Research Journal of Engineering Sciences ISSN 2278 – 9472
Vol. **12(2),** 8-21, May **(2023)** *Res. J. Engineering Sci.*

Experimental research on the mechanical characteristics of fiber-reinforced hybrid polymer composites

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Available online at: www.isca.in, www.isca.me
Received 31st December 2022, revised 17th March 2023, accepted 1st May 2023

Abstract

Materials that are renewable, biodegradable, and natural are intended to replace synthetic ones in current research. Due to its unique attributes and environmental friendliness, natural fiber composites are a hot topic of research. Natural fibers are more accessible, manageable, and biodegradable than synthetic fibers, giving them an edge. Assessing changes in the mechanical characteristics of polypropylene reinforced with chopped pineapple leaf and abaca fiber is the aim of the current investigation. Additionally, the impact of the fiber's chemical processing, content, and ratio on its mechanical characteristics was examined. In Bangladesh, there are numerous sources of fiber, including abaca and pineapple leaves. Abaca fiber and pineapple leaf were both chemically processed with 5% sodium hydroxide (NaOH). In order to create uneven and discontinuous structures, hybrid polypropylene composites reinforced with pineapple leaf and abaca fiber were created via compression molding. It ranged from 3:1 to 1:1 to 1:3 in terms of the ratio of pineapple leaf fibers to abaca fibers. Percentages of 5, 10, 15, and 20% fiber loading were used. When reinforcing of polypropylene with 5 wt% pineapple leaf and abaca fiber was done in a 3:1 ratio, the best set of mechanical properties were obtained. However, fiber reinforced composites that had been treated with NaOH showed superior mechanical properties over untreated composites.

Keywords: Hybrid composite, polypropylene, abaca fiber, pineapple leaf fiber, mechanical features.

Introduction

Due to their biodegradability, affordability, high specific strength, and desirable physical characteristics, natural fibers (NFs) are used in a variety of applications, including rope, strands, reinforcing agents for biocomposites, and home appliances. They are additionally employed in the building and construction, as well as in the automobile, aircraft, sporting goods, and home appliance industries[1-3]. Most NFs belong to one of three groups: those that are based on plants, animals, or minerals[4]. Less research has been done on these materials as a result of asbestos, the main component of mineral base fibers, being detrimental to human health[5]. Researchers are focussing particularly on plant-based fibers among all NFs due to their potential qualities, including their low cost, biodegradability, abundance, and strong physical and mechanical properties[6-9]. The majority of commercial bio-composites are made from plant fibers from the stalk, leaf, and seed bases, while bio-composites made solely for research are only made from fibers from the stalk, grass, and wood bases[10]. The complicated structure of plant fibers is depicted in Figure 1 by the cell wall and a central lumen channel. The primary wall, secondary wall, and middle lamella are the three components of a cell wall. Water travels via the lumen, whereas the main wall controls mechanical activity. A pectin, hemicellulose, and lignin-rich matrix surrounds a primary wall of cellulose that is disorganized. The inside wall (S3), the middle wall (S2), and the external secondary wall are the three crystalline cellulose walls that make up the secondary wall (S1)[5].

Cellulose, wax, lignin, hemicellulose, pectin, and wax are the chemical components of plant fibers. The cellulose microfibril network serves as a reinforcing agent in the matrix phase of plant fibers, which is made up of hemicellulose, lignin, and pectin. The main structural element of the fiber is the cellulose microfibril, and the hemicellulose components, which are connected to cellulose by hydrogen bonds, act as a matrix to bond the two together[11]. Plant fibers from sources like bamboo, lady's finger fiber, abaca fiber, jute, cotton, flax, hemp, sisal, and others have drawn more attention in recent years due to the possibility of using them in composites[12-19]. However, there are many additional plant species that can be used in place of fibers, many of which are grown solely for the food industry[20]. The branches and stems of okra, wheat straw, nettle, corn, and banana pseudo-stems are a few examples of food plants whose waste parts can be employed as sources of fiber for composite reinforcing applications[21-25].

This process combines biodegradable components manufactured from renewable resources to produce fiber from agricultural waste, making it environmentally friendly. It benefits rural populations as well since it enables them to use more of their

crops, which promotes growth. More arable land may be set aside in order to feed the world's growing population[26].

Abaca fiber, often known as Manila hemp, is produced using the cellulose fibers from the pseudostem of the *Musa textilis* plant. It is a plant belonging to the Musacea genus, which also includes the banana[27]. One of the many agricultural plants that may be found in tropical areas is the abaca plant. Abaca fiber is a byproduct of banana growing that can be exploited for industrial purposes with minimum further effort. Due to Daimler Chrysler's pioneering use of abaca fiber in under floor protection for passenger automobiles, abaca fiber reinforced composites are currently becoming more and more popular. The inventive combination of PP thermoplastic and abaca fiber was created by researchers at Daimler Chrysler, and Rieter Automotive has begun the compression molding process for its manufacture. According to reports, abaca fiber has a high tensile strength, rot resistance, and a flexural strength that is comparable to glass fiber[28]. Abaca is the first natural fiber to pass the strict criteria for parts used on the exterior of motor vehicles in terms of resilience to factors like stone impact, weather exposure, and moisture. Due to the attraction or interaction between the hydroxyl groups of the fiber components and water molecules, both natural and abaca fiber exhibit significant hydrophilicity. Starting in the non-crystalline region and moving toward the crystalline region, fiber and water interact in many ways. Cellulose (non-crystalline, crystalline), hemicellulose, and other hygroscopic materials absorb water by a procedure termed hydration that requires accessible hydroxyl groups. The exothermic reaction that happens when a cellulose molecule absorbs a water molecule produces cellulose hydrate, which serves as a catalyst for further absorption[29]. The use of lignocellulosic fiber as reinforcement in composite materials is constrained by the material's high moisture sensitivity, which results in dimensional instability. Low interfacial properties between the fiber and polymer matrix, which are caused by natural fibers' hydrophilic nature, typically restrict these materials' capacity to operate as reinforcing agents. To improve the fiber interface, chemical alterations and chemical coupling agents are taken into account. Chemical coupling agents are frequently substances that have two different functions. The cellulose's hydroxyl groups must be reacted with in the first step, and the matrix's functional groups must be reacted with in the second[30]. Chemical procedures like acetylation, mercerization, methylation, cyanoethylation, benzoylation, permanganate treatment, and acrylation can lower the quantity of moisture that fibers absorb[31-36].

Pineapple leaf fibers are a common agricultural waste and a good alternative to synthetic fiber in Bangladesh. Pineapple-leaf fiber (PALF) is one of the most important plant-based fibers for composite materials due to its moderate specific strength and stiffness compared to other natural fibers. Although the pineapple industry places a high value on the fruit, the leaves are regarded as fruit waste and used to create natural fibers[37]. When used as a reinforcing element in composite applications, they are in direct competition with glass fibers[38]. Pineapple leaves are mostly composed of cellulose (70–82%), lignin (5–12%), and ash (1.1%). Because of their exceptional strength, pineapple leaves can be employed as reinforcement for composites made of biodegradable polymers.

Due of the desire for numerous competing properties in contemporary composite materials, the creation of innovative composites has accelerated. The reinforcing layers of these so-called hybrid composite materials contain at least two distinct fiber types. Polymer hybrid composite materials are currently the most popular. The behavior of individual components, where there is a balance between the inherent benefits and drawbacks, determines how hybrid composites behave. Additionally, the benefits of one type of fiber could be combined with what the other lacks by employing a hybrid composite made of two or more types of fiber. By doing this, composite materials may find it easier to balance their costs and benefits. Fiber content, individual fiber length, orientation, degree of fiber interweaving, bonding between the fibers and matrix, arrangement of the fibers, and failure strain of individual fibers are the primary factors influencing a hybrid composite's properties[39].

One of the most popular polymers used today, polypropylene (PP), is used to make many different products, including textiles, stationery, plastic parts and reusable containers of many kinds, lab equipment, loudspeakers, auto parts, and polymer banknotes. Due to a unique combination of features, it shines in numerous applications. Due to its exceptional mechanical properties, including high flexural strength, great impact strength, low coefficient of friction, and superior fatigue resistance, polypropylene was chosen for the current experiment. It has exceptional resistance to moisture and electricity in addition to having excellent chemical resistance to a number of bases and acids. Damage can more readily be remedied.

Development of hybrid polypropylene composites reinforced with abaca and pineapple leaf fibers is the main goal of the present work, along with an evaluation of the effects of fiber fraction and ratio on the mechanical properties of the produced composites. More investigation was done to learn how alkali treatment changed the mechanical properties of the fiber found in abaca and pineapple fibers.

Materials and methods

Materials: One can manually, chemically, or mechanically extract a fiber. The ideal way for obtaining fiber in a good quantity and quality while still being environmentally friendly is mechanical extraction. The pineapple leaf and abaca plant were presents from a nearby field for this inquiry. We gathered the fiber from both the stems and the leaves of the abaca and pineapple plants. Even after extraction, moisture remained in the fibers. Thus, fibers were dried after extraction. From a

neighboring grocery, we bought NaOH and commercial-grade polypropylene (PP). The PP was in the shape of granules, was white in color, and had a melting point of 160°C.

Methods: Fiber Surface Treatment: Abaca fiber and pineapple leaf underwent an alkali treatment to make them more compatible with the matrix. Both times, the exact identical procedure was used. To create the fibers, 5% NaOH was used. The dried, extracted fiber was thoroughly steeped in the solution prior to extraction to make sure every fiber was soaked. The fiber solution was then heated in a beaker for about 2.5 hours at 70°C. After that, distilled water and tap water were used to wash the fibers. The fibers that still contained water were finished drying in an oven.

Preparation of a Composite: First, using the hot press process, raw abaca and pineapple fibers were mixed in varying proportions (5, 10, 15, and 20 weight percent) with a polypropylene matrix to form hybrid composites. Making two composites with a 10 wt% fiber content and a ratio of 1:3 or 3:1 between pineapple and abaca was the next stage. Last but not least, abaca fiber and pineapple that had been treated with 5% NaOH were combined in a 3:1 ratio to generate a unique composite.

Characterizations: Mechanical Examination: Testing for tensile, flexural, and hardness was done on the created composites. Each test and kind of specimen underwent five tests. Tensile tests were performed using an Instron machine with a maximum capacity of 50 KN in accordance with ASTM D 638-01 [40]. Each test was conducted at a crosshead speed of 10 mm/min up to the point of tensile failure. The identical Instron apparatus stated above was used to conduct flexural testing in accordance with ASTM D 790-00 [41]. 1 mm per second was the cross head speed. Due to the position of the supports and the loading nose, which put the loading nose in the middle of the supports, the axes of the cylindrical surfaces were parallel. Data on load deflection were gathered by applying the load to the specimen at the specified cross head motion. When the test specimen's outer surface started to tear, the test was stopped. The following equations were used to compute the flexural strength and modulus, respectively:

$$\mathrm{FS} = \frac{3\mathrm{PL}}{2\mathrm{bd}^2} \qquad (1)$$

$$\mathrm{FM} = \frac{\mathrm{L}^3\mathrm{m}}{4\mathrm{bd}^3} \qquad (2)$$

Where: P is the load, L is the distance of the span, b is the beam's width, d is its depth, and m is the gradient (slope) of the curve's initial straight-line section. FS stands for the outer fiber tension at mid-span.

Hardness is the property of a substance that prevents it from becoming permanently indented. A Shore Durometer, a popular tool for measuring the hardness of rubbers, elastomers, and polymers, was used to determine the composite's hardness. There are many Durometer scales that can be used with materials that have different properties. In this experiment, the Shore D scale was used.

Results and discussion

Tensile Features: The stress-strain curve was used to determine the tensile characteristics of hybrid composites. Figure-2 depicts the change in tensile characteristics caused on by fiber loading. Figure-2(a) illustrates the relationship between tensile strength and fiber loading. When compared to composites constructed of pure polypropylene, the tensile strength of composites with loadings of 5, 10, 15, and 20% was reduced by 25, 33, 38, and 43%, respectively. A weak interfacial region between the hydrophobic matrix and the hydrophilic cellulose fiber expands when the amount of fiber is increased[42,43]. As a result, over time, the link between the fiber and matrix degrades[44]. The outcome was a gradual loss in tensile strength. To improve fiber contact, it would be able to make chemical modifications. For molecules to successfully interlock with the matrix, chemistry can change or activate them. Some examples of chemical processes include the use of alkali, silane, benzoylation, maleated coupling agents, isocyanates, acrylation, permanganate, and other substances[36]. Alkali treatment improved interfacial bonding in this investigation. A graph of the tensile modulus values for the hybrid composites formed from pineapple leaf and abaca fibers vs. the amount of fiber utilized is shown in Figure-2(b). The graph shows that as fiber loading increased, the tensile modulus values increased as well, surpassing those of pure polypropylene. In comparison to pure polypropylene, the tensile modulus of composites with 5, 10, and 20% fiber loading rose by 16, 20, and 15%, respectively. This is because as fiber loading increased, the stress-strain curve of the composite grew steeper and more brittle. Micro-spaces have partially separated due to insufficient interfacial bonding, preventing stress from propagating between the fiber and the matrix.

The level of blockage rises together with the increase in fiber loading, increasing the tensile modulus[45]. Polypropylene matrix is less stiff than composite matrix. The picture, however, demonstrates that at 15 and 20 weight percent fiber loading, the tensile modulus dramatically decreases. Composites with fiber loadings of 15% and 20% could not be as good as those with a 10% fiber loading because they might not adhere to the filler matrix. A larger fiber content in the fibers could cause them to agglomerate, misalign with the matrix, and show flaws[46]. Figure-2(c) illustrates the percentage of elongation at break for the hybrid composites as a function of fiber loading. Because fibers have a lower elongation at break than the polypropylene matrix, it has been discovered that when fiber is introduced to the matrix, the elongation at break is significantly reduced. However, as fiber loading increased from 10% to higher values, the composites' stiffness dropped, leading to a slight rise in the elongation at break.

Figure-3 compares various combinations of pineapple leaf and abaca fibers in terms of their tensile strength, tensile modulus, and elongation at break. Any composite's tensile strength is influenced by the fibers' internal structure and chemical make-up. The cellulose concentration of abaca fiber is lower (56–63%) than that of pineapple leaf fiber (70–82%), which causes it to have a lower tensile strength (430–813 MPa) than pineapple leaf fiber (413–1627 MPa). In contrast to composites engaging those fibers at 1:1 and 1:3, hybrid composites engaging those fibers at 3:1 ratios had higher tensile strength (Figure-3(a)). In comparison to the other two composites, the hybrid composite reinforced with pineapple leaf and abaca fiber (at a 3:1 ratio) had a greater tensile modulus (Figure-3(b)). Abaca fiber has a tensile modulus of 31.1-33.6 GPa, which is lower than that of pineapple leaves, which have a tensile modulus of 34.5-82.5 GPa. Larger pineapple fiber insertion concentrations require higher stress, which raises tensile modulus, in order to achieve the same deformation. Composites built with 75% abaca fiber showed higher% elongation at break than those prepared with 75% pineapple fiber (Figure-3(c)). It appears likely that this is the case because abaca fiber elongates more at break than pineapple fiber.

By chemically treating the fibers with 5% NaOH, the adhesion between pineapple leaf and abaca fiber and polypropylene was enhanced. It is expected that after alkaline treatment, the interfibrillar region will become less dense and rigid, which will cause the fibrils to reorganize themselves more in the direction of tensile stress. This form of the fibrils would result in better load distribution and, thus, more stress buildup in the fiber when it is stretched [45]. Alkaline treatment is said to have two effects on the fiber: it roughens the surface, which encourages mechanical interlocking; and it exposes more cellulose on the surface, increasing the number of potential reaction sites. The mechanical properties are greatly influenced by cellulose. Increasing the cellulose content improves the mechanical characteristics[47]. Figure-4 depicts the tensile characteristics of the hybrid composites reinforced with abaca and pineapple leaves following an alkali treatment. Figure-4 shows the 19% and 50%, respectively, increases in the tensile strength and tensile modulus caused by chemical processing. The percentage of elongation at break did, however, decrease by 25% after treatment with sodium hydroxide because the matching composites had increased stiffness.

Flexural Features: The flexural load-extension curve and associated equations were used to evaluate the flexural characteristics of samples with various fiber compositions. Figure-5 displays the flexural strength and flexural modulus for composites reinforced with raw pineapple leaf and abaca fibers at various fiber loadings. The polypropylene matrix's flexural strength increased when fiber additions of 5% and 10% were made (Figure-5(a)). This may be due to the filler's filler matrix adhesion being strengthened by the polymer chain's favorable entanglement with the filler[48]. As the fiber content was increased, flexural strength somewhat reduced. Weak filler matrix adherence may be the cause of composites with 15% and 20% fiber content as contrasted to composites with 10% fiber content. As fiber content rises, the fibers develop defects that are partially out of alignment with the matrix. The flexural modulus values for hybrid polypropylene reinforced by natural pineapple leaf and abaca fibers at various fiber loadings are shown in Figure-5(b). When fiber loading is increased by up to 10%, flexural strength increases. The composites' flexural strength values exceeded those of the polypropylene matrix. Because abaca and pineapple leaf have high moduli, more force is needed to cause the same deformation when more fibers are present[49]. Due to the fiber's incorporation into the adaptable polypropylene matrix, the flexural modulus increased (tough abaca and pineapple leaf). Between the 15% and 20% fiber loadings, the modulus values were essentially constant. For a variety of fiber ratios, flexural strength and modulus data are displayed in Figure-6. When pineapple leaf and abaca fiber were utilized as reinforcement in a 3:1 ratio rather than a 1:3 ratio, the composite had a higher flexural strength and modulus. Between 70 and 82 percent more cellulose is included in pineapple leaf fiber than in abaca fiber. As a result, it was discovered that composites with greater fiber from pineapple leaves had better bending properties.

Figure-7 depicts how alkali treatment affected flexural characteristics. The interfacial contact between the fiber and matrix can be improved by alkali treatment. As a result, there is a greater chance of load transmission between the matrix and the reinforcing fibers. There is also a greater chance that the matrix will actually come into touch with some surface area[49]. The outcome was a rise in the flexural strength and modulus of 6% and 11%, respectively.

Hardness Test Results: Figure-8(a) depicts the hardness values as a function of fiber loading for hybrid composites reinforced with abaca and pineapple leaf fibers. Polypropylene matrix is naturally flexible. The addition of the fiber strengthens the composite. A composite's hardness is defined by how evenly the fibers are distributed throughout the matrix[50]. When fiber is added, the matrix's elasticity is likewise reduced, creating a composite that is stiffer[39,51]. In comparison to pure polypropylene, the hardness of hybrid composites consistently increased by 3, 5, and 4% for composites with a fiber loading of 5, 10, and 15%, respectively. Hardness levels somewhat declined as fiber loading increased. The production of fiber agglomerates may result in a drop in hardness value when fiber loading increases at higher values. Figure-8(b) illustrates a varied fiber ratio for hardness modification. Higher pineapple fiber content reinforced composites showed higher levels of toughness as compared to other reinforced composites. This is likely the case because pineapple leaf fiber has more cellulose than abaca fiber. The improved mechanical properties, especially hardness, are principally caused by the higher cellulose content[47]. The devaluation of the cementing element brought on by the alkaline treatment of the fiber causes the cellular structure to disintegrate. Thus, there is less of a void, the

cellulose chains are more closely packed, and the matrix and fiber connect more successfully[52]. As a result, in Figure-8(c), the composites reinforced with alkali-treated fibers had hardness values that were 2% higher than those reinforced with raw fibers.

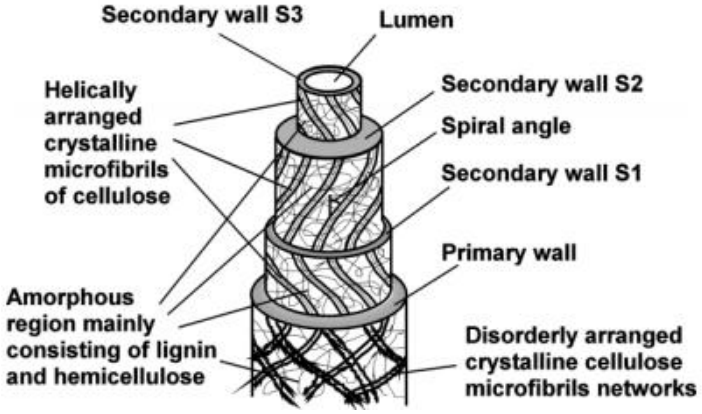
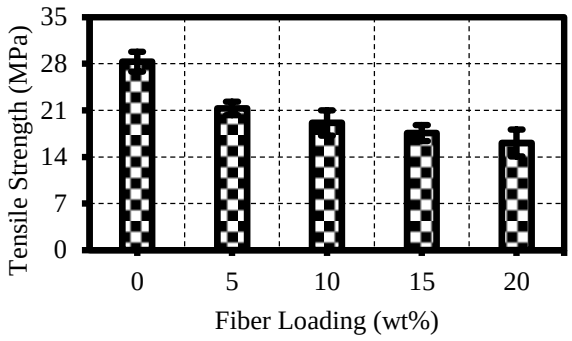


Figure-1: The secondary wall S2, which makes up around 80% of the total thickness of a natural vegetable fiber cell's structure and serves as the major load-bearing element, is the cell's structural foundation [5].

(a)



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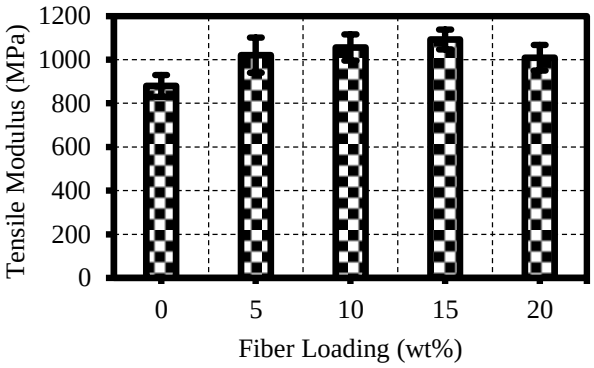


(c)

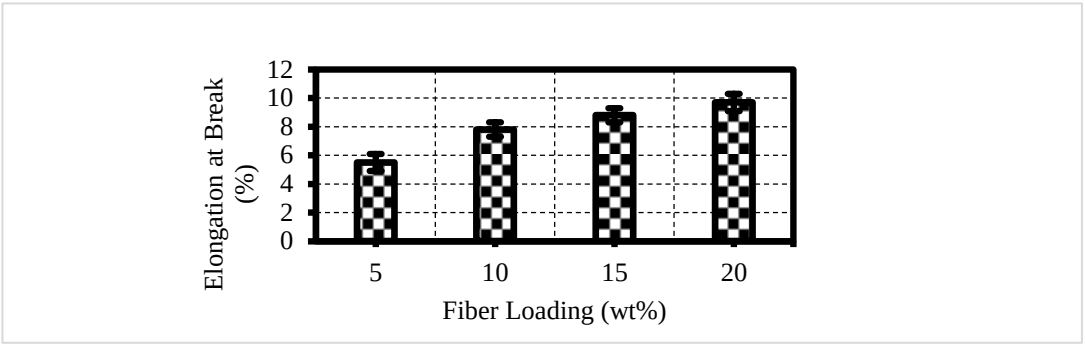
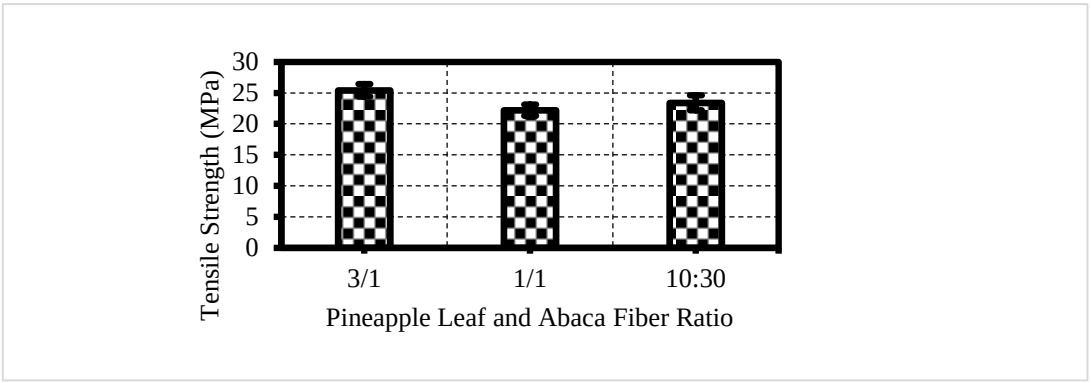
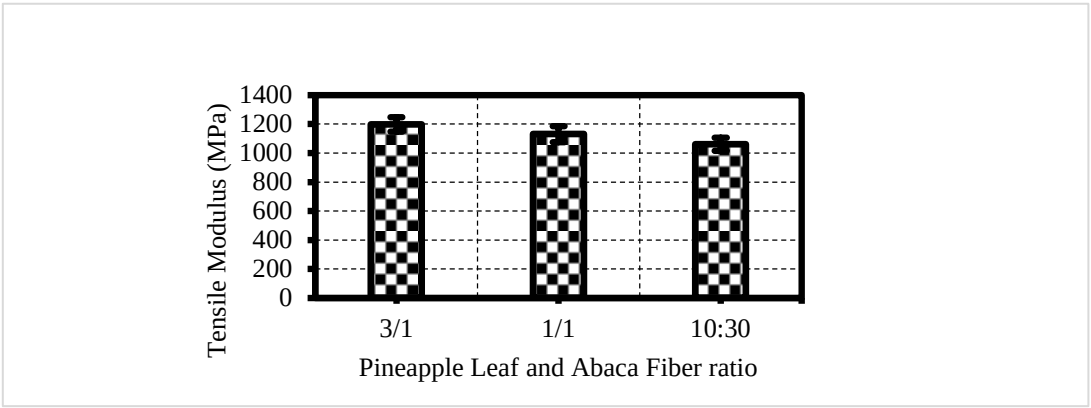


Figure-2: Changes in (a) tensile strength, (b) tensile modulus, and (c) elongation at break (%) in response to fiber loading.

(a)



(b)



(c)

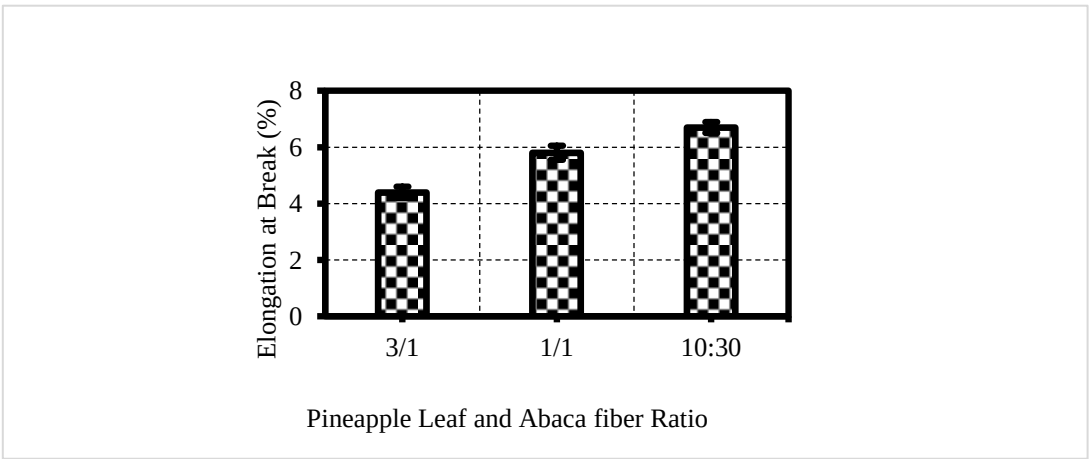
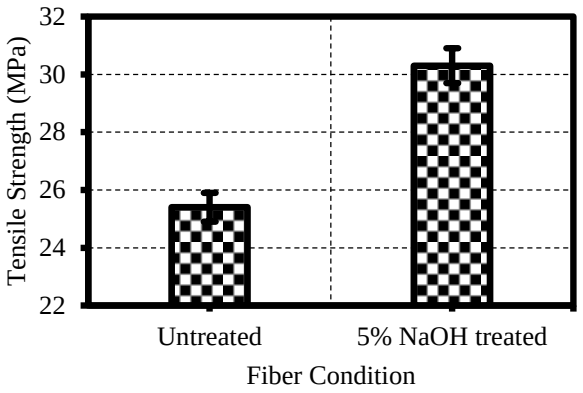


Figure-3: Changes in (a) tensile strength, (b) tensile modulus, and (c) elongation at break (%) for various fiber ratios at 10% fiber loading.

(a)



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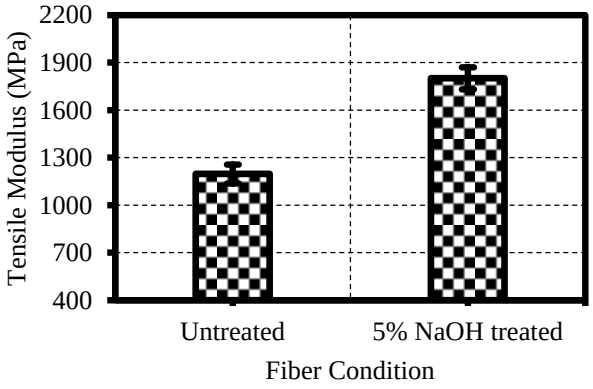

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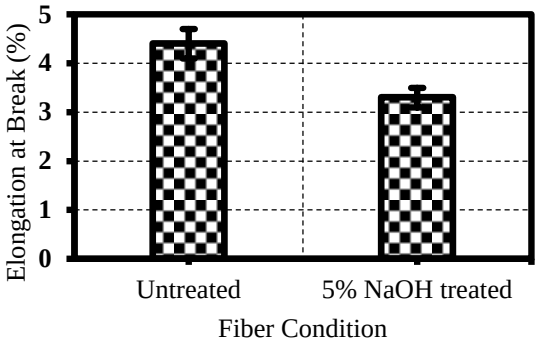
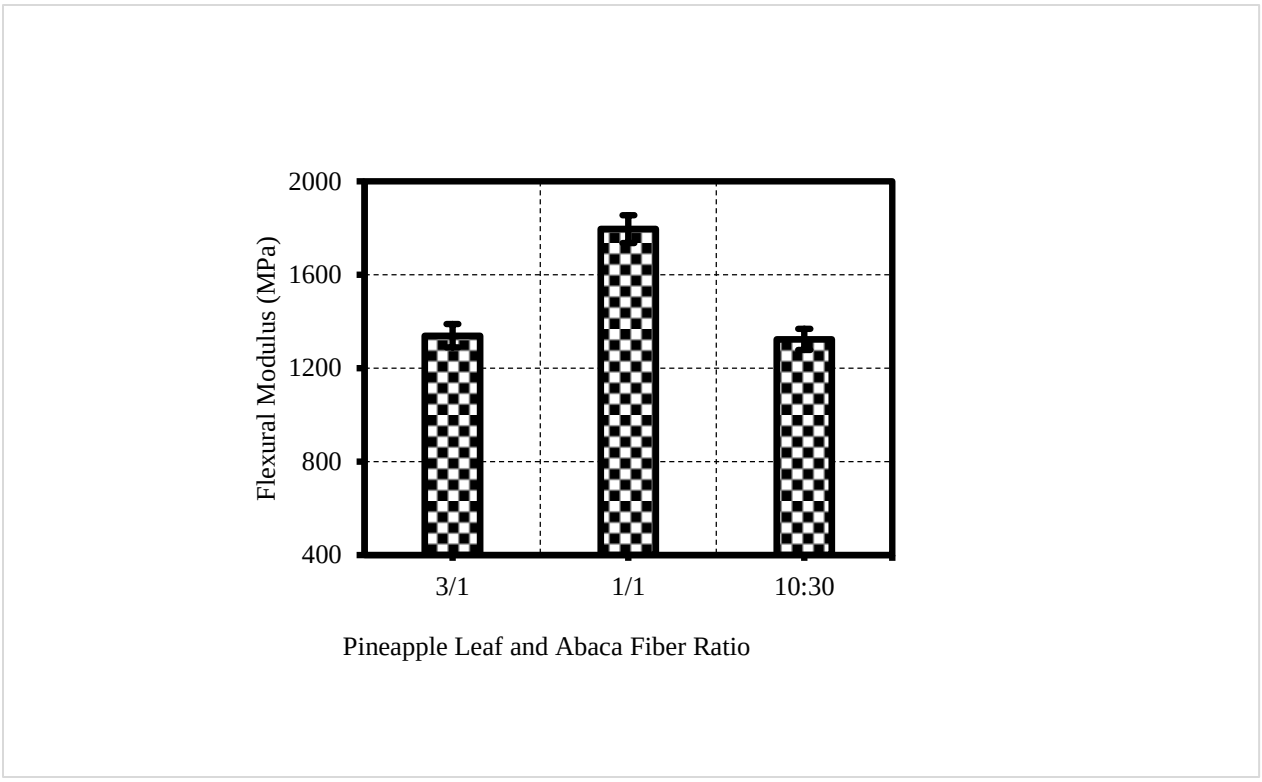
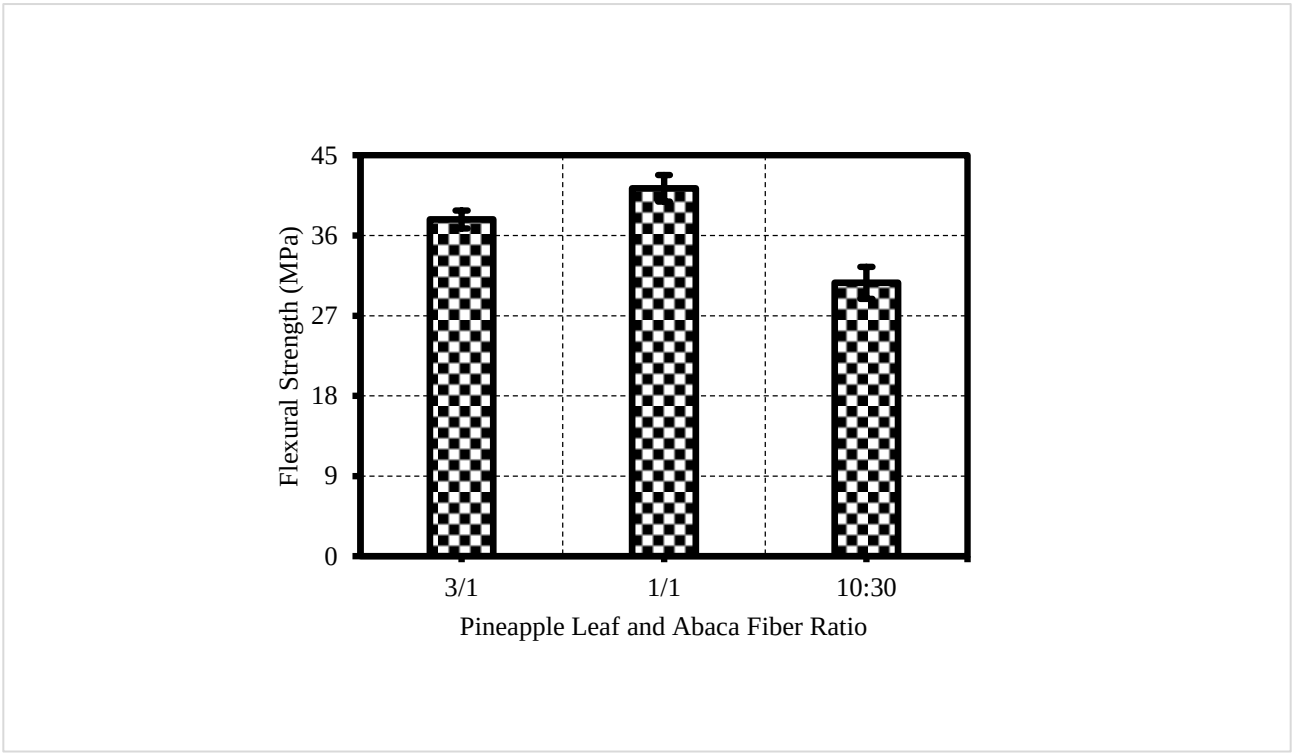


Figure-4: The effects of treatment with sodium hydroxide on (a) tensile strength, (b) tensile modulus, and (c) elongation at break (%).

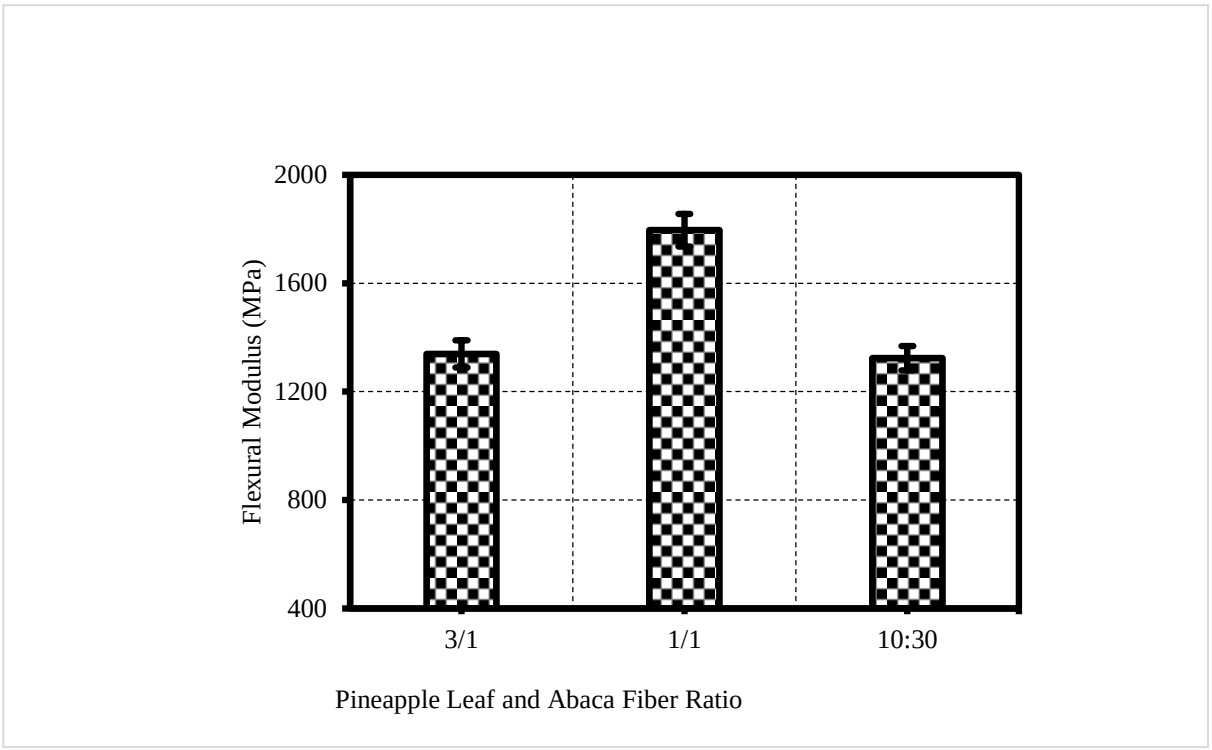


(a)

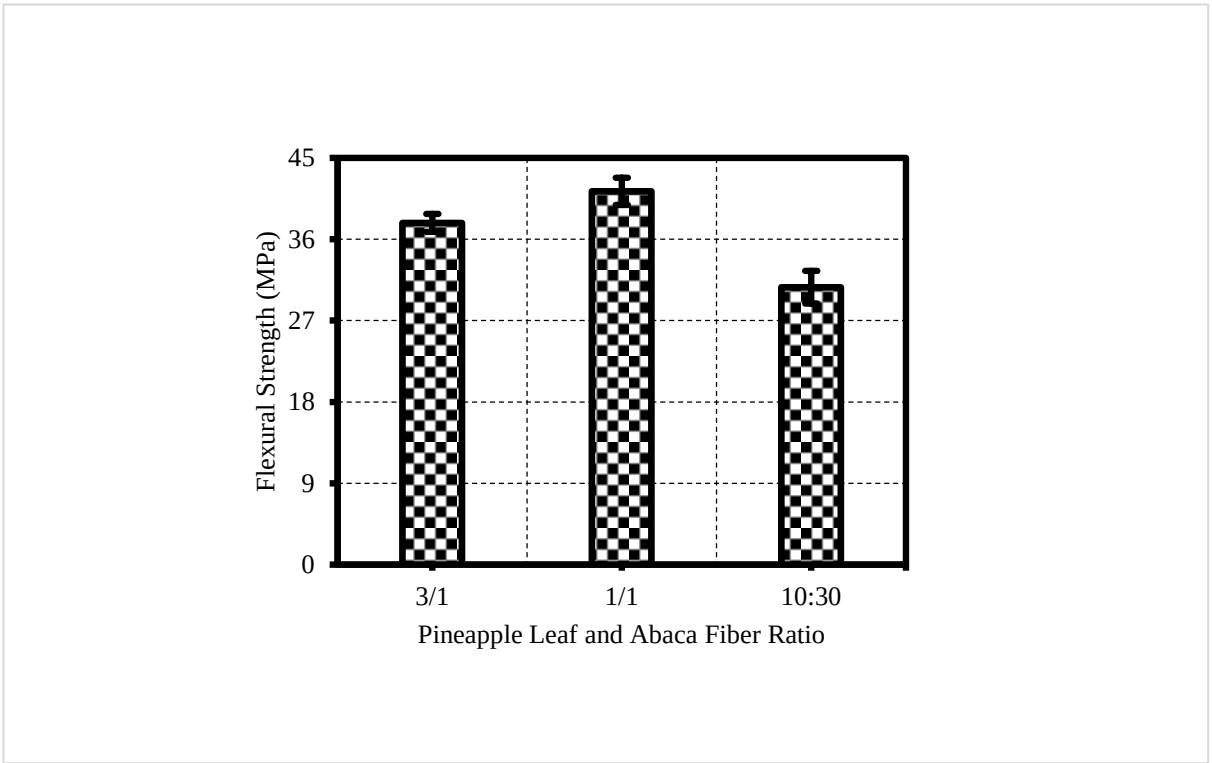


(b)

Figure-5: Changes in (a) flexural strength, and (b) flexural modulus in response to fiber loading.

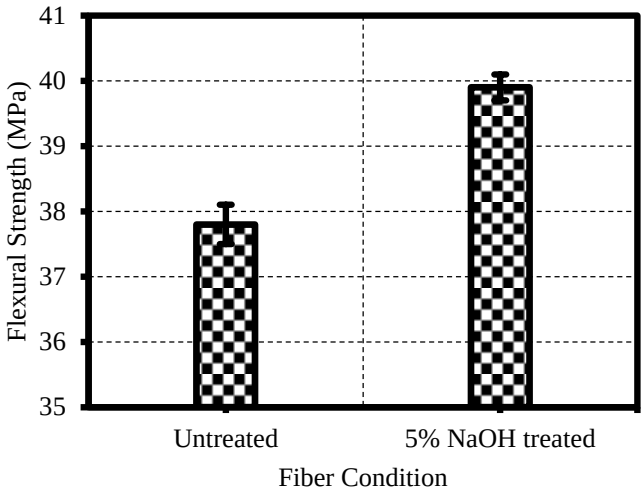


(a)

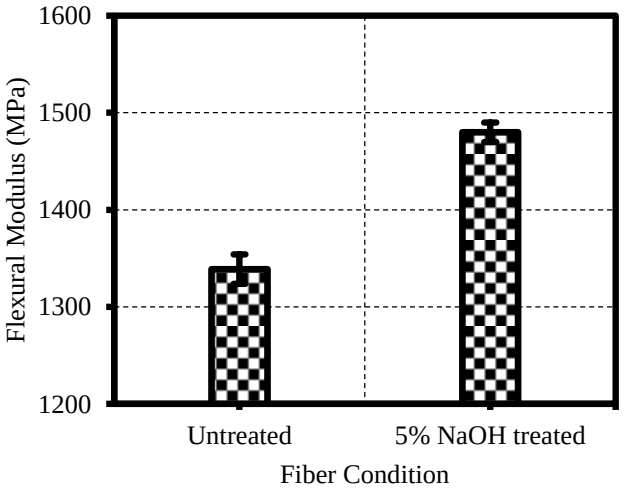


(b)

Figure-6: Changes in (a) flexural strength, and (b) flexural modulus for various fiber ratios at 10% fiber loading.



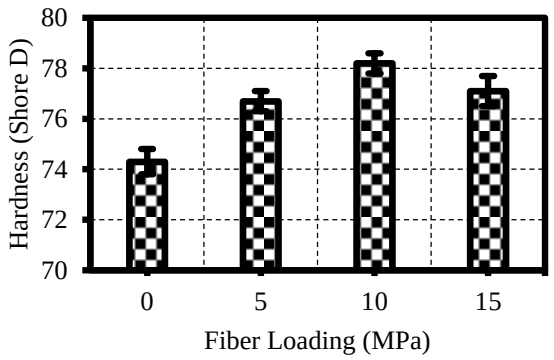
(a)



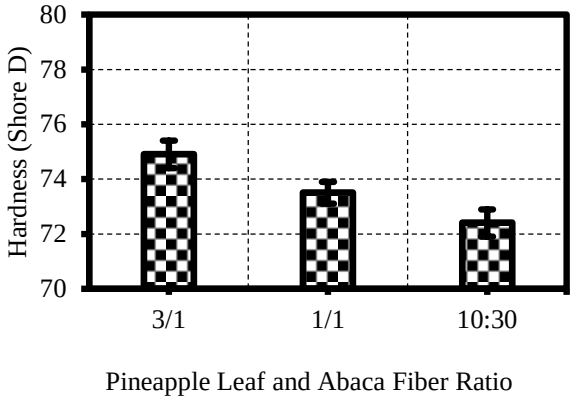
(b)

Figure-7: The effects of treatment with sodium hydroxide on (a) flexural strength, (b) flexural modulus.

(a)



(b)



(c)

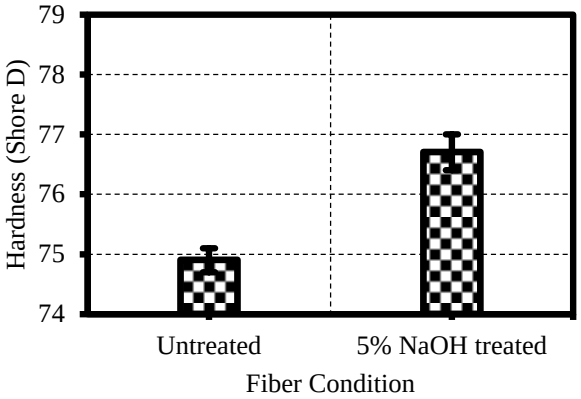


Figure-8: Hardness varies in relation to (a) fiber loading (b) fiber ratio and (c) alkali treatment.

Conclusion

The current work used compression molding to create hybrid polypropylene composites reinforced with abaca and pineapple leaf fiber. The primary objective was to use hybrid fibers to strengthen polypropylene in order to enhance its mechanical qualities. The use of a hybrid pineapple leaf and abaca fiber early in the process increased all mechanical properties of polypropylene, with the exception of tensile strength. The hybrid fiber was added to the polypropylene matrix at a concentration of 10% by weight in order to get the best combination of mechanical properties. In terms of tensile strength, tensile modulus, flexural strength, and hardness, abaca fiber and pineapple leaf fiber were combined in a 3:1 ratio to create the strongest hybrid composite. However, after being treated with sodium hydroxide, the hybrid composites containing fiber reinforcement performed better.

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