INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 21, ISSUE 4, 2024, 11809 – 11820
DOI: https://doi.org/10.15282/ijame.21.4.2024.6.0909

RESEARCH ARTICLE

Effect of Alkalization Time on the Toughness and Strength of Jute Sack Waste Lamina Composite as an Alternative Car Bumper Material

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ABSTRACT – Alkaline conditions, such as the concentration of Sodium Hydroxide (NaOH) and the duration of soaking time, significantly affect the mechanical properties of natural fiber and its composites. The objective of this study is to investigate the effect of alkali treatment on the impact toughness and tensile strength of laminated composites made from jute sack (burlap) waste woven fibers, which can potentially be used as a substitute material for vehicle bumpers. The experimental group comprised specimens that were alkalized by manipulating the duration of soaking and the concentration of alkali in the woven fibers of jute sack waste, with a fiber orientation pattern of 0°/+90°/0°/+90°/0°. The fiber immersion time is 24 hours, 48 hours, and 72 hours when using a 5% NaOH concentration. Epoxy resin serves as a composite matrix, specifically epoxy resin and epoxy hardener. Two sets of specimens underwent tests to measure their tensile and impact strengths. The result of the study reveals that the jute sack laminated epoxy composite with a fiber orientation of 0°/+90°/0°/+90°/0° had the maximum tensile strength and impact strength after a 48-hour alkaline treatment at 14.99 MPa and 0.010 J/mm^2, respectively. The alkali treatment has successfully enhanced the tensile strength of the jute fiber by approximately 42.49% and 39.66% when compared to the untreated jute fiber. The study concludes that the utilization of alkaline process with NaOH improves the surface area of the fiber, compatibility with polymer matrix and mechanical strength.

ARTICLE HISTORY
Received : 07th Mar. 2024
Revised : 13th Aug. 2024
Accepted : 18th Oct. 2024
Published : 17th Nov. 2024

KEYWORDS
Jute sack waste
Alkalization
Laminate composite
Toughness
Tensile strength

1. INTRODUCTION

Jute fiber-reinforced composites have been of extensive interest in the last decade due to their requirement as green and biodegradable materials for numerous applications [1]. Jute fibers, extracted from the bast of the jute plant, are economically competent renewable materials for reinforcement in composites, which is attributed to their excellent mechanical properties, such as high tensile strength and low density [2]. When jute fibers are used for reinforcing composite materials, they are responsible not only for their improvement in mechanical and physical performance but at the same time they can be advantageous due to sustainable, biodegradable aspects as well [3]. This makes these composites attractive for various construction, automotive, and packaging industries that necessarily advance towards a more environmentally conscious selection of materials [4].

Two vital factors controlling the optimum utility of jute fiber-reinforced polymer composites are (a) arrangement of fiber orientation and (b) surface modification, particularly with alkaline treatment [2], [5]. The chosen fiber orientation is intended to strategically benefit the mechanical properties of both polymer and composite (-90°), and +45 fibers encountered in the composite come with tensile properties, which are improved by fiber directed at 0°. However, it improves flexural properties of interaction through sheer resistance [6], [7]. The optimized isotropic behavior and balanced distribution of mechanical properties that result from this geometric configuration make it highly suitable for applications that demand strength in multiple directions [8].

Apart from this geometrical structure, the surface of jute fibers changed, especially when alkaline-treated. This treatment significantly enhances the interfacial adhesion between fibers and the polymer matrix. The alkaline treatment induces surface roughness to the fibers and removes impurities for bonding [9], [10]. This was attributed to the improved hydration (plasticizing) of the polymer matrix, increasing surface adhesion and interfacial strength. The exceptional mechanical properties of the jute fiber-reinforced polymer composites are achieved by harmonious interaction between surface modification and geometric arrangement [9], [11]. Therefore, these composites are used extensively in automotive parts and construction materials. In order to have a comprehensive study into the effects of tailored fiber orientations and surface modifications in optimizing jute fiber-reinforced polymer composites, it is crucial that further detailed investigation be conducted with respect to these factors [12], [13].

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Soaking time in the alkali treatment process is of great importance for both the mechanical and surface properties of jute fiber-reinforced epoxy composites [14]. Literally, alkali treatment is a process where the desired fiber or material (in this case, natural fibers) undergoes an immersion in a Sodium Hydroxide (NaOH) solution. This, in turn, can increase fiber-matrix interfacial interaction by driving away contaminants and changing their surface [15]. The effect of different immersion periods on some significant mechanical properties evidences some clear trends. All of this is due to increased impact strength and energy absorption capacities, which stem from the longer soaking times thanks to enhanced interfacial bonding. Elimination of impurities produces a rougher fiber surface, hence creating more bonding between jute oil fibers and epoxy matrix [2], [14]. Tensile strength tended to increase soaking times following the removal of lignin and hemicellulose levels, which improved the adhesion. Nevertheless, optimization is still required, as prolonged treatments could lead to decreased benefits or eveniber damage [16]. At the same time, elongation (i.e., material ductility), which is affected by interfacial bonding, may be optimized with reasonable soaking times. An increased soaking time significantly affects the external morphology of jute fibers, leading to a rough and porous surface that improves mechanical interaction with the epoxy matrix [11], [17]. A detailed study of these phenomena will provide valuable information for researchers and industries trying to tailor different jute fiber-epoxy composite properties towards some specific applications. This includes the delicate balance between better adhesion on one hand while avoiding crunching or probable fiber degradation on another. Scanning electron microscope images allow the visualization of structural variations in addition to the interpretation of how the sample reacts for different soaking times [9].

According to the literature above, this study aims to investigate variations in the alkaline treatment period on impact and tensile properties of recycled jute sack (burlap) waste as a reinforcing agent for epoxy resin composites. This study is consistent with the Sustainable Development Goals (SDGs) program, which explicitly applies to saving waste materials and reducing environmental impact in promoting recycling and sustainability principles. Thus, the study's performance will provide practical knowledge on how jute sack waste optimization can be used in high-performance applications and promote green production with low-cost, sustainable materials for manufacturing automotive components.

2. METHODS AND MATERIALS

2.1 Materials

2.1.1 Jute sack waste

The jute sacks (burlap) used in the study were purchased from a supplier in Semarang, Indonesia (Figure 1). This jute sack is often used as a container for coffee grounds/beans, with dimensions of 90 cm × 100 cm and a capacity of 70 kg. Jute fiber is ecologically friendly, one of the renewable natural fibers, lightweight, has higher thermal qualities, is non-corrosive, is less expensive than other natural fibers, is biodegradable, and is non-abrasive [5], [18]. They also have high strength, thermal conductivity, low density, and low cost. Jute fibers have an elongation of 3.5-4.5%, a tensile strength of 393-723 MPa, and a density of 1.3 g/cm^3 (Table 1). The material employed in this study was jute fiber sacks, which are commonly used as multi-functional storage containers. Plain weave jute bags were utilized. Plain weave has a clear diagonal pattern, is simple, has more uniform load distribution, is easier to make and maintain, and is stronger. Jute bags come in various weave configurations, the most common of which is 1/1 plain weave [11].

Figure 1. Jute suck waste

Table 1. Physical and mechanical properties of jute fiber [19]

Properties	Value
Elongation at break (%)	3.5 ~ 4.5
Tensile strength (MPa)	393-723
Density (g/cm^3)	1.3
Young's modulus (GPa)	2.5

2.1.2 Epoxy resin

The epoxy resin used in this study is the Colorchem brand, purchased from a chemical supplier in Semarang, Indonesia (Figure 2). This adhesive, also known as a matrix, is utilized to adhere jute bags. It is composed of resin and hardener in a ratio of 1:1. Epoxy resin is a thermosetting epoxy with several uses in the aerospace, automotive, and marine sectors. As a matrix, epoxy resin has several applications, including coatings, aerospace industries, composites, bio-medical applications, and electronics materials [20]. Epoxy resin and epoxy hardener are utilized. Aside from serving as a binder, epoxy resin may also improve toughness, shrinkage, corrosion resistance, and heat resistance [21]. Epoxy resin has a tensile strength of up to 85 MPa and an elongation of 5% with a density ranging from 1.11 to 1.23 g/cm^3, as depicted in Table 2.

Figure 2. Epoxy resin and hardener

Table 2. Physical and mechanical properties of epoxy resin [22]

Properties	Value
Elongation at break (%)	5
Heat distortion temperature (°C)	120
Tensile strength (MPa)	~ 85
Density (g/cm^3)	1.11 ~ 1.23
Compressive strength (MPa)	~ 11
Tensile elastic modulus (GPa)	~ 3.2
Flexural strength (MPa)	~ 130
Linear expansion coefficient (in 10^{-6} /°C)	60
Water absorption/24 h (%)	0.14
Rockwell hardness/6.35 mm,100 kg	100
Shrinkage rate (%)	1 ~ 2

2.2 Fabrication of Laminate Composites

This study used an experimental approach with pre-experimental designs, a static group comparison type consisting of control and experimental groups. The research made use of jute sack trash. The process of alkalization preparation starts by creating a solution of NaOH with a concentration of 5% using the volume ratio, as determined by prior research conducted by other researchers [23], [24]. Jute sacks were immersed in NaOH for varying durations of 24, 48, and 72 hours in accordance with methods used by previous researchers [25], [26], [27]. Subsequently, the jute sacks were rinsed in distilled water and allowed to dry at room temperature for 48 hours. The hand layup technique is used to create composite fiber jute sacks. Jute sack fibers without and with alkalization are weighed using a fiber volume percentage of 50% by weight. Before printing, combine resin and hardener in a 1:1 ratio.

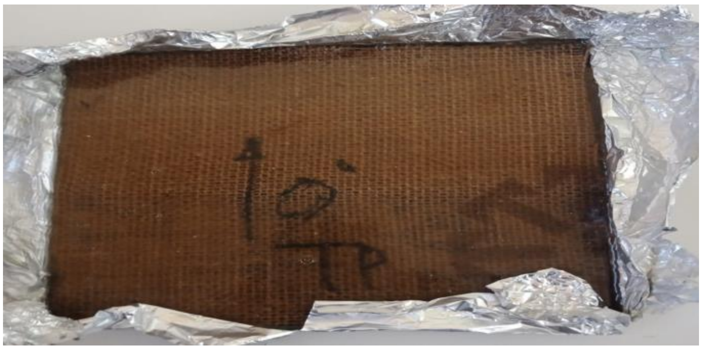


Figure 3. Composite of jute sack waste

The construction process involves arranging the jute sack fibers in a specific 0°/+90°/0°/+90°/0° pattern based on the method that was established in previous research [28], [29]. Afterward, the matrix is poured for each layer and evenly spread using a brush. The mold is closed, and pressure is applied to make the composite surface level and prevent delamination. Aluminum foil is applied to the mold before the composite molding process begins. The pieces of jute sack fiber are inserted one by one in the mold, with the fiber orientation shifting between 0°/+90°/0°/+90°/0° for each layer (Figure 3). Each layer is poured with a resin/hardener combination and uniformly smeared with a brush to allow the layers to connect. After all the layers have been put, pressing continues with a 5 kg load on top to keep the composite surface smooth and avoid delamination. Pressing is performed at room temperature for 24 hours.

2.3 Mechanical Properties

2.3.1 Impact test

Impact testing was used to quantify the energy absorbed by jute sack waste-based laminate composites before and after alkalization treatment with varied soaking periods. The more significant the amount of energy absorbed, the greater the level of material damage [30]. The Charpy technique was used for testing in the Mechanical Engineering Laboratory at Universitas Negeri Semarang, which used a GOTECH model GT-7405-MDH impact testing equipment. The Charpy impact method was chosen as it is useful in measuring material toughness owing to dynamic loads. This testing equipment produces 25 joules of energy and has a pendulum swing speed of 3.46 m/s. Eq. (1) is used to compute the impact strength:

$$IS = \frac{E}{A}. \tag{1}$$

IS = Impact strength (J/mm^2)
E = Energy absorption (J)
A = Cross-sectional area (mm^2)

Figure 4 displays the dimensions of the impact test specimens following the ASTM D4812 standard for Charpy testing [31]. The impact test specimen has the form illustrated below.

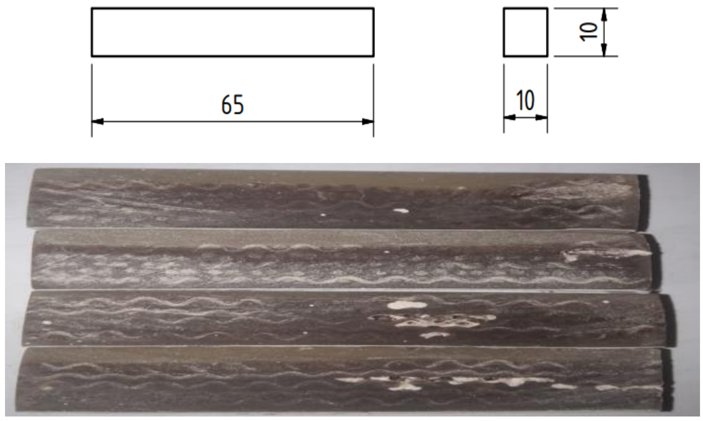


Figure 4. The dimensions of the standard impact test according to ASTM D4812

2.3.2 Tensile test

Tensile testing was performed to determine the maximum tensile strength of jute sack waste laminated composites, both without and with alkali treatment, via fiber soaking time modification. Maximum tensile strength testing is used to establish how much force is required to hold the material before it fails [32]. Tensile testing was performed in the Mechanical Engineering laboratory at Universitas Negeri Semarang utilizing a Universal Testing Machine brand GOTECH model GT-TCS-2000 with a capacity of 2,000 kg. The maximum load is the machine's result. Using Eq. (2), calculate the composite's maximal strength by comparing the maximum load per unit area:

$$\sigma_u = \frac{P_u}{A}. \tag{2}$$

σ_u = Tensile strength (kg/mm^2)
P_u = Ultimate load (kg)
A = Cross-sectional area (mm^2)

Meanwhile, use Eq. (3) to compute the composite's elongation after testing by comparing the change in measuring length with the original measuring length:

$$\varepsilon = \frac{l_t - l_0}{l_0} \, x \, 100\%. \tag{3}$$

ε = Elongation (%)
l_0 = Initial length measurement (mm)
l_t = Final length measurement (mm)

Figure 5 displays the dimensions of the specimens for tensile testing following the ASTM D368 standard [33]. The following graphic depicts the form of the tensile test specimen.

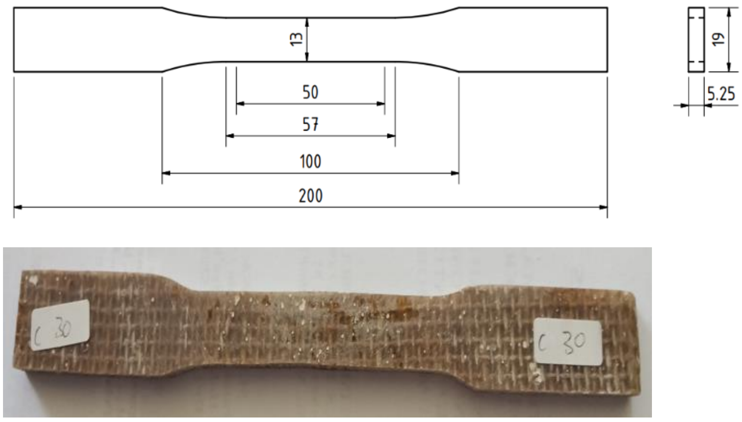
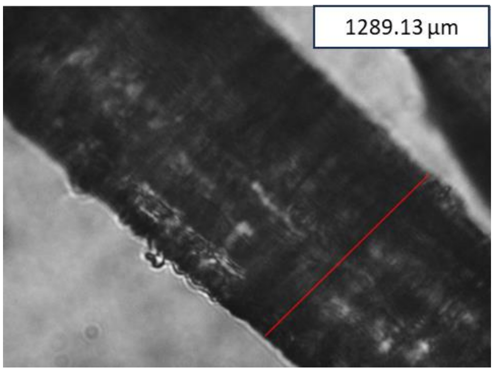


Figure 5. The dimensions of the standard tensile test according to ASTM D638

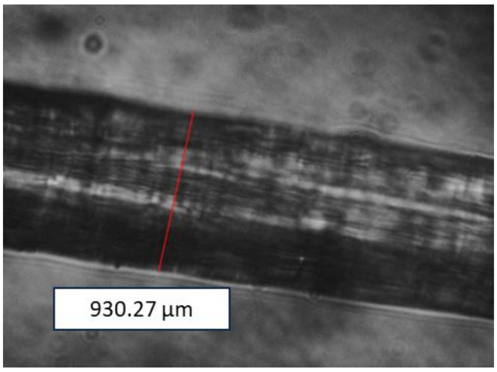
3. RESULTS AND DISCUSSION

3.1 Fiber Surface Morphology

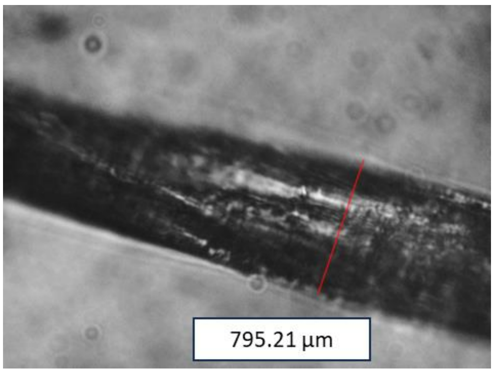
A B-510MET-R optical microscope, produced in Italy, was utilized to examine the effects of alkaline treatment on jute sack fibers. The microscope has a magnification of 100 times. Figure 6 illustrates the surface diameter of single jute fibers before and after alkaline treatment. Figure 6(a) displays the untreated jute fiber with a diameter of 1289.13 µm. Figure 6(b) depicts the jute fiber that underwent alkalization for a period of 24 hours. The treated fiber had a diameter of 930.27 µm, which was 27.84% smaller than the diameter of the untreated fibers. After undergoing a 48-hour alkalization treatment, the fiber's diameter decreased by 38.31% to 795.21 µm. Following a duration of 72 hours, the diameter saw a decrease of 43.99%, leading to a final measurement of 721.95 µm, as observed in Figure 6(d).



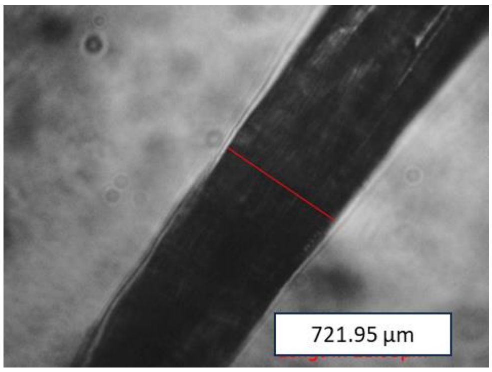
(a) No alkaline



(b) Alkaline for 24 hours



(c) Alkaline for 48 hours



(d) Alkaline for 72 hours

Figure 6. The surface morphology of jute fiber before and after immersion in an alkaline solution

The images of fiber surface morphology in this study indicate that increasing the duration from 24 hours to 72 hours of immersing jute fibers in an alkaline solution can lead to a reduction in the diameter of the fibers. The study conducted by Bogdan et al. revealed that the immersion process led to a decrease in fiber diameter, which was attributed to the elongation and increased density of the fibers [34]. A non-cellulosic and impurities components, such as lignin, pectin, and hemicellulose as a part composition in the natural fiber, are decomposed using alkali treatment and resulting enhance interfacial adhesion between reinforcement and matrice in composites [35], [36], [37]. Based on the literature review, treating fiber with an alkaline process known as mercerization using NaOH enhances the fiber's surface area, mechanical strength, and compatibility with polymer matrices, making it more appropriate for composite applications [38], [39].

3.2 Impact Test Results

Figure 7 illustrates the influence of the alkali treatment method on impact energy for epoxy composite jute sacks. Results revealed that the impact energy was increased by 61.77% (1.12 J) concerning untreated jute sack laminate composites, which had an impact value of 0.68J for soaking duration conditions at 5% NaOH solution form and soaked in 24 hours. This result revealed that the improvement of fiber-matrix adhesion by alkali treatment was attributed to non-cellulosic components (lignin and hemicellulose, amongst others) in the raw material that was removed [36], [37]. The stronger bonding led the composite to better draw in impact energy. When the soaking time was extended to 48 hours, an even more significant increase of 104.41% (1.39 J) could be observed, which suggested that this duration allowed maximum fiber/matrix interaction. The 48 hours specimen was applied for a suitable period to offer adequate surface cleaning with limited cellulose degradation, resulting in the fibers' maintained structural integrity and increased composite toughness. This result finding aligns with a previous study by Kabir et al. [40]. However, while improving at 44.12%, soaking for 72 hours appeared to lead to lower energy impact. After being in contact with that alkali solution for 72 hours, it could break down those cellulose fibers a little, indicating that it works against the improved bonding. Hence, the 48-hour soaking period appears as an optimal balance between surface modification and fiber preservation, resulting in composites producing the highest impact energy.

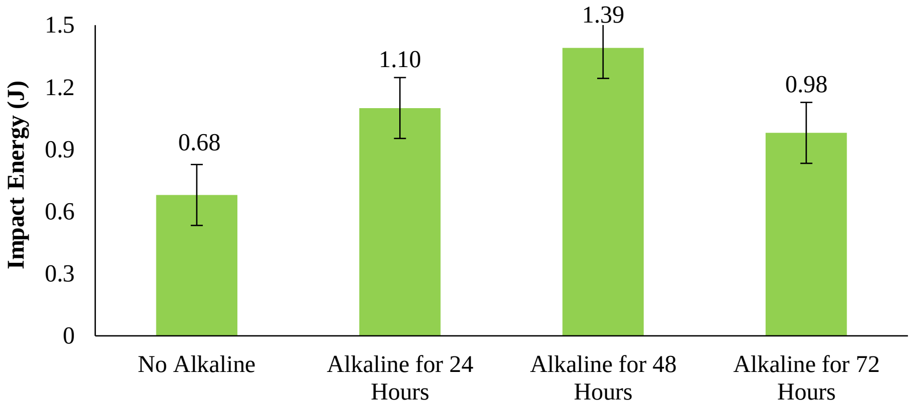


Figure 7. Impact energy of jute/epoxy composites with different alkali treatment methods

The impact strength of jute fibers is significantly influenced by the duration of immersion in a 5% alkaline solution, particularly during extended treatment periods of 24, 48, and 72 hours. The trend observed in the impact strength correlates closely with the impact energy of the composites (Figure 8). Results indicate that a 24-hour alkali treatment led to a 39.66% enhancement in impact strength compared to untreated jute sack laminated composites. Furthermore, after 48 hours of soaking, the impact strength increased by 72.41% relative to the untreated jute sack laminated composite. Additionally, a 72-hour alkali treatment resulted in a 43.10% improvement compared to the untreated jute sack laminate composite. The results demonstrate that the duration of alkaline treatment plays a critical role in enhancing the mechanical properties of jute fibers, particularly their impact strength. The increase in impact strength at different soaking durations can be attributed to several factors, such as alkali treatment effectively modifies the roughness of the fiber surface, and the increased roughness can improve the interfacial bonding between the fibers and the polymer matrix in composite materials.

Next, an increase in impact strength after 48 hours of soaking (72.41%) indicates an optimal treatment duration where sufficient surface modification occurs without excessive degradation of the fiber structure. This balance allows for enhanced crystalline structure while retaining flexibility, which is crucial for absorbing impact energy. Prolonged exposure to alkaline solutions can lead to fiber degradation, resulting in reduced ductility and increased brittleness. The fibers may lose some structural integrity, which can offset the benefits gained from initial surface modifications [13], [41]. The maximum impact strength obtained in this study remains lower compared to the findings of Ragupathi et al., who investigated the enhancement of impact resistance in automobile bumpers using natural fiber composites made of jute fiber. In their research, the composite bumper was manufactured through the hand layup process, where jute fibers were strategically placed and sequentially coated with liquid resin. The resulting composite bumper exhibited an impact strength of 7.14 J/mm², demonstrating superior impact resistance compared to the current study [42].

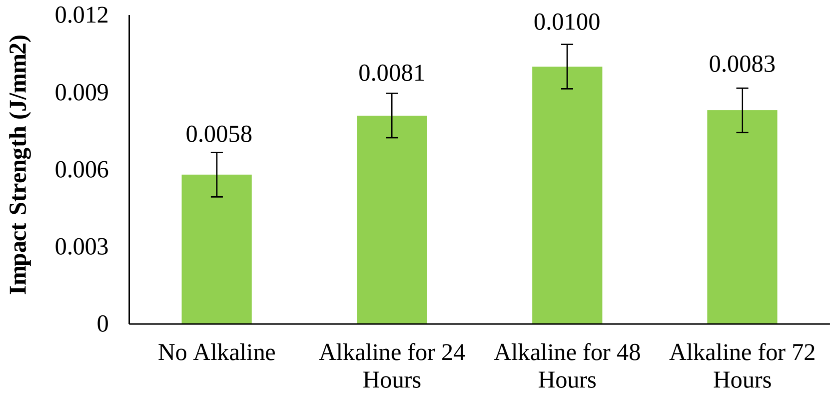
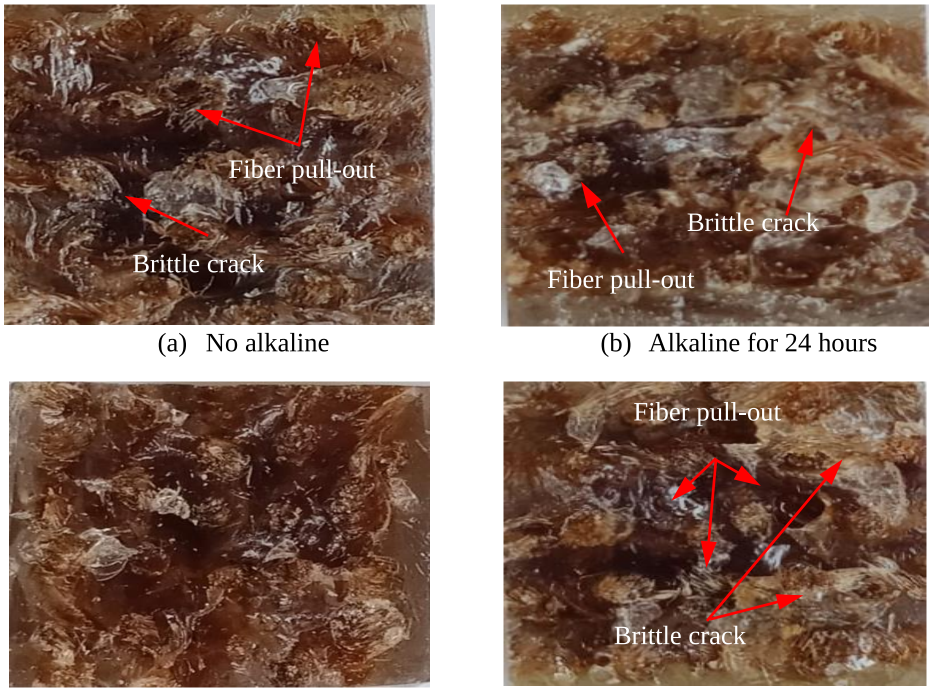


Figure 8. Impact strength of jute/epoxy composites with different alkali treatment methods

Figures 9(a) to 9(d) display the cross-sectional image of the impact test results for specimens without alkali treatment, 24-hour alkali, 48-hour alkali, and 72-hour alkali. For composites that have undergone insufficient alkali treatment, brittle cracking is often observed as the dominant failure mode. In these cases, the matrix and fibers tend to fracture simultaneously under the impact, resulting in a clean, brittle fracture surface (Figures 9(a) and 9(b)). This brittle behavior suggests that the fiber-matrix bonding is inadequate, leading to minimal energy absorption during impact [43]. In contrast, composites that have undergone optimal alkali treatment, such as the 48-hour immersion process mentioned earlier, typically exhibit reduced fiber pull-out and less brittle fracture behavior (Figure 9(c)). This suggests that the alkalization process has enhanced the interfacial bonding, enabling better load transfer and improving the composite's ability to absorb and dissipate impact energy [14]. Fiber pull-out occurs when the interfacial bonding between the fibers and the matrix is too weak to maintain cohesion under the stress of impact. This phenomenon is particularly pronounced in cases of prolonged immersion during alkali treatment, where the surface roughness and interlocking between fibers and the matrix become insufficient (Figure 9(d)). In these scenarios, the excessive treatment can lead to fiber degradation, weakening the fiber-matrix bond and increasing the likelihood of fiber pull-out during impact [44]. Fiber pull-out occurs when the interfacial bonding between the fibers and the matrix is too weak to maintain cohesion under the stress of impact [45].



(a) No alkaline (b) Alkaline for 24 hours

(c) Alkaline for 48 hours (d) Alkaline for 72 hours

Figure 9. Fracture cross-sectional form for impact strength testing

3.3 Tensile Test Results

Figure 10 displays the tensile strength results to demonstrate the effect of the duration of alkali treatment on the mechanical properties of laminated jute sack fiber-reinforced epoxy composites. The observed trends were due to a complex interaction between fiber surface modification and fiber integrity during alkali treatment. The tensile strength of the laminated untreated jute sack fiber-reinforced epoxy composite is approximately 10.52 MPa. After a 24-hour alkali treatment, the tensile strength of the laminated jute fiber composite increased to 12.48 MPa, reflecting an 18.63%

improvement. Extending the soaking duration to 48 hours resulted in a further increase, with the tensile strength reaching its peak at 14.99 MPa, representing a 42.49% enhancement. However, a decline in tensile strength (12.65 MPa) was observed when the jute fibers were immersed in the alkali solution for 72 hours. The result indicates that the 48-hour alkali treatment of jute sack fiber allows for sufficient removal of impurities while maintaining the integrity of cellulose fibers. This optimal balance between effective surface cleaning and fiber preservation contributes to the enhanced mechanical properties of the composite. In contrast, a 72-hour treatment reduces tensile strength, and excessive alkali exposure may start to degrade the fibers. The period of time of alkali treatment is a critical factor in identifying the tensile properties of materials, especially in composite applications. [9], [13], [35]. Consequently, shorter treatment durations might fail to change the fiber surface sufficiently, leading to insufficient bonding between fibers and matrix. This weak bonding prevents it from transferring load during mechanical loading, which in turn affects the overall strength and performance of the composite. However, if alkali treatment continues longer than desired, it will degrade the fibers. Constant contact with high pH solutions may deteriorate fiber structure, reducing tensile strength and integrity. Due to this degradation, mechanical properties can be reduced, negating the improvements observed by better fiber-matrix adhesion [46], [47].

Wagh et al. [48] investigated the tensile strength of natural fiber-reinforced polymer composites specifically for automotive bumper beam applications. In their study, they compared the performance of sisal and flax fibers. The results revealed that the tensile strength of the flax composite was significantly higher, with a maximum tensile strength of 204.9 MPa, representing a 90% increase over the sisal composite. Another study explored the use of rice straw fiber-reinforced epoxy composites with varying fiber loadings, observing that the highest tensile strength reached 14.75 MPa at a 30% fiber loading [49]. This finding aligns closely with the results of the current study, indicating a comparable trend in tensile strength improvement. These comparative studies highlight the variability in tensile strength among different natural fibers when used in polymer composites, emphasizing the importance of selecting the appropriate fiber type, matrix type, and treatment method to optimize the performance of composites for specific applications like automotive bumper beams [50].

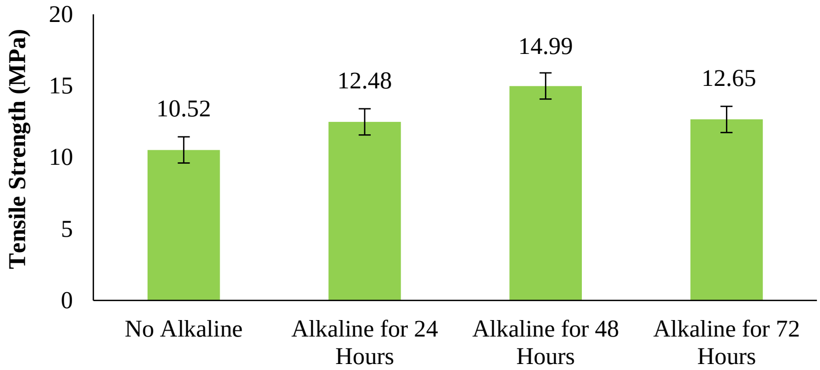


Figure 10. Tensile strength of jute/epoxy composites with different alkali treatment methods

Figure 11 illustrates the results data indicating that the composite treated with 5% alkali concentration for 24 hours experienced a 12.50% reduction in elongation compared to the untreated jute sack laminate composite. When compared to jute sack laminated composite without alkali treatment, 48 hours of soaking resulted in a 31.25% decrease in elongation. Meanwhile, alkali treatment of jute sack fiber for 72 hours resulted in a 12.50% decrease in elongation when compared to laminated composites containing jute sack fiber that was not alkali treated. The results suggest that the tensile elongation decreases with the increased duration of soaking the jute sack fiber. In nature, jute fiber contains two types of cellulose: amorphous and crystalline [51]. The primary concern of alkali treatment is the amorphous regions, which contribute to the fibers' elasticity and flexibility [52]. Prolonged treatment can result in the excessive removal of these areas, which can cause the fiber structure to become more rigid, leading to increased stiffness and decreased tensile elongation [53], [54].

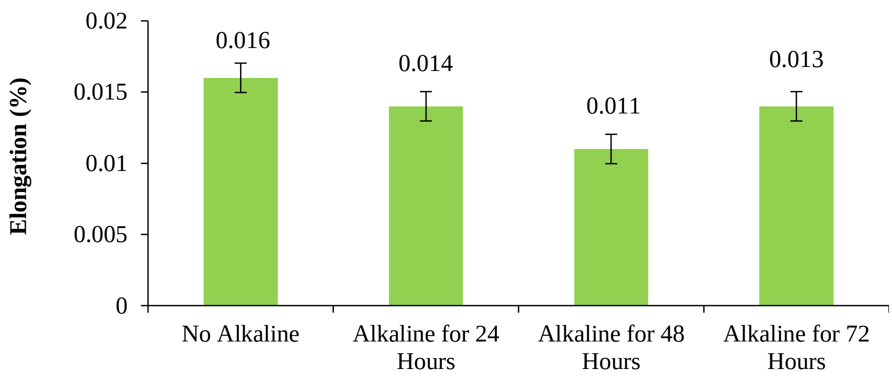
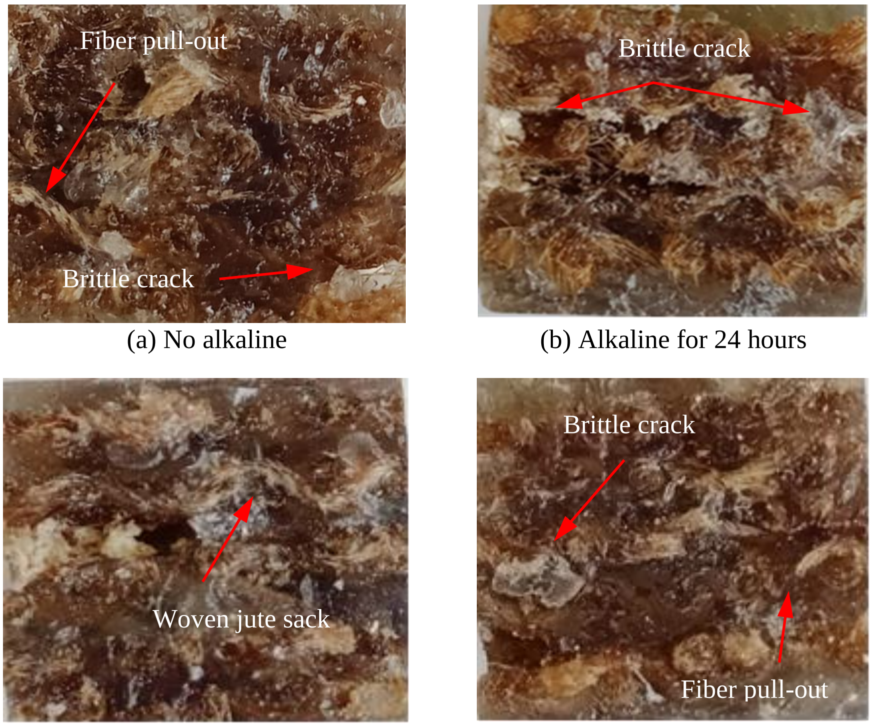


Figure 11. Elongation of jute/epoxy composites with different alkali treatment methods

Figure 12 illustrates the cross-sectional morphology of jute sack laminate composites with varying alkalization durations under tensile loading, highlighting the fracture behavior. The results indicate that brittle cracking is the dominant failure mode, characterized by the simultaneous fracture of both the matrix and fibers. This brittle failure is associated with minimal plastic deformation and significant fiber pull-out, particularly in composites that have not undergone alkali treatment (Figure 12(a)), which suggests poor fiber-matrix bonding [55]. The images clearly display the brittle cracks, with a noticeable distinction between fibers and matrix (Figures 12(b) and 12(d)). Such a failure pattern is attributed to poor bonding between the fibers and matrix, which renders minimal energy absorption and high shear stress at the fiber-matrix interface [56]. The optimal tensile strength of 14.99 MPa observed in jute sack-reinforced epoxy composites after a 48-hour immersion process demonstrates no evidence of brittle cracking or fiber pull-out in the corresponding image (Figure 12(c)). This indicates that the alkalization treatment was effective and sufficient.



(a) No alkaline (b) Alkaline for 24 hours

(c) Alkaline for 48 hours (d) Alkaline for 72 hours

Figure 12. Fracture cross-sectional form for tensile strength testing

4. CONCLUSION

Several research findings on the toughness and tensile strength of used jute sack laminated composites as an alternative material for vehicle bumpers reveal that the highest tensile strength of used jute sack laminated composites with a fiber orientation of 0°/+90°/0°/+90°/0° is 14.99 MPa after 48 hours of alkaline treatment. The maximum tensile strength is 42.49% greater than the previously utilized jute sack laminated composite without alkali treatment, which was 10.52 MPa. The impact strength of the jute bag laminated composite after 48 hours of soaking was 0.0100 J/mm^2, a 72.41% increase over the jute sack laminated composite without alkali treatment, which was 0.0058 J/mm^2. This study suggests that jute sack waste composites are a viable, sustainable alternative material for car bumpers. The study's findings also offer crucial information on the optimization of jute sack waste using green technology for the use of high-performance, environmentally friendly automotive components and the development of cost-effective and long-lasting materials. These findings are also consistent with the SDGs program, which aims to convert waste materials into new materials, reduce the usage of new raw materials, reduce environmental impacts, and promote the notion of sustainable recycling.

ACKNOWLEDGEMENT

Universitas Negeri Semarang financed this research with the 2023 UNNES DPA Fund Implementation Assignment Agreement Letter Number 34.12.4/UN37/PPK.10/2023.

CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

AUTHORS CONTRIBUTION

Heri Yudiono (Writing - Original Draft; Supervision)

Januar Parlaungan Siregar (Writing - Original Draft; Formal Analysis)

Sarwi Asri (Investigation; Data Curation)
Hanif Hidayat (Methodology, Investigation)
David Badi'ul Chikam (Methodology, Investigation)
Johan Andric Aprilian (Validation; Visualization)
Toni Agung Supriyadi (Resource; Data Curation)
Tezara Cionita (Writing - Review & Editing; Formal analysis)
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