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INFLUENCE OF POST-TREATMENT AND WATER ABSORPTION ON MECHANICAL PERFORMANCE OF SUSTAINABLE WOVEN FLAX/EPOXY COMPOSITES

Vijay Mohan Shetty[1]

Research Scholar, Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad, 500007, Telangana State, India

Email id: vijaymohan66@gmail.com

M. Madhavi[2]

Professor, Department of Mechanical Engineering, Maturi Venkata Subba Rao (MVSR) Engineering College,

Hyderabad, 501510, Telangana State, India

Email id: madhavimatalpud72@gmail.com

P. Ramesh Babu[3]

Senior Professor, Department of Mechanical Engineering, University College of Engineering,

Osmania University, Hyderabad, 500007, Telangana State, India

Email id: prbmecchou@yahoo.com

Abstract: Sustainable materials, like woven flax/epoxy composites, are crucial for reducing environmental impact and conserving natural resources. They offer an eco-friendly alternative to traditional materials by minimizing carbon emissions and waste. Additionally, these materials contribute to the development of a circular economy, where products are designed for reuse and recycling, extending their lifecycle and reducing the need for virgin resources. Water absorption in composites can lead to swelling, reduced mechanical properties, and degradation of the material over time. This is particularly important in natural fabric composites, where moisture can penetrate the fabric, affecting their structural integrity. Proper post-treatment can mitigate these effects by enhancing the fabric resistance to water, thus maintaining the composite's performance. Composite laminates were fabricated using the hand layup technique, with varying laminate orientations. This study explores the effect of alkali treatment on the mechanical performance of woven flax/Epoxy-reinforced composite laminates. The laminates were treated with 5% and 10% sodium hydroxide (NaOH) to surface for outdoor environmental conditions. The mechanical properties like tensile strength, and flexural strength of the composites were assessed to evaluate the impact of alkali treatment. Results showed that alkali treatment effectively reduced water absorption and among the procedure of testing 5% treated laminates given better results than 10% of alkali treated laminates.

Keywords: Mechanical Properties, Hand layup technique, woven flax fabric, epoxy resin composite**.**

1.Introduction

Natural fibers, such as flax, are gaining increasing attention as sustainable alternatives to synthetic fibers in composite materials. Flax fibers, derived from the flax plant, are lightweight, biodegradable, and environmentally friendly, making them an ideal choice for green composites. These fibers are often combined with polymer matrices, such as epoxy resin, to form composites with improved mechanical properties, suitable for various applications in the automotive,

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aerospace, and construction industries. However, flax fibers have limitations, such as their relatively low bonding strength with resin matrices, which can lead to suboptimal mechanical performance in composites. To address this, various surface modification techniques, including chemical treatments, have been employed to enhance fiber-matrix adhesion and improve the overall properties of flax fiber-based composites. One common and effective chemical treatment is alkali treatment, typically performed using sodium hydroxide (NaOH) solutions. Alkali treatment is known to remove non-cellulosic components like lignin, hemicellulose, and waxes from the fiber surface, resulting in an increase in surface roughness and improved compatibility between the fiber and the resin matrix. This treatment can significantly improve the mechanical properties of flax fiber composites by enhancing fiber-resin bonding, leading to higher strength and stiffness. The hand layup technique, a simple and cost-effective method for composite fabrication, is often used in the manufacturing of natural fiber composites. This method involves manually layering fibers and resin to create a composite structure, followed by curing to form a solid composite material. The orientation of the fibers during this process also plays a critical role in determining the mechanical properties of the final composite.

2.Literature Review

The mechanical properties of flax fiber composites are significantly influenced by the orientation of the fibers during fabrication. The hand layup technique allows for precise control over fiber orientation, which is critical for achieving desired strength characteristics. Studies have shown that unidirectional fibers provide superior tensile strength, while multidirectional or random orientations tend to improve flexural strength by better distributing stress across the composite.

A study by Chandra et al [1] demonstrated that alkali treatment significantly enhanced the tensile strength of flax fiber composites. Alkali treatment with 5% NaOH resulted in a 30% increase in tensile strength compared to untreated fibers. According to Saha et al [2] alkali treatment with higher concentrations (10% NaOH) improves the interfacial bonding between the fiber and resin, leading to better mechanical properties. However, an excess concentration of NaOH led to fiber degradation, which reduced the tensile strength of the composite. According to Gupta et al. [3] flax fiber composites with unidirectional fiber orientation demonstrated superior tensile strength compared to those with random fiber orientations. Additionally, composites with 45-degree angled fibers exhibited better flexibility and impact resistance. Studies such as Dutta et al. [4] have shown that the hand layup method ensures uniform fiber distribution, which is essential for achieving balanced mechanical properties. The orientation of fibers within the layers can be adjusted during the hand layup process to achieve different mechanical properties. Abdu Mohammed et al. [5], developed composite that can be used for automobile interior panels and for housing panels, etc. Also, the FFEPS composite was prepared from expanded polystyrene waste and available flax fibers thus the material is recycled at the end of its life. Santosh Kumar et al. [6], develop green composites from flax–ramie reinforced with bio-epoxy matrix using hand compression molding. The fibers are reinforced unidirectional at 10%, 20%, 30%, and 40% weight fraction and characterized the structural, physical, and tribological behaviour of developed composites. The structural integrity and thermal stability have been analyzed using degree of crystallinity and 2 sophth gravimetric behaviour of composites. Taofeeq D. Moshood et al. [7], this study seeks to comprehensively understand biodegradable plastics production and applications research, product prospects, sustainability, sourcing and ecological imprint. Academic and industry interest in biodegradable plastics for sustainability has exploded in recent years. Venkatesh Naik et al. [8], proposes the use of natural fibers will help achieve the countries sustainable development goals of eradicing poverty, promoting sustainable industrialization, developing sustainable cities and

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societies, and responsible production and consumption of material by creating job opportunities in rural and less developed areas. Albert Hernandez-Estrada et al. [9], This work investigated the impact that the processing of hemp (C. sativa L.) fibre has on the mechanical properties of unidirectional fibre-reinforced epoxy resin composites loaded in axial tension, and particleboard reinforced with aligned fibre bundles applied to one surface of the panel. Nicholas Fantuzzi et al. [10], suggests that material characterization for bio composites used for automotive industrial applications. The mechanical properties are utilized in the design of components of an electric micro-car for the green innovation of automotive industry. Azizatul Karimah et al. [11], Understanding the basic properties of natural fibers is important to determine the optimal intended uses for instance as high-quality bio-composite raw material. This review describes the characteristics, and potential uses of some natural fibers in order to improve their sustainability and economic values. Mohammad Khoirul Huda et al. [12], This literature review focuses on the progress of the development of polymeric materials applied in the automotive field. Referring to defined inclusion and exclusion criteria, 30 articles in polymer composite studies published between 2015 and 2020 were selected for further investigation. Saleem Raza et al. [13], reviewed the synthetic design of renewable biomass-based monomers, and their recently developed important environmental applications. They particularly 3sophth on the synthesis and remarkable applications of bio-based monomers as well as the materials based on them from the perspectives of preparation and environmental applications, because these two are closely related and have been investigated extensively. C. H. Lee, et al. [14], Studied Natural fibres are a gift from nature that we still under 3sophth can be classified into several groups, and bast natural fibre reinforcement in polymer composites has the most promising performance, among others. However, numerous factors have reported influences on mechanical properties of the fibre-reinforced composite, including natural fibre retting processes. S.S. Godara et al. [15], the displacement and stress analysis and design optimization of the automobile vehicle frontal bumper beam is achieved by designing eight different cross sections with the help of mechanical modeling-based software Creo. K. Vijaya Kumar et al. [16], considered bamboo for the analysis in predicting the mechanical performance of natural fiber hybridized with synthetic fibers. The overall results revel that G/B/G/G (45% E-Glass fiber, 15% Bamboo fiber and 40% Epoxy resin) composite specimen offers more mechanical strength than the other three hybrid orders. The numerical analysis results have validated the obtained experimental results. Yadvinder Singh et al. [17], proposed a significant difference in mechanical behavior can be achieved for untreated coir fiber and chemically treated coir fiber reinforcement. A chemically treated coir fiber provides a rougher fibre surface, which is advantageous for interfacial adhesion of coir fiber/matrix, whch leads to mechanical interlocking and lesser pull out. H. Sreenivas, et al. [18], have concluded that Sustainability and increased ecological awareness have encouraged researchers to develop effective and novel materials by exploiting natural sources in the automotive sector. Lightweight, eco-friendly, and sustainable use of natural fiber reinforced composites (NFRC) is increasingly considered by automakers and researchers. Xianghong Li et al. [19], evaluated the synergistic inhibition effect of walnut green husk extract (WGHE) and potassium iodide (KI) on the corrosion of cold rolled steel (CRS) in trichloroacetic acid (Cl3CCOOH) solution by weight loss, electrochemical techniques and surface analysis. Results show that WGHE moderately inhibits the corrosion of CRS in Cl3CCOOH media. Zhong et al. [20] conducted extensive experimental work to examine the hygrothermal performance of CFRP and GFRP composites. To speed up hygrothermal ageing, specimens were immersed completely in a general bath of water that was set to 80°C. The impact test results revealed that the impact characteristics of CFRP composites were improved by absorbed moisture during hygrothermal ageing.

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3.Methodology

The methodology covers the preparation of natural flax/ epoxy laminates using hand layup method and exposed for alkali treatment processes to asses for mechanical testing procedures as per ASTM standards.

Flax comes from the stem of the flax plant of the species Linum usitatissimum. Flax fibre is classified as a natural cellulose, bast and multicellular fibre. When the fibre is processed into fabric, then it is called as Lenin. It is one of the strongest fibres, and it is considered for their strength, durability, and absorbency, as well as their unique texture. In addition to its traditional uses, flax fibre is becoming increasingly popular in modern times as a sustainable alternative to synthetic fibres. and the chemical composition is as shown below Table

Table 1: Structural composition of Flax fibre

Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectins (wt%)	Micro fibril angle (degree)	Moisture content (wt%)
71	18.6–20.6	2.2	2.3	6-7	10

3.1 Materials

- Flax Fibers: Natural flax fibers were sourced from a reliable supplier and used in their raw form without any presentment for the control group. The flax fibers were carefully cleaned to remove any debris or loose fibers before use.

Table 2: Properties of Flax fibre

Fiber	Property	
Flax	Density (g/cc)	1.52
	Fiber diameter (mm)	0.8 - 1.2
	Tensile strength (MPa)	348 – 580
	Youngs Modulus (GPa)	19.8
	Elongation at the breakage (%)	2.9
	Break force (N)	8.2
	Moisture absorption (%)	7

- Epoxy Resin: A commercial-grade epoxy resin system was used as the matrix material. The resin was mixed according to the manufacturer's instructions, ensuring proper curing and optimal bonding with the fibers.
- Sodium Hydroxide (NaOH): Two concentrations of NaOH (5% and 10%) were prepared by dissolving the appropriate amount of NaOH pellets in distilled water. These solutions were used for the alkali treatment of the flax fibers.

3.2 Process of Extraction of Flax fibres

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- **Collection of plants** - when the stems of the plant turn yellow and the seeds turn green to pale brown. The plants are pulled out by the roots. These are tied into bunches as shown in below fig:1
- **Drying and Rippling-** after pulling the Flax, plant is tied in bundles and left to dry for few days. The leaves and seeds are removed from the stems by a process called Rippling. shown in below figure 2 For this, the head of the stem is passed through coarse comb. After the removal of leaves and seeds, the stems are again tied up in bundles.
- **Retting-** this is an important process. The fleshy part of the stem is rotted by contact with water. Retting is a ferment process where the Pectin Ovurum (Pectin eater) bacteria eat the gum(pectin) which bind the fiber to the stem. The following process is done as follows:
- **Dew Retting-** stems are spread out in fields and are exposed to rain, sun and dew for several weeks, until, the stalk begins to separate from the fiber. It takes around 15-30 days. Because of long exposure to the sun and other natural conditions, causes to discoloration of the fiber.
- **Water Retting-** the bundle of the stems is kept in running or segmented water for about 2 weeks. Swift running of water carries away the bacteria and thus slow down the fermentation. The stem bundles are covered with wooden blocks to give extra weight. After 2 weeks the stalks (upper portion of stem) separate out from the fiber and the bundles are taken out of the water and left to dry.
- **Breaking and scutching**- when the stems are completely dry, fiber are separated from these stems when the decomposed woody tissue is dry. It is crushable by passing through iron Rollers. The breaking operation break the outer stalk. It reduces the stalk to small pieces of bark called slivers. Scutching is done with the help of scutching machine which removes the broken slivers by means of rotating wooden peddles, thus releasing the flax fiber from the stem or it separates the fibers from woody stalk.
- **Weaving, finishing & dyeing**- bleaching is given to the yarn and later on dyeing is done. The reason being the Linen yarn is in natural color i.e. grey or yellowish grey. Dyeing cannot be done directly because it is not white in color. That is why bleaching is done before dyeing.

Figure 1: 1) Flax Plant 2) Collection of plants 3) Drying process 4) Rippling process 5) Water retting 6,7) Setup for breaking and scutching of fibres from stalk. 8) Flax fibre rolls 9) Final produced Fabric

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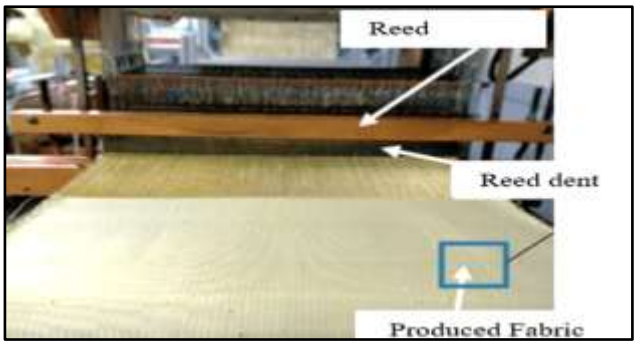

Figure 2: Final Produced Fabric

3.3 Hand layup Technique

The Hand lay-up fabrication process was carried out using basic equipment, often sharing the same molds as compression moulding technique. In this method, a Catalyzed resin was first applied to the surface of the mould. Then, fabric layers were placed individually onto the mould and manually impregnated with resin using brushes and rollers.

Figure 3: Hand layup mold.

3.3.1 Water Absorption:

Water absorption tests of the developed composites were conducted as per ASTM D570 by immersion in distilled water along with 5% of NAOH and 10% NAOH at room temperature for a long time period to reach a stable equilibrium or saturation point.

Figure 4: Treated specimen for water absorption

The samples were taken out after each time interval and water particles are wiped out from the surface of the specimen using filter paper. Samples are weighed immediately within 30 s to avoid error due to evaporation, using an electronic balance (AY220 type, ±0.1 mg accuracy). After weighing, the sample is immersed in the water bath to permit water absorption until the saturation point is reached after 30-45 Days. The weight difference of the specimen gives the value of the water absorption. The water content percentage (Mt), is calculated using Eq (1).

$$M_t(\%) = \frac{W_t - W_o}{W_o} \times 100 \quad \text{..... (1)}$$

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where W_0 - initial weight of the test sample, W_t - weight of the sample at time 't'.

The water absorption behaviour of the sample kept in the water bath can be studied as Fickian behaviour. Therefore, Eq. (2) has been used

$$\frac{M_t}{M_\infty} = 4\left(\frac{Dt}{\pi h^2}\right)^{\frac{1}{2}} \quad \text{..... (2)}$$

Table 3: Maximum water absorption of flax fibre composite at 5 % NaOH

Time (hours)	Weight Gain (%)					
	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
0	0	0	0	0	0	0
24	0.35	0.47	0.43	0.56	0.68	0.78
48	0.68	0.90	0.83	1.08	1.30	1.51
72	0.98	1.30	1.19	1.56	1.88	2.18
96	1.26	1.67	1.53	2.00	2.41	2.79
120	1.52	2.01	1.85	2.41	2.90	3.36
144	1.75	2.33	2.13	2.78	3.35	3.89
168	1.97	2.62	2.40	3.13	3.77	4.37
192	2.17	2.88	2.65	3.45	4.16	4.82
216	2.36	3.13	2.87	3.75	4.52	5.24
240	2.53	3.36	3.08	4.02	4.85	5.62
264	2.69	3.57	3.28	4.27	5.15	5.97
288	2.84	3.76	3.46	4.50	5.43	6.29
312	2.97	3.94	3.62	4.72	5.69	6.59
336	3.10	4.11	3.77	4.92	5.93	6.87
360	3.21	4.26	3.91	5.10	6.15	7.13
384	3.32	4.40	4.04	5.27	6.35	7.36
408	3.42	4.53	4.16	5.43	6.54	7.58
432	3.51	4.65	4.27	5.57	6.72	7.78
456	3.59	4.77	4.38	5.70	6.88	7.97
480	3.67	4.87	4.47	5.83	7.02	8.14
504	3.74	4.96	4.56	5.94	7.16	8.30
528	3.81	5.05	4.64	6.04	7.29	8.45
552	3.87	5.13	4.71	6.14	7.40	8.58
576	3.93	5.21	4.78	6.23	7.51	8.70
600	3.98	5.27	4.84	6.31	7.61	8.82
624	4.03	5.34	4.90	6.39	7.70	8.93
648	4.07	5.40	4.95	6.46	7.79	9.02
672	4.11	5.45	5.00	6.52	7.86	9.11
696	4.15	5.50	5.05	6.58	7.94	9.20
720	4.00	5.50	5.05	6.00	7.00	9.00
744	4.00	5.50	5.05	6.00	7.00	9.00
768	4.00	5.50	5.05	6.00	7.00	9.00
792	4.00	5.50	5.05	6.00	7.00	9.00
816	4.00	5.50	5.05	6.00	7.00	9.00
840	4.00	5.50	5.05	6.00	7.00	9.00
864	4.00	5.50	5.05	6.00	7.00	9.00
888	4.00	5.50	5.05	6.00	7.00	9.00
912	4.00	5.50	5.05	6.00	7.00	9.00
936	4.00	5.50	5.05	6.00	7.00	9.00
960	4.00	5.50	5.05	6.00	7.00	9.00

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Table 4: Maximum water absorption of flax fibre composite at 10 % NaOH

Time (hours)	Weight Gain (%)					
	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
0	0	0	0	0	0	0
24	0.52	0.60	0.84	0.72	0.77	0.75
48	0.99	1.15	1.61	1.39	1.48	1.45
72	1.43	1.66	2.31	2.01	2.13	2.09
96	1.83	2.14	2.99	2.57	2.74	2.68
120	2.21	2.57	3.58	3.10	3.30	3.23
144	2.55	2.97	4.13	3.58	3.81	3.74
168	2.87	3.34	4.66	4.03	4.29	4.20
192	3.17	3.69	5.15	4.44	4.73	4.63
216	3.44	4.00	5.58	4.82	5.13	5.03
240	3.69	4.30	6.00	5.18	5.51	5.40
264	3.92	4.56	6.37	5.50	5.85	5.74
288	4.13	4.81	6.71	5.80	6.17	6.05
312	4.33	5.04	6.71	6.08	6.47	6.34
336	4.51	5.26	6.71	6.33	6.74	6.60
360	4.68	5.45	6.71	6.57	6.99	6.85
384	4.84	5.63	6.71	6.79	7.22	7.08
408	4.98	5.80	6.71	6.99	7.43	7.28
432	5.11	5.95	6.71	7.17	7.63	7.48
456	5.23	6.09	6.71	7.34	7.81	7.66
480	5.35	6.23	6.71	7.50	7.98	7.82
504	5.45	6.35	6.71	7.65	8.14	7.97
528	5.55	6.46	6.71	7.78	8.28	8.11
552	5.64	6.56	6.71	7.91	8.41	8.24
576	5.72	6.66	6.71	8.02	8.53	8.36
600	5.79	6.74	6.71	8.13	8.65	8.47
624	5.86	6.83	6.71	8.23	8.75	8.58
648	5.93	6.90	7.50	8.32	8.75	8.67
672	5.99	6.97	7.50	8.40	8.76	8.76
696	6.04	7.03	7.50	8.40	8.76	8.84
720	6.00	7.00	7.50	8.40	8.76	9.00
744	6.00	7.00	7.50	8.40	8.76	9.00
768	6.00	7.00	7.50	8.40	8.76	9.00
792	6.00	7.00	7.50	8.40	8.76	9.00
816	6.00	7.00	7.50	8.40	8.76	9.00
840	6.00	7.00	7.50	8.40	8.76	9.00
864	6.00	7.00	7.50	8.40	8.76	9.00
888	6.00	7.00	7.50	8.40	8.76	9.00
912	6.00	7.00	7.50	8.40	8.76	9.00
936	6.00	7.00	7.50	8.40	8.76	9.00
960	6.00	7.00	7.50	8.40	8.76	9.00
984	6.00	7.00	7.50	8.40	8.76	9.00

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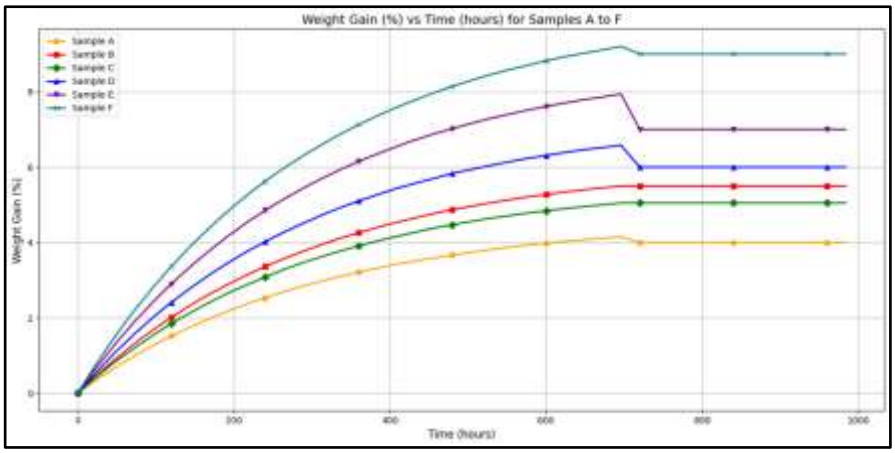

Figure 5: Water absorption behaviour for sample A-F at 5% NaOH

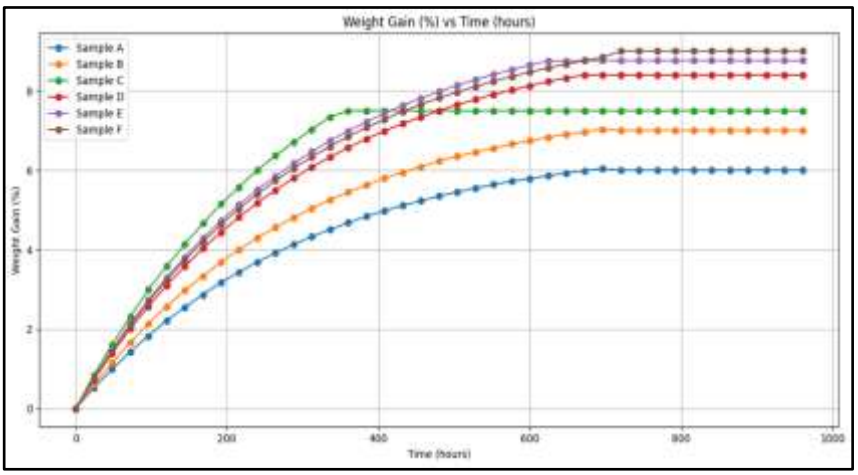

Figure 6: Water absorption behaviour for sample A to F at 10% NAOH

Tensile test :The tensile strength of the composite depends on how well the stress can be transferred from the broken to the surviving fibers through shear in the resin at the interface and the amount of stress a sample can withstand before failure occurred. The Tensile tests were conducted as per ASTM D3039-17 standard as shown in fig 7. Each time the flat specimen of size 250×25×3 mm3 was subjected to uniaxial load at both ends. For finding the properties each specimen was tested and the gauge length was kept as 50 mm and the crosshead speed was maintained at 2 mm/min.

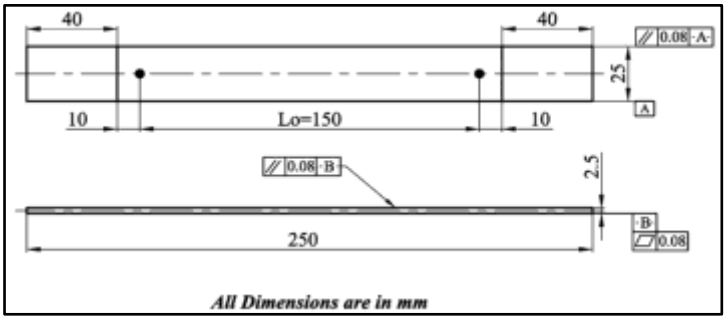

Figure 7: shows ASTM Standard specimen dimensions for Tensile Test

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Figure 8: Specimens for Tensile Test before and after

Flexural Test

Flexural strength is defined as the capability of laminated composites to withstand the bending before reaching the breaking point. The flexural properties were tested using the same machine with special three-point bending attachments. Testing was conducted as per ASTM D790-10 standard as shown in figure The bending test was performed on a 6 flat specimen of different orientations of size 90×12.5×3 mm^3 at a crosshead speed of 2 mm/min considering a beam span of 50 mm

Figure 9: a) Shows the specimens for ASTM Standard test specimen (b) Prepared specimen (c)Flexural test setup (c) Specimens after Test

4. Results and Discussions

The results of the study demonstrate that alkali treatment significantly impacts the mechanical performance of woven flax fabrics used in hand layup composites with variable fiber orientations. In this section, we discuss the findings related to water absorption, tensile strength, flexural strength, and the interaction between fiber orientation and alkali treatment.

The tensile strength of flax fiber-epoxy composite samples was evaluated for both untreated and alkali-treated fibers. The following results outline the tensile strength values observed for the composites at different treatments and conditions

Table 5: shows the Results of Tensile strength for untreated and treated samples.

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Sample No.	TS @ Untreated	TS @ 5% NaOH	TS @ 10% NaOH
Sample A	134.133	125.11	120.91
Sample B	120.11	109.18	108.12
Sample C	117.6	112.21	100.15
Sample D	121.33	100.84	90.78
Sample E	119.733	91.24	80.79
Sample F	118.667	85.34	75.78

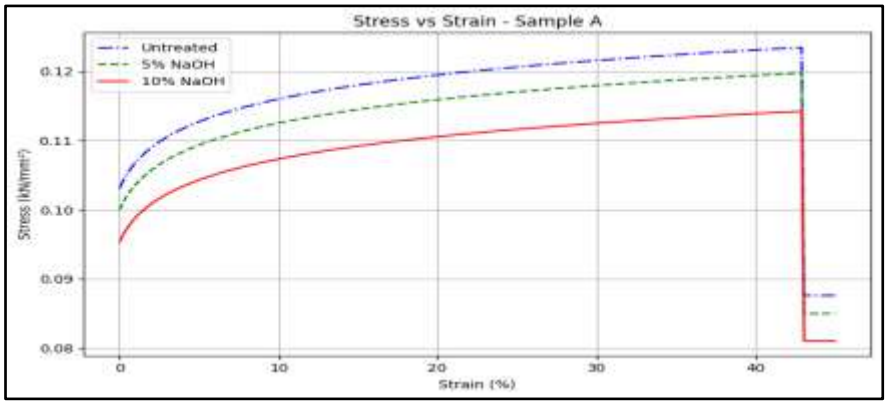

Figure 10: Stress vs Strain curve for sample A at untreated, 5 % & 10% NaOH

The fig 10 Stress vs. Strain curve for Sample A indicates that the highest tensile strength was achieved in samples treated with 5% and 10% NaOH. This improvement is due to the ability of the fibers to align at angles of either 0 degrees or 90 degrees, which enhances their ability to handle the applied load. This orientation allows the fibers to effectively transfer stress along the load path, maximizing mechanical efficiency. Although the tensile strength of the sample treated with 10% NaOH showed a slight decrease, this can be attributed to surface degradation of the fibers caused by the higher NaOH concentration, which likely weakened the fiber-resin bonding. Nonetheless, when compared to untreated fibers, the alkali treatment generally results in improved tensile strength.

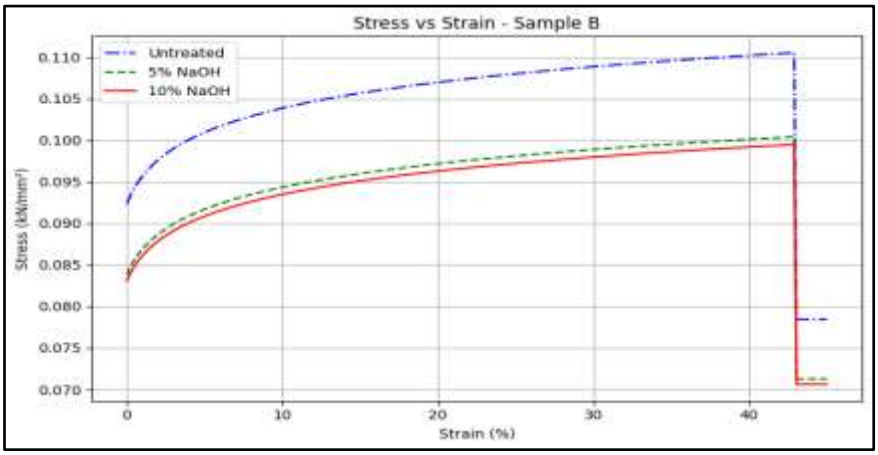

Figure 11: Stress vs Strain curve for sample B at untreated, 5 % & 10% NaOH

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The fig 11 Stress vs Strain curve for Sample B reveals similar trends to Sample A with respect to the impact of alkali treatment on tensile strength. The untreated sample shows a lower initial tensile strength, while both the 5% NaOH and 10% NaOH treated samples exhibit improved performance. However, the 5% NaOH-treated sample outperforms the untreated one, and the 10% NaOH-treated sample displays a further increase in stress, but with a slight reduction in strain before failure, indicating some fiber degradation at the higher NaOH concentration.

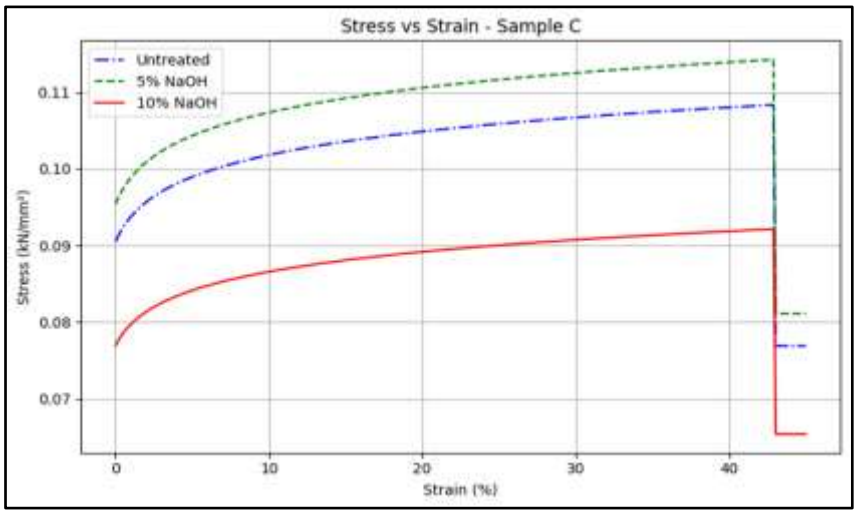

Figure 12: Stress vs Strain curve for sample C at untreated, 5 % & 10% NaOH

In compared to untreated fibres, Sample C has the most significant decrease in tensile strength, with a decrease of -24 MPa, or approximately 19%. The stress-strain curve shows a more gradual increase in stress with strain due to the stress discontinuities created by the alternate orientations in the fibre arrangement. Performance is most drastically reduced in the 10% NaOH-treated sample. This could be because the high concentration of NaOH causes debonding between the fibres and the matrix, or because it creates weak spots at the interface between the fibres and the resin. This indicates that modest alkali treatment can improve bonding, but that larger NaOH concentrations (like 10%) might reduce the composite's strength overall because of structural flaws at the fiber-matrix interface.

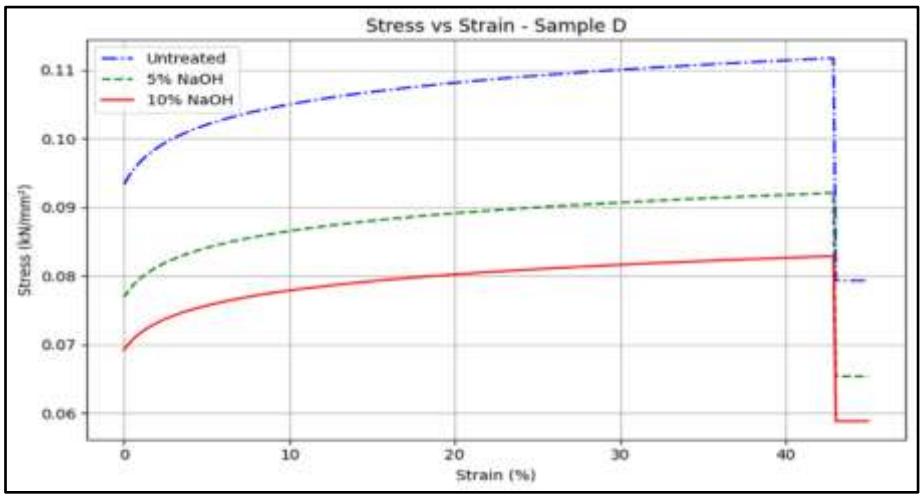

Figure 13: Stress vs Strain curve for sample D at untreated, 5 % & 10% NaOH

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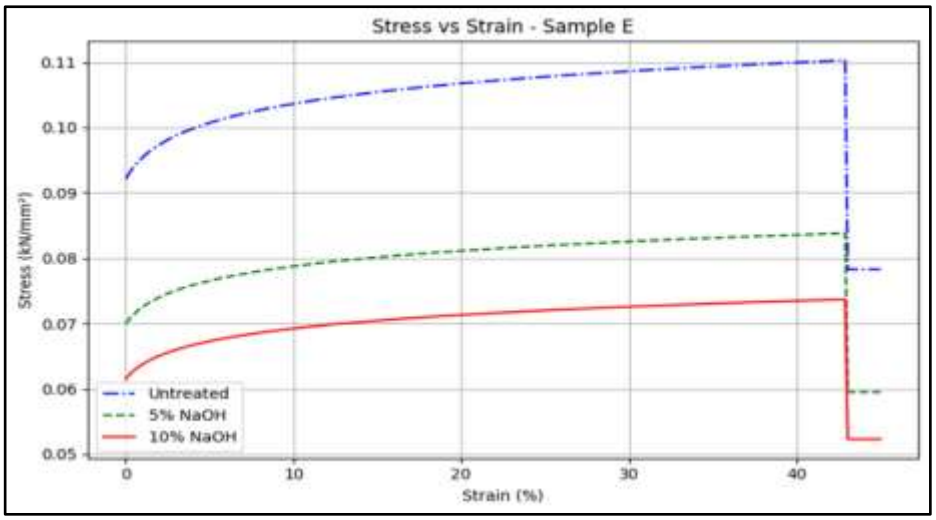

Figure 14: Stress vs Strain curve for sample E at untreated, 5 % & 10% NaOH

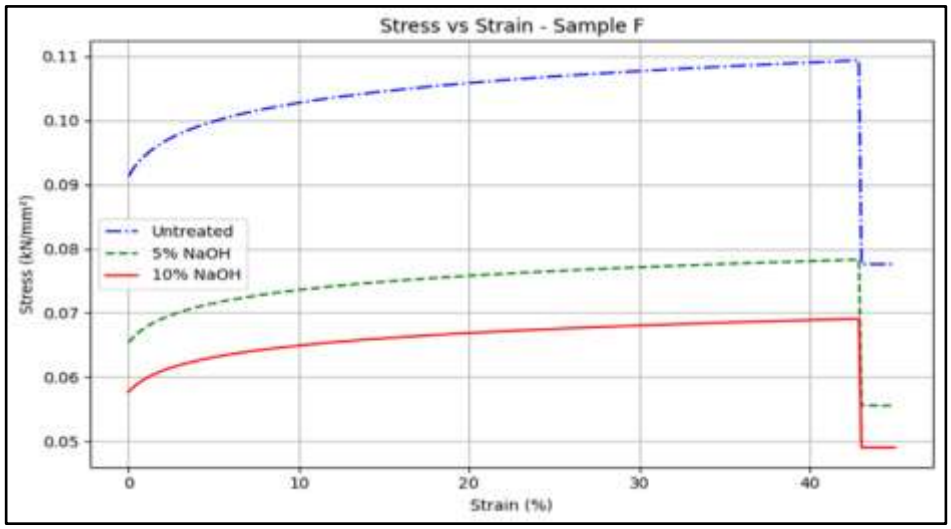

Figure 15: Stress vs Strain curve for sample F at untreated, 5 % & 10% NaOH

Above fig 13,14,15 Samples D, E, and F exhibit a 10-12% reduction in tensile strength after alkali treatment, particularly at the 10% NaOH concentration. This reduction is likely due to weakening of the resin-fiber interface, which leads to increased microcracks and the formation of internal voids within the composite material. The complex hybrid and angle-ply layups in these samples result in non-unified load-bearing directions, meaning the fibers are not all aligned in the same direction to effectively support the applied loads. This lack of alignment reduces the overall structural integrity and load distribution capacity, contributing to the observed decrease in tensile strength. The alkali treatment, while improving some fiber-matrix bonding, may also exacerbate these issues, particularly at higher concentrations.

The flexural strength of the flax fiber-epoxy composite samples was measured to assess the impact of alkali treatment on their bending resistance. Flexural tests were performed following the ASTM D790 standards to determine how well the composites could resist bending stresses under load.

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Table 6: Flexural strength for untreated and treated samples results

Sample No.	FS @ Untreated	FS @ 5% NaOH	FS @ 10% NaOH
Sample A	168.775	115.12	110.22
Sample B	160.899	95.8	92.43
Sample C	162.222	100.11	96.34
Sample D	163.556	110.22	106.67
Sample E	161.33	105.83	100.15
Sample F	159.899	90.23	87.21

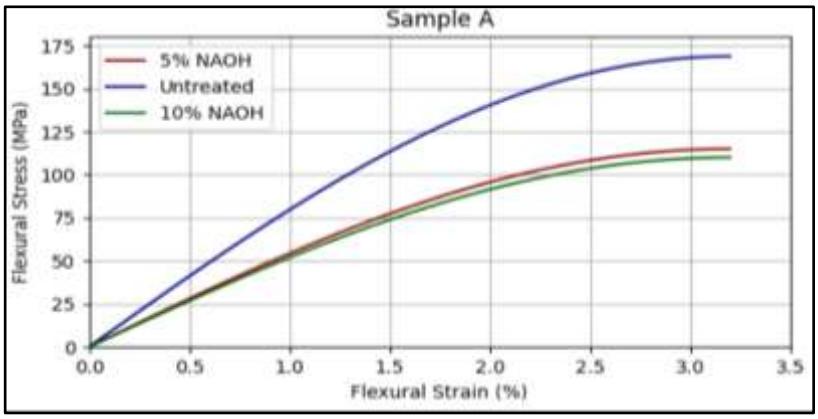

Figure 16: Stress vs Strain curve for sample A at untreated, 5 % & 10% NaOH

The flexural strength of Sample A decreased gradually due to water absorption, with the 10% NaOH treated sample showing fig 16 a sharp decline. This is primarily because the water weakens the fiber-matrix adhesion, causing the fibers to shift relative to the matrix. As a result, stress transfer becomes less effective, leading to reduced flexural strength

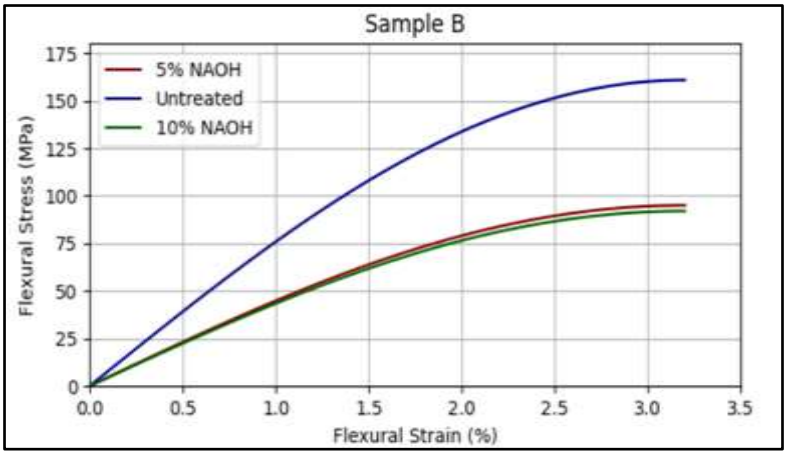

Figure 17: Stress vs Strain curve for sample B at untreated, 5 % & 10% NAOH

The flexural strength of woven flax/epoxy composites in Sample B decreased with increasing water absorption. While water weakens the fiber-matrix adhesion, the damage plateaus after reaching a saturation point, as seen between the 5% and 10% NaOH treated samples. The minimal decline between these two levels suggests that beyond a certain point, additional water does not significantly further damage the composite.

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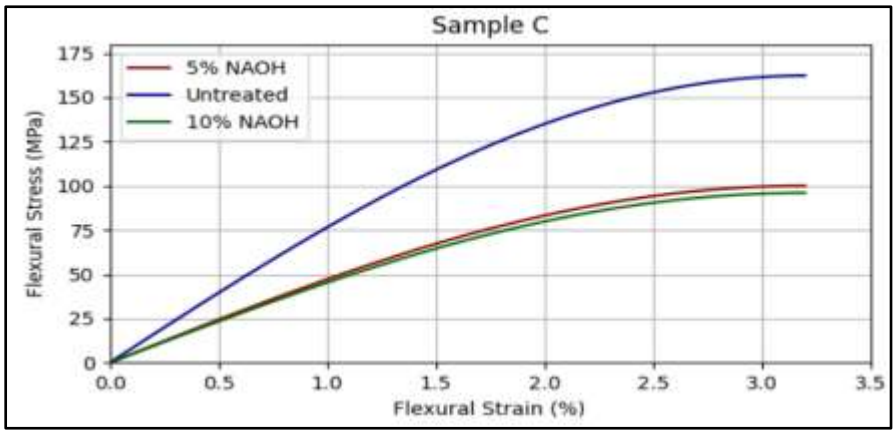

Figure 18: Stress vs Strain curve for sample C at untreated, 5 % & 10% NaOH

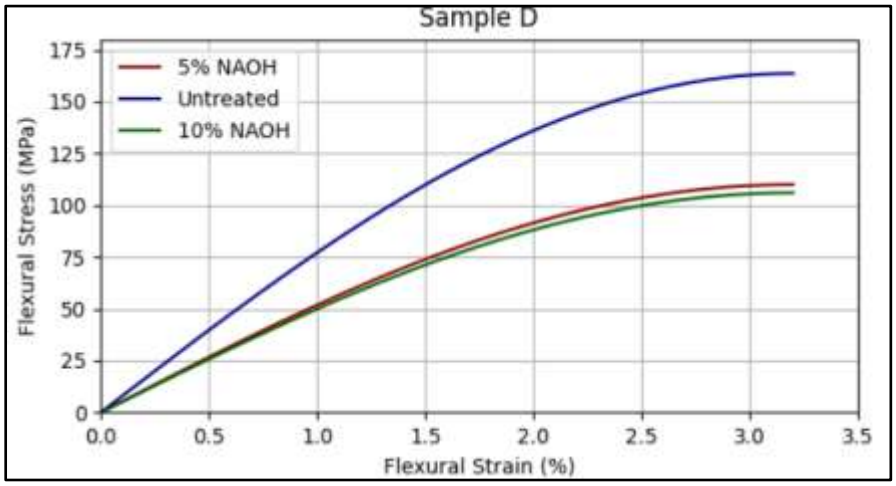

Figure 19: Stress vs Strain curve for sample D at untreated, 5 % & 10% NaOH

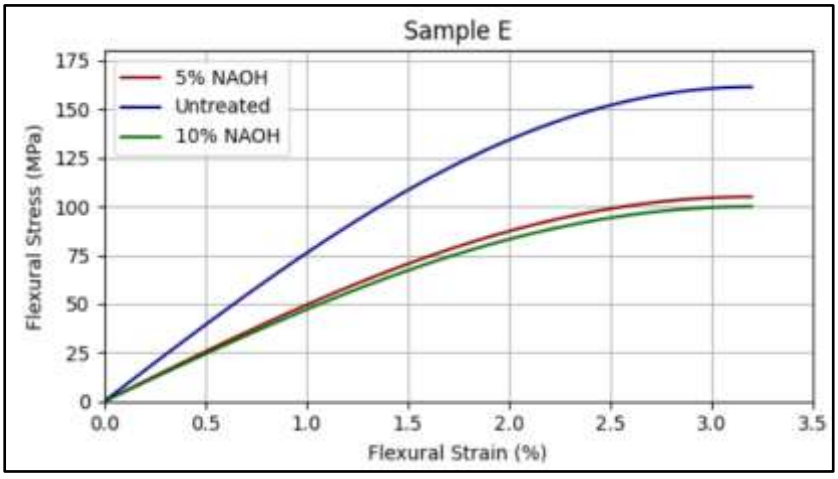

Figure 20: Stress vs Strain curve for sample E at untreated, 5 % & 10% NaOH

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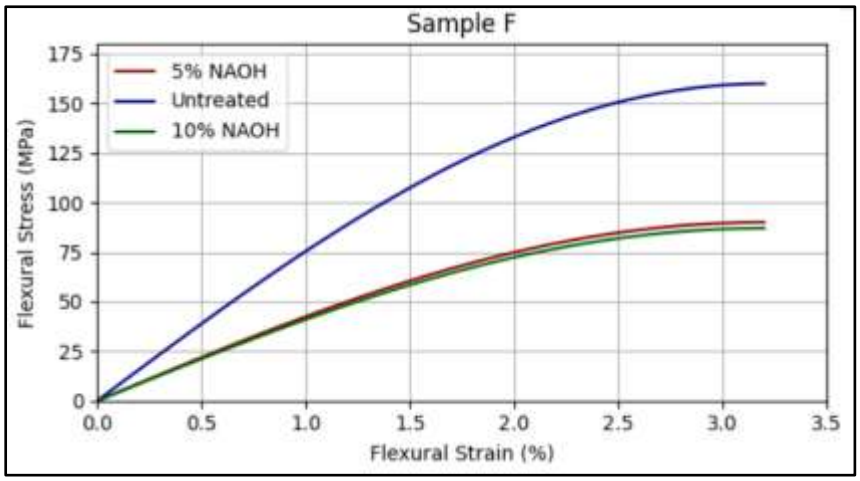

Figure 21: Stress vs Strain curve for sample F at untreated, 5 % & 10% NaOH

From the above fig. 18 to 21 It was observed that the mechanical properties of the woven flax/epoxy composite, particularly its flexural strength, gradually declined with increased water absorption. This degradation is primarily attributed to the weakening of fiber–matrix adhesion due to water ingress, which compromises interfacial bonding. As water penetrates the composite, it disrupts the load transfer efficiency between fibers and the matrix, leading to relative fiber slippage and overall reduction in structural integrity. However, the difference in flexural strength between the 5% and 10% water absorption levels was minimal, suggesting the presence of a saturation point. Beyond this threshold, further moisture uptake has a diminishing impact on mechanical performance. This plateau may indicate that most of the accessible interfacial sites susceptible to hydrolytic degradation have already been compromised, and additional water primarily occupies voids or less critical regions of the matrix.

5. Conclusions:

This study investigated the effect of alkali treatment on the mechanical performance of woven flax fabrics used in hand layup composites, with a particular focus on the influence of fiber orientation and treatment concentration (5% and 10% NaOH). The key findings of the research can be summarized as follows.

From the above results show a consistent trend across all six samples (A–F): both tensile strength (TS) and flexural strength (FS) decrease progressively with increasing NaOH concentration from untreated → 5% NaOH → 10% NaOH treatment.

- Tensile Strength (TS): Untreated samples consistently exhibit the highest tensile strength. For example, Sample A drops from 134.13 MPa (untreated) to 125.11 MPa (5% NaOH) and 120.91 MPa (10% NaOH).
- Flexural Strength (FS): Similarly, flexural strength reduces after alkaline treatment. Sample A shows a reduction from 168.78 MPa (untreated) to 110.22 MPa at 10% NaOH.
- Across all samples, Sample A consistently demonstrates the highest mechanical strength in both untreated and treated conditions, suggesting it has the most favorable fiber orientation or internal structure. Sample F generally exhibits the lowest mechanical performance post-treatment, highlighting its sensitivity to alkaline degradation.

Alkaline (NaOH) treatment reduces both tensile and flexural strength of the samples across all orientations (A–F), with strength loss increasing with higher NaOH concentration. This suggests that while mild alkali treatment may slightly preserve properties (e.g., 5% NaOH), harsher treatments (10%)

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significantly compromise mechanical integrity. Sample A stands out as the most mechanically robust orientation in all conditions

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