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Investigation on Physical and Mechanical Properties of Water Hyacinth Petiole Mat-Reinforced Epoxy-Based Composites

Tufayel Ahmed[1], *Md. Saif Hasan*[1*], *Md. Arafat Rahman*[2]

[1]Department of Materials and Metallurgical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh
[2]Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

Natural fiber composite (NFC) is popular as alternatives to synthetic ones. This shift reflects a growing interest in sustainable and eco-friendly options such as water hyacinth, which is scientifically known as Eichhornia crassipes. In this study, the plant was explored as a potential reinforcement material in epoxy-based composites. The fabrication relied on a solution casting method, mixing epoxy, and hardener in a 3:1 ratio where woven mats were treated in NaOH, while others consisted of unidirectional strips and powdered versions. The physical properties such as tensile strength, flexural strength, hardness, and water absorption of as synthesized NFC was evaluated through ASTM guidelines. The findings showed that the NaOH-treated woven composites performed the best overall. It is noted that the as synthesized NFC exhibited tensile and flexural strength of 10.11 MPa and 12.48 MPa, respectively, with Shore D hardness of 75. Water absorption remained low at just 3.02% over seven days whereas untreated woven mats yielded comparative physical properties. Furthermore, unidirectional strips and powdered fibers exhibited partly due to poor stress transfer and high moisture uptake compared to treated woven mats. It is noted that this study is unique due to skipping the usual fiber extraction steps, instead, whole petioles were used in various setups. This study showed the alkali-treated petioles from water hyacinth have real potential which could lead to low-cost composites.

Keywords: Natural Fiber Composites, Water Hyacinth, Alkali Treatment, Epoxy, Casting.

1. Introduction

Demand for sustainable materials that protect the environment has grown fast over the last few years. Various industries now seek options beyond synthetic composites. Such materials rely on resources that cannot renew themselves. They also create major problems for the environment in the long run. Reinforcements made from glass or carbon fibers offer solid strength along with lasting durability. Processing them takes considerable energy though. Recycling proves difficult too. Over time this approach feels far from sustainable [1]. Researchers therefore focus more on natural fibers these days. Such fibers renew easily and break down naturally. They cost less overall. Strength holds up well for uses in light structures [2].

Water hyacinth, or Eichhornia crassipes, has drawn notable attention compared to other natural fibers. This free-floating aquatic plant ranks among the worst invasive weeds worldwide. It proliferates rapidly across tropical and subtropical regions disrupting aquatic biodiversity in significant ways. The plant clogs waterways as well. Local economies in affected areas experience substantial financial setbacks consequently [3]. Even with these harmful effects, the plant features petioles rich in fibers and cellulose making it a viable source for producing composites [4]. Transforming this environmental issue into a useful reinforcing material allows water hyacinth to address ecological problems and engineering needs. Research has looked into using water hyacinth fibers in polymer composites. Flores Ramirez et al. [5], focused on polyester as a matrix reinforced with these fibers. The study revealed that moderate levels of fiber addition elevated the mechanical properties. Whereas, higher fiber amounts resulted in inadequate dispersion. Sumrith and Dangtungee [6], investigated water hyacinth reinforced bio-based epoxy systems. Evidence from their work indicated the importance of fiber alignment in the tensile performance of the composite. Sulardjaka et al. [7], built on prior efforts through chemical modifications such as alkalization and esterification. These processes strengthened the fiber-matrix interface. Substantial increase in tensile properties are observed due to fiber treatments.

The investigation of Arivendan et al. [8], promoted water hyacinth as a natural fiber and verified that it may successfully reinforce epoxy composites for lightweight applications. Similarly, Jappes et al. and Arivendan et al. [9], highlighted the potential of water hyacinth composites to convert aquatic waste into valuable resources such as packaging, furniture, and interior elements. Smriti et al.'s recent study [10], extracted nanocellulose from water hyacinth fiber, which can enhance the plant's capacity to strengthen materials.

Thangiah et al. [11], looked at different methods for removing fibers from water hyacinth. They found that retting and alkali treatment significantly improve fiber quality and composite performance. This work was

*Corresponding Author Email Address: tufayelhimu@gmail.com

expanded upon by George et al. [12], who used characterization methods such as SEM, FTIR, and XRD to demonstrate how chemical treatments increased fiber crystallinity. To achieve the greatest performance, Haque et al. [10], also pointed out that bulk processing natural fibers into composites requires the right curing and fabrication techniques.

Other research has examined more than only the fibers that were removed. Paper sheets manufactured from various water hyacinth plant sections were studied by Widhata et al. [13]. They claimed that the petiole's mechanical qualities were superior to those of the stems and leaves. This implies that it has a special benefit for reinforcing. Sulardjaka et al. [1], [7], investigated the effects of dimensional stability and moisture absorption on water hyacinth composites. They concluded that hydrophilicity is much reduced by alkali treatment. Retting and surface modification treatments also increase water resistance and long-term durability, according to George et al. [12].

These researches are mainly based on fiber separation processes such as retting, decortication, and grinding although they prove that water hyacinth could be a potential reinforcing material. Those methods take up a lot of time. They hardly ever make sense for small operations or places in out of the way spots. Water hyacinth pops up the most in those rural areas. On top of that, studies do not often line up different shapes of it for fair testing. Things like fine powders or mats woven together. Or even strips laid out in one direction. All done under matching setups.

To overcome these limitations, we circumvent the extraction process in this work. It uses full water hyacinth petioles as woven, unidirectional, and powdered forms, with and without alkaline treatment. The project aims to enable a cost-effective and scalable route for sustainable composites. It evaluates the mechanical behavior (tensile and flexural strength), water absorption, reinforcement form both systematically to identify a practical form of reinforcement.

2. Methodology

Water hyacinth (Eichhornia crassipes) petioles were collected from a local pond in Bangladesh and used as the main reinforcement in epoxy composites. The petioles were thoroughly washed with distilled water to remove soil and dirt from the surface then sun-dried for seven days to minimize moisture contents. After drying, the petioles were flattened manually using a wooden roller to get uniform thickness for composite fabrication. The overall steps of preparation, from raw material collection to specimen cutting is summarized in Fig. 1.

To investigate the role of structure and modification, four types of reinforcements were produced: untreated woven mats, NaOH treated mats, unidirectional strips and powdered. Woven mats were formed by weaving laid down strips into a square mesh, and unidirectional forms were made with the strips held parallel without crossing.

For chemical treatment, woven mats were immersed in 5 wt.% NaOH solution for two hours, rinsed thoroughly with distilled water until neutral pH was achieved and then oven-dried at 60°C for 24 hours. Powdered reinforcement was prepared by grinding the dried petioles and sieving them through a 40-mesh screen. The step-by-step preparation stages of woven composite are shown in Fig. 2, where the progression from raw petioles to woven mats and finally to composite sheets is illustrated.

Composite fabrication was carried out using the solution casting method. According to Arivendan et al. (2022), composites with 30 wt.% fiber reinforcement had the highest tensile and flexural strengths, suggesting that a 30% fiber ratio offers the best mechanical performance [9] In this study, Bisphenol A-based epoxy resin (Araldite LY 556), hardener (Ardor HY 951) were collected from Epoxy Resin BD, Dhaka, Bangladesh. The epoxy resin and hardener were mixed in a 3:1 weight ratio to form the matrix [14].

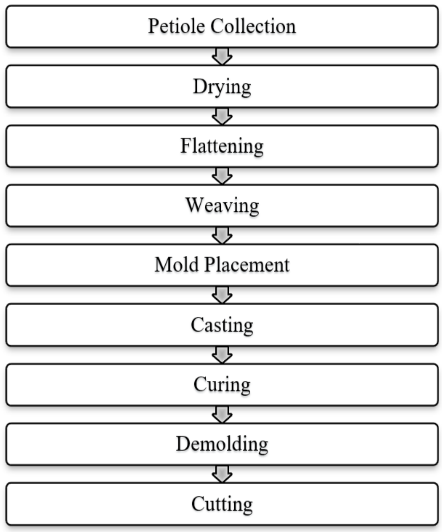

Fig. 1 Flowchart of the methodology

The prepared reinforcements were placed inside a stainless-steel mold of dimensions 150 × 150 × 4 mm^3 and the resin–hardener mixture was poured over them in liquid form ensuring complete wetting of the fibers. The solution casting method was also used to prepare samples for powder reinforcement. Epoxy resin and water hyacinth powder were mixed first, then add the hardener. The fiber ratio 30 wt.% also followed here. The mixture was then poured into molds and cured at room temperature.

The solution casting process allowed uniform distribution of resin across the reinforcement, reducing the risk of void formation. The composites were left to cure at room temperature for 72 hours.

After curing, the panels were carefully removed from the mold and cut into ASTM-standard specimens. For each variation, three samples were prepared and tested to ensure result consistency and reliability. A representative image of the four types of composites after demolding shown in Fig.3.

Mechanical and physical tests were carried out to characterize the composites. Tensile properties were measured according to ASTM D3039 using rectangular specimens of 150 × 25 × 5 mm^3 at a crosshead speed of 5 mm/min. Flexural strength was determined following ASTM D790 by a three-point bending setup with a span length of 80 mm and crosshead speed of 5 mm/min. The hardness tests were performed according to the Shore D scale, and the water absorption behavior was determined by following the ASTM D570 standard in which weighed samples were immersed in distilled water (at room temperature) at certain periods (7 days).

This systematic approach was useful to compare the effect of not only reinforcement form (woven, unidirectional and powdered) but also treatment used (treated vs. untreated) in the context where there were uniform processing and testing conditions so as to have a clear comparison for overall performance of composites.

3. Results and discussion

3.1 Tensile Properties

The tensile properties findings in Fig. 4 indicated clear changes in performance depending on the reinforcing form and treatment. The NaOH-treated woven composite had the highest tensile properties of all of the samples, measuring tensile strength 10.11 MPa and tensile modulus 2387.34 MPa.

The improvement stems from enhanced adhesion at the interface between petiole fibers and the epoxy matrix. Alkali treatment removes hemicellulose along with surface impurities. That process creates a rougher surface texture. Such roughness aids in stronger bonding interactions [7]. Even the untreated woven composite displayed solid results. Its tensile strength and tensile modulus hit 7.12 MPa and 1803.19 MPa respectively. Evidence points to the woven petiole structure enabling mechanical interlocking [1]. Stress transfer works effectively here too. All this holds even without any chemical treatment applied.

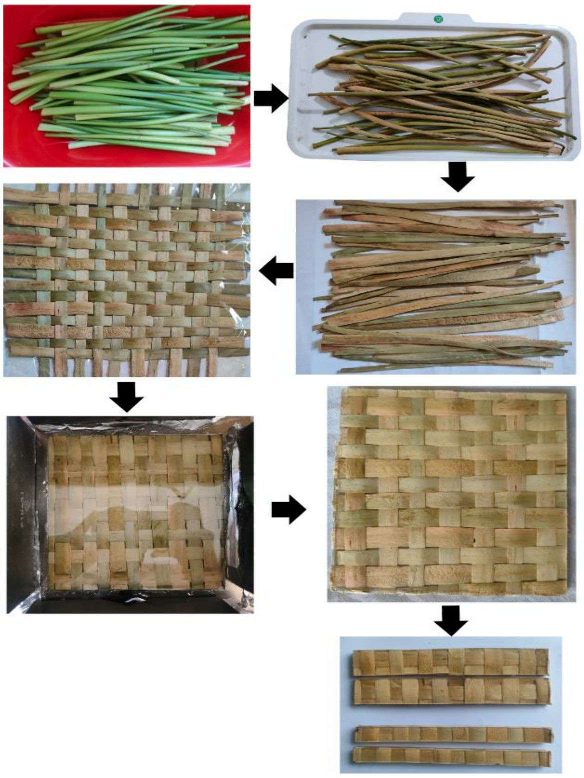

Fig. 2 Stepwise preparation of water hyacinth

In contrast to other configurations, the unidirectional and powdered composites exhibited considerably lower tensile strengths with values of 5.3 MPa and 3.24 MPa, respectively. The tensile modulus for unidirectional is 798.55 MPa and for powdered composite 241.68 MPa. The unidirectional samples underperformed mainly because they struggled to manage stresses applied from multiple directions. Powdered samples encountered difficulties related to discontinuous fibers, which resulted in irregular stress distribution across the material. Observations from these tests suggest that both the structural design and the adhesion between fibers and matrix play essential roles in determining overall tensile strength & modulus. A woven structure, when combined with chemical treatment, appears to deliver substantially improved outcomes.

Fig. 3 Composite samples after demolding.

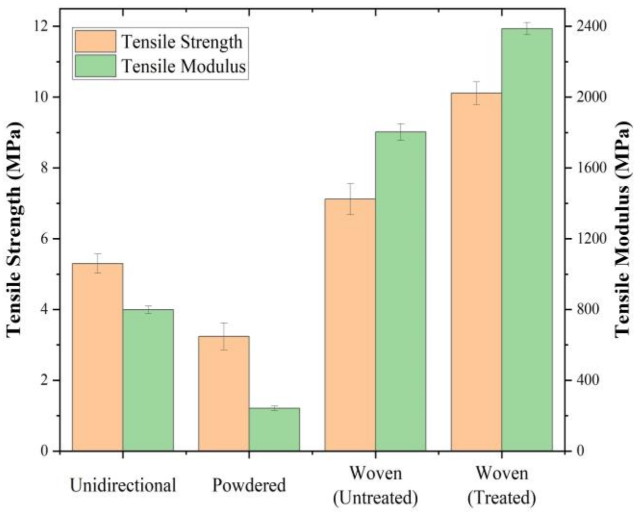

Fig. 4 Tensile properties of the composites.

3.2 Flexural Properties

The flexural tests produced results that matched up pretty-well with what came out of the tensile testing. Fig. 5 shows how the woven composites treated with NaOH gives a maximum flexural strength of 12.48 MPa & flexural modulus of 2812.33 MPa. Chemical Treatment enhance the flexural strength [15]. For the untreated woven ones, that result of flexural strength & modulus are 10.75 MPa and 1803.19 MPa, respectively. Woven setups seemed to handle things better overall.

They could spread out the bending stresses over multiple paths for the load. That kind of spreading cut down on failures that stayed stuck in one spot. The treatment with chemicals played a part too. It made the handoff of loads smoother right where the fibers meet the matrix. In the end, cracks took longer to show up and grow.

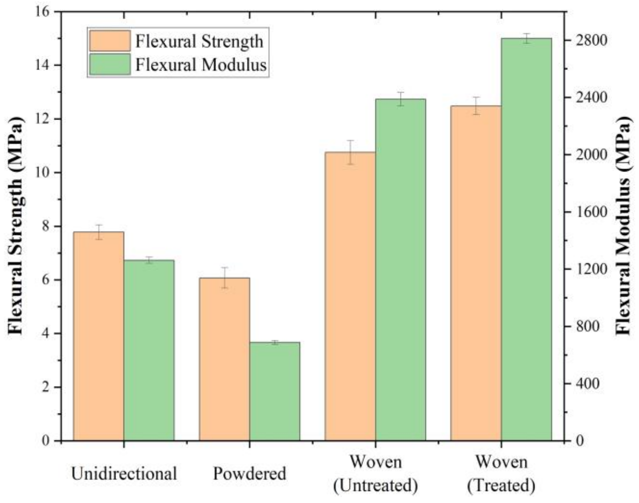

Fig. 5 Flexural properties of the composites.

Meanwhile, tests on the unidirectional composites showed a flexural strength of 7.78 MPa. The powdered composite shows strength of 6.07 MPa. These numbers seem relatively low overall. Their Modulus shoes also low from others. This points to clear limits in how one-dimensional alignment reacts to the mixed stresses from bending. It does not perform well in those situations. The powdered material faced the same old problem of lacking solid structural links. Things remained disconnected as usual. Looking at the bigger picture, woven setups seem to perform better against flexural forces. Evidence suggests this advantage increases with added chemical treatments.

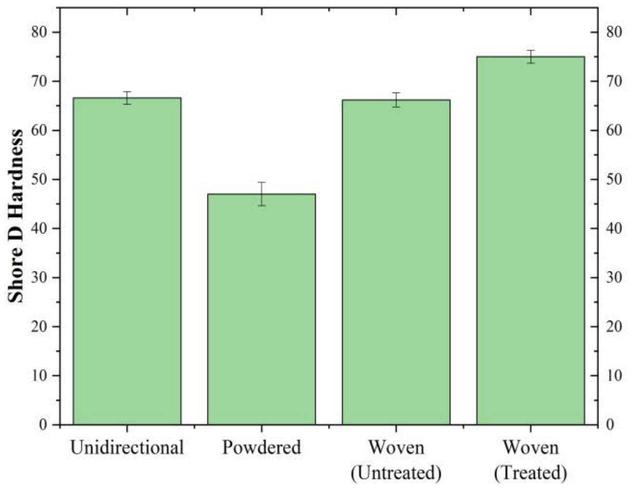

Fig. 6 Hardness (Shore D) of the composites.

3.3 Hardness

The hardness test shows a pattern that matches the tensile and flexural characteristics in Fig. 6. The NaOH-treated woven composites achieved the highest hardness level of 75 Shore D. Evidence suggests that the interaction between chemical processing and the woven structure is crucial. Alkali treatment likely removed hemicellulose and surface contaminants from the fibers. This process probably improved the bond between the fibers and the matrix [8]. Additionally, the woven structure appears to provide better overall stability. It also helped limit any concentrated bending during the indentation test.

The unidirectional composites and the untreated woven ones displayed comparable hardness values. These measurements registered at 66.86 and 66.2 on the Shore D scale. Evidence indicates that fiber alignment, combined with interlacing, contributes moderately to enhanced hardness. This effect appears to persist even in the absence of chemical treatments. For the untreated woven samples, the lack of processing likely limited the strength of interfacial bonding. Such limitations, in turn, seem to have hindered substantial improvements in overall performance.

Powdered composites showed the lowest hardness in the group. That value reached just 47 on the Shore D scale. Such a result points to clear limitations in discontinuous fiber reinforcements. Fibers lack continuous connections there, so they fail to transfer stresses effectively or resist them at key points. In turn, the epoxy matrix seems more vulnerable to deformation and intrusion once loads apply.

These findings make it clear that reinforcement geometry and chemical treatment both play major roles in determining hardness levels. Treated woven structures appear to enhance load transfer while also boosting resistance to deformation in meaningful ways. Powdered reinforcements, by contrast, tend to undermine the overall performance of the composite material.

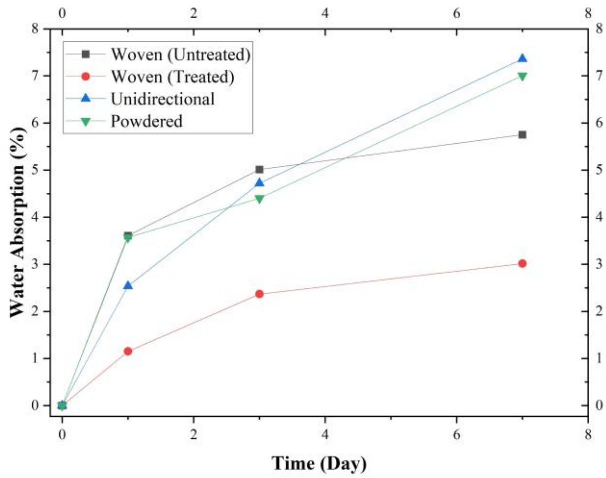

Fig. 7 Water absorption of the composites after 7 days.

3.4 Water Absorption

The water absorption test highlights how untreated natural fibers tend to soak up moisture easily. It also points out just how well alkali treatment works in composites to cut that down. Looking at Fig. 7, after seven days soaking in water, the woven composite treated with NaOH had the least uptake. That came in at only 3.02 percent. This really shows a solid gain in keeping things stable size-wise.

The application of alkali treatment appears to decrease the number of hydroxyl groups found in the fibers. This modification likely diminishes the fibers' capacity to attract water [16]. Consequently, water absorption within the entire composite material becomes more limited.

Untreated woven samples absorbed roughly 5.75 percent water. Unidirectional composites took up the highest amount. They reached 7.36 percent. Powdered versions were not far behind at 7.01 percent. Higher absorption rates probably come from voids within the material. Resin wetting that is not complete contributes as well. Exposed ends of fibers allow water to enter via capillary action.

Over time, too much water absorption weakens the connection between fibers and matrix. That degradation hurts the mechanical properties. Evidence points to chemical treatments as key for real world uses in these composites.

4. Conclusion

This study demonstrated the potential of water hyacinth petioles as effective reinforcement in epoxy composites. Untreated and NaOH-treated forms, including woven mats, unidirectional strips, and powders, were evaluated for their mechanical and physical properties. The main findings can be summarized as follows:

1. NaOH-treated woven composites exhibited the highest mechanical performance with tensile strengths and modulus of 10.11 MPa and 2387.34 MPa respectively.
2. The flexural properties for treated woven composites gives best results with strengths 12.48 MPa and modulus 2812.33 MPa.
3. Woven structures generally performed better than unidirectional and powdered composites due to improved stress distribution.
4. Treated woven composites also showed the lowest water absorption (3.02%) and the highest hardness (75 Shore D).

The results show that water hyacinth petioles can be used as strong, cheap, and environmentally friendly reinforcements in epoxy composites. This method not only gives people a long-lasting option to synthetic fibers, but it also shows how to use an invasive aquatic plant as a useful raw material.

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