possibly responsible to reduce the hardness of the composite. The reduction in the hardness of the composites due to these treatments may limit their resistance to wear. In contrast to other treatments, the combined treatment maintains the composite's hardness.

Moisture Resistance Properties

Moisture resistance is a crucial characteristic of any composite as it impacts the mechanical properties, durability, dimensional stability, resistance to biological degradation, and versatility in various applications. Absorbed water tends to weaken the adhesion between the fiber and matrix, as a result the mechanical strength of the composites tends to decrease and ultimately the durability is reduced.

Figure 8 represents the variation of water absorption percentage of the composites with different fiber treatments. A lower water absorption percentage indicates better resistance against moisture of the composites. It can be observed that NaOH-treated composites have 32.7% less water absorption compared to untreated composites. This enhanced moisture resistance can be beneficial in applications exposed to humid or wet conditions.

The improvement in moisture resistance can be attributed to the removal of lignin and hemicellulose due to NaOH treatment. Hemicellulose in bio-fibers is mainly responsible for water absorption as it is more accessible than the crystalline region of the cellulose [40].

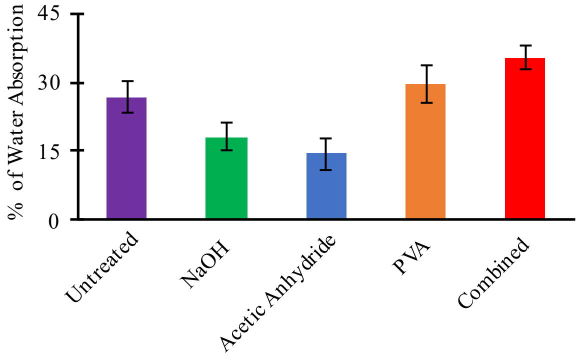


Figure 8. Variation of percentage of water absorption of the studied composites manufactured with various treated fibers.

Among all the treatments, acetic anhydride treatment achieves the highest moisture resistance. This treatment results in 46% less water absorption compared to untreated composites. Acetic anhydride treatment removes the hydrophilic hydroxyl groups in hemicellulose and replaces them with hydrophobic acetyl groups [27]. As a result, the composite's tendency to react with water is greatly reduced which significantly improves its moisture resistance capacity. In contrast, treatment with PVA coating negatively impacts the moisture resistance performance of composites.

The PVA-treated composite exhibits 11% more water absorption than the untreated fiber-based composite. This is due to the hydrophilic nature of PVA [37]. The large number of hydroxyl groups present in PVA easily form hydrogen bonds with water molecules, increasing its solubility in water. The combined treated fiber-based composites exhibit a 32% increase in water absorption compared to the untreated fiber-based composite. This is possibly because of the presence of PVA, which reduces moisture resistance and introduces hydrophilic properties.

4. Conclusions

In this study, the effects of different chemical treatments (NaOH, acetic anhydride and PVA coating) of kenaf fiber on the mechanical and moisture resistance properties of kenaf fiber-based bio-composites were explored. The bio-composites were manufactured using a combination of hand lay-up and compression molding technique. The surface morphology of the composites was analyzed using Scanning Electron Microscopy (SEM). A series of experimental tests including tensile test, impact test, hardness test, and water absorption test were conducted to evaluate the properties of manufactured bio-composites. The following specific conclusions can be drawn from the thorough investigation of this study:

1. NaOH treatment enhances the mechanical properties of the composite (tensile strength by 6%, elongation by 64% and impact strength by 17%). This is achieved by improving the fiber-matrix adhesion and dispersion of fiber within the matrix. However, this treatment reduces stiffness by 26% and hardness by 17% due to increased flexibility of the composite. Additionally, NaOH treatment significantly improves moisture resistance by 32.7% through the removal of the water-absorbing component (hemicellulose) from the fiber.

2. The acetic anhydride treatment improves the moisture resistance by 46% by replacing the hydrophilic hydroxyl group with the hydrophobic acetyl group in the fiber. This treatment increased fiber flexibility, resulting in an 118% improvement in elongation. The weak fiber-matrix bonding resulted from this treatment, combined with increased flexibility, contributed to a 59% enhancement in impact strength. However, this treatment leads to the formation of micro-cracks and excessive delignification in the fiber, which caused a reduction in tensile strength by 33%, stiffness by 64%, and hardness by 61%.

3. The PVA coating improves the elongation by 152% and impact strength by 43.8% due to inherent flexibility of PVA. However, the hydrophilic nature of PVA leads to decrease in strength by 23%, stiffness by 67% and moisture resistance by 11%. Additionally, the enhanced flexibility due to the PVA coating resulted in a 28% reduction in hardness.

4. The combined effect of NaOH, acetic anhydride, and PVA treatments of fibers results in a balanced set of mechanical properties of the composites. While the tensile strength and hardness remain unchanged, enhanced flexibility leads to a 102% increase in elongation and a 25% improvement in impact strength. However, this increased flexibility comes with a 56% reduction in stiffness. The combined treatment also decreases moisture resistance by 32%, primarily due to the hydrophilic nature of PVA.

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