Investigate the Effects of Fiber Surface Chemical Treatment on the Mechanical Properties of Bamboo Fiber Reinforced Polyester Resin Composites

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Abstract. The main objective of this study is to investigate the effects of the fiber surface treatment on the mechanical properties of bamboo fiber reinforced polyester resin composite materials for different applications. To investigate the mechanical properties of the materials different chemical treatments and experimental testing setups have been used. Four different types of testing samples were prepared from bamboo fiber reinforced polyester resin composites using untreated bamboo fiber, 10 Vol% NaOH treated bamboo fiber (10TBF), 20 Vol% NaOH treated bamboo fiber (20TBF), and 10 Vol% NaOH plus corn starch soaked for 30 min treated bamboo fiber. To characterize the mechanical properties of the fabricated composite materials, the WAW 1000D hydraulic universal tensile testing machine with ASTM ISO-6892 standard, ABAQUS CAE finite element analysis, and GOM Correlate Software integrated digital image correlation (DIC) analysis were used. The results obtained indicate that the use of higher volume percentage of NaOH treatment chemical leads to uniform distribution of stress fields on the surface of materials. In addition to that, the use of 10 Vol% NaOH plus corn starch soaking of bamboo fiber gives improved elastic and elongation properties.

Keywords: Bamboo fiber · Tensile test · Mechanical properties · NaOH · Corn starch · DIC tensile test · Finite element analysis

1 Introductions

A composite material commonly consists of two or more materials constituents in which one of the constituent materials is the reinforcing phase which can be in the form of fibers, sheets, or particles embedded or segregated in the matrix phase. The constituents of composite materials have different physical and chemical properties with separate and distinct individual properties. The primary phase of composite material is termed as a matrix having a continuous character and acts as a binder and holds the

M. L. Berihun (Ed.): ICAST 2021, LNICST 412, pp. 350–364, 2022.
https://doi.org/10.1007/978-3-030-93712-6_24

fibers in the desired position thereby transferring the external load to the reinforcing phase [1].

Most modern industrial components such as wind turbine blades, aircraft, ships and automotive parts are manufactured from a massive number of synthetic fibers composites. Modern composite materials consisted of a significant proportion of the engineered materials market ranging from everyday products to sophisticated comfortable applications such as in the field of mining and metallurgy, in hydraulic components and water tanks, in the cryogenics fuel tank, for a helmet and in transparent roofs. It is also known that composite materials have proved their usefulness as weight-saving materials. Composite materials have taken a large share of the manufacturing sector as a source material to produce different parts and the most commonly used synthetic fibers are glass, carbon, basalt, aramid fibers and others. However, these synthetic fibers have many drawbacks from the fact that their non-degradable behavior incurred disposal challenges, recycling problems and environmental impact which leads to enormous pollution to the surrounding environment. In response to this challenge, researchers are working on sustainable and recyclable materials to replace synthetic materials with natural and zero-waste economy materials. Currently, attention has been given to materials such as natural fibers including bamboo, jute, sisal, and other agricultural byproducts for engineering applications to control environmental degradation and to minimize materials cost [2]. Natural fibers which are mostly composed of cellulose such as hemp, sisal, kenaf and bamboo are used as a replacement for glass fibers (or synthetic fibers) in polyester-based composite due to the low cost of raw materials, low density, availability and environmental friendly [3].

Bamboo fiber is characterized as a highly energy-efficient, renewable and biodegradable natural resource with great potential to replace synthetic fiber. The strength-to-weight ratio of bamboo fiber is comparatively higher than conventional metallic fibers. Bamboo fibers are often known as natural glass fibers due to their high strength to their weight derives from fibers longitudinally aligned in their body [4]. Lignin, cellulose and hemicellulose are the important components in bamboo and these components constitute 90% of the total weight of bamboo [5]. Ethiopia has about 1 million hectares of highland and lowland bamboos. Thus, 67% of African bamboo resources and more than 7% of the world's total area are found in Ethiopia [6].

Currently, studies have generally trying to address the treatment of fibers to improve the performance of natural fiber composites and expand their industrial applications. One of the most effective methods used for improving the properties of natural fiber composites is applying a chemical treatment of fiber surface to enhance a matrix to fiber interface bonding and uniform distribution of matrix and fiber mixture to achieve optimum properties [7].

Bamboo fiber has several advantages over other natural fibers such as high growth rate, strength, and fixing the carbon dioxide. Also, it can be compared with glass fiber because of its lightweight, biodegradability, and low cost. Therefore, there is a great interest in using bamboo fiber as reinforced composite material in different applications. Several methods and adhesions have been used to improve the mechanical properties of bamboo fibers as reinforced composite. This can help to comprehend that bamboo fiber and bamboo fiber-reinforced composite can be used in more applications. In this study, NaOH chemical fiber treatment and corn starch soaking have been considered to improve the bamboo fiber surface roughness and other elastoplastic properties [8].

2 Materials and Methods

The bamboo fiber was extracted manually and the densities of bamboo fiber were tested using a pycnometer. The NaOH treated bamboo fiber reinforced composites were manufactured by hand-layup and compression techniques in a random orientation with fiber to polyester resin matrix ratio of 30:70 [9]. In this composite sample fabrications, the compression pressure at the time of curing was 0.027 MPa and the composite sample specimen were cured for 24 h at room temperatures [10]. The mechanical properties of the polyester resin reinforced with sodium hydroxide (NaOH) treated bamboo fiber composite materials were investigated. The samples of bamboo fiber composite materials with pure bamboo fiber, 10 Vol% NaOH (10TBF), 20 Vol% NaOH (20TBF), and 10 Vol% NaOH treated plus soaked with corn starch chemicals (STBF) for 30 min were used for the characterization of mechanical properties. The bamboo culm was collected from highland areas around Injibara city, in the North-Western part of Ethiopia as a green form. The sodium hydroxide (NaOH) and corn starch chemicals were purchased from the local market in Bahir Dar. And also, polyester resin and its hardener were taken from the poly fiber private manufacturing company in Bahir Dar.

The bamboo culm was peeled to obtain the strips and bundles of strips were soaked in water for three days, subsequently, the wetted strips were beaten and scraped with a sharp-edged knife and combed. It is commonly known that the physical process of scraping had a strong effect on the fiber quality and breakage which needs the careful scraping process [8, 12]. As shown in Fig. 1, the retting extraction method was used to extract fiber from the scraps which is one of the methods of many forms of mechanical extraction methods such as the steam explosion method, crushing, grinding, rolling in a mill, and retting. Mechanical extraction methods are used for the extraction of bamboo fiber for various applications in industries for making bamboo fiber-reinforced composites [8, 12]. The fibers extracted using a grinding method and crushing method are mostly used for particle composite fabrication [5]. Bamboo fibers can be used to reinforce both thermosetting and thermoplastic matrices. Thermosetting resins such as epoxy, polyester, polyurethane, phenolic are commonly used matrix materials in composites for higher performance applications [13, 14]. In this study, polyester resin, sodium hydroxide (NaOH), corn starch, treated and untreated bamboo fibers materials were used to fabricated bamboo fiber reinforced polyester resin matrix composite.

2.1 Treatment Methods

In this study, both sodium hydroxide (NaOH) and corn starch chemical treatments have been used to see the effects of bamboo fiber surface modification on the mechanical properties enhanced by the fiber-matrix interface bonding variations. Different treatment methods can be used to modify the bamboo fiber surface including alkali, acetyl, saline, enzymatic and other coupling agents. Alkali treatment method is one of the

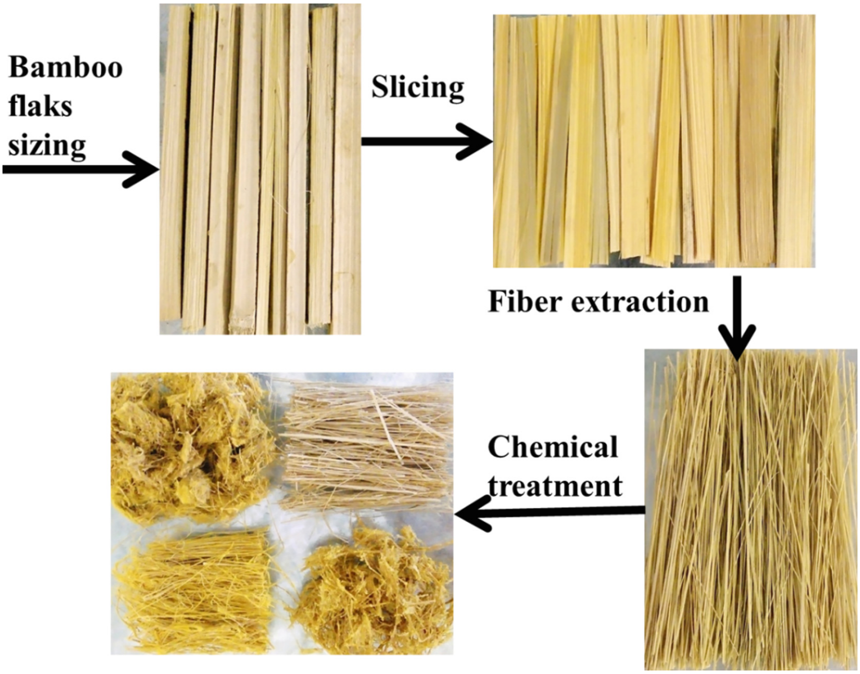

Fig. 1. General process layout of the retting bamboo fiber extraction method used to extract fiber for further chemical treatment applications.

simplest and most effective bamboo fiber treatment methods which can easily remove lignin. The most widely used chemical in the alkaline treatment process is sodium hydroxide (NaOH) solution [10, 16]. In addition to that, corn starch was used to further enhance the roughness and hardness of the fiber surfaces [17].

2.1.1 NaOH Treatment of Bamboo Fiber

Alkali treatment can make the fiber surface clean and rough by removing waxes, hemicellulose, pectin and parts of lignin. The removal of these fatty-like components from the bamboo fiber can lead the fiber to have low moisture absorption properties, reduce fiber weight, improve fiber roughness and its adhesive property at the fiber-matrix interface, and also improve fiber rigidity and stiffness [18, 19]. Before the process of alkali treatment, the bamboo fibers need to be washed thoroughly with tap water to remove any debris, dirt, and undesired particles and then, dried at room temperatures for more than seven days [20].

The bamboo fibers were treated with sodium hydroxide (NaOH) solution at 10%, and 20% volume (Vol%) of concentration in water as shown in Fig. 2. The bamboo fibers were soaked in NaOH solutions for 72 h at room temperature. In addition to that bundles of the bamboo fibers were treated with 10 Vol% of NaOH solutions for 72 h and soaked in corn starch chemicals for 30 min. The bamboo fibers were then washed with cold water and distilled water to remove absorbed alkali from the fiber. The washed fibers were dried at room temperature for four weeks to remove the moisture from the bamboo fiber. The dried fibers were stored in a sealed plastic bag to avoid atmospheric moisture contaminations before the composite manufacturing process or fabrications.

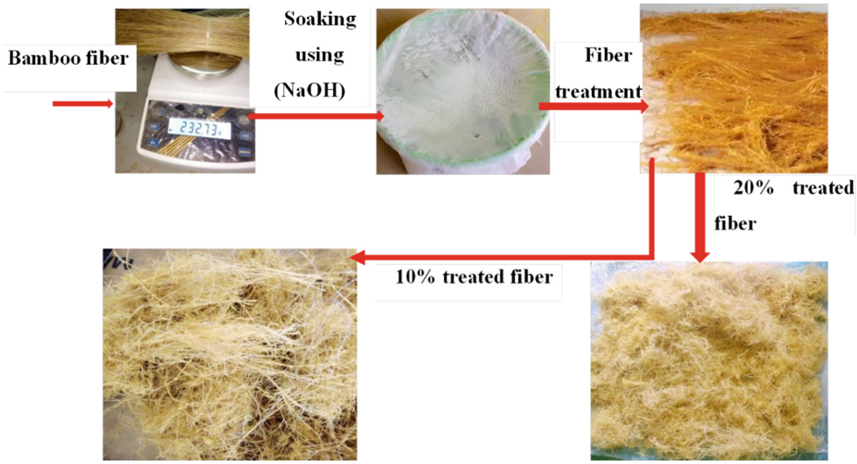

Fig. 2. Illustrations of bamboo fiber treatment process using sodium hydroxide (NaOH) chemical solution

2.1.2 NaOH (10 Vol%) Plus Corn Starch Soaking Treatment of Bamboo Fiber

During the corn starch chemical treatment process, the bamboo fiber was treated with 10 Vol% NaOH for 72 h, dried for one month at room temperature, and then, the bamboo fiber was further treated with corn starch chemical. The corn starch chemical to water ratio was determined based on the Bahir Dar Textile Share Company manual guide. The manual guide states that for 50 kg corn starch flour, 600-L water is needed. Based on this information, 0.5 g corn starch flour was used and the amount of water needed for 0.5 g corn starch flour was calculated. The amount of water needed for the given fiber composite materials and corn starch flour was 6 L. The corn starch treatment process considers boiled water at (100 °C) using a digital stove water boiler, subsequently, the bamboo fiber and corn starch flour were inserted into the beaker and cooked for 30 min and also stirred continuously for the uniform cooking of the bamboo fiber. After finishing the cooking process the bamboo fiber was dried at room temperature and made ready for a composite manufacturing process, as shown in Fig. 3.

Fig. 3. NaOH (10 Vol%) and corn starch soaking treated bamboo fiber.

2.2 Experimental Setup for Tensile Test

As shown in Fig. 4, a WAW 1000D hydraulic universal tensile testing machine was used with an overhead displacement of 0.1 mm/min. The ASTM ISO-6892 standard dimensions of three samples were taken for the tensile test of each type of sample specimen.

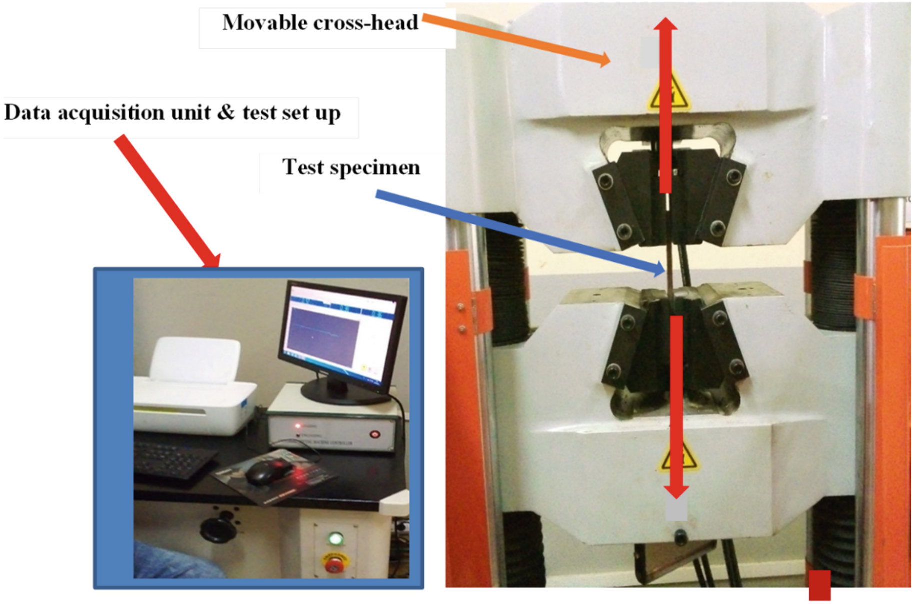

Fig. 4. Graphical illustration for the experimental tensile test setup.

2.3 Finite Element (FE) Analysis Using ABAQUS CAE

The tensile test sample specimens with ASTM standard dimensions were modeled using finite element analysis ABAQUS CAE Software. By considering the random fiber orientations and the complexity of length variations, the composite materials were taken as an anisotropic material during FE modeling. As indicated in Table 1, all the basic mechanical properties of each type of material were taken from the tensile test experimental results to fill in the ABAQUS CAE material property options. The number of elements was determined based on the mesh convergence analysis of each type of specimen and the hexagonal mesh 3D solid element type was considered for modeling each composite sample material. In this case, the number of elements for the tensile test model is 160. The convergence test was done with different mesh densities and the least percent of error of maximum stresses was selected to generate the FE analysis results. The convergence test percent error for pure bamboo fiber (PBF), 10 Vol% treated bamboo fiber (10TBF), 20 Vol% treated bamboo fiber (20TBF) and 10 Vol% plus corn starch treated bamboo fiber (STBF) was 0.058%, 0.050%, 0.18% and 0.19% respectively. Figure 5(a) shows the boundary conditions and applied load and Fig. 5(b) shows the mesh type.

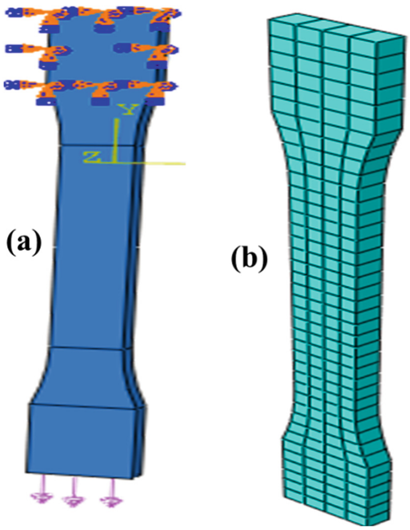

Fig. 5. The ABAQUS CAE tensile test FE analysis. (a) boundary conditions and (b) mesh type

2.4 Digital Image Correlation (DIC) Experiment

For the purpose of digital image correlation (DIC) analysis, a 120 mm × 15 mm × 5 mm tensile test specimens with 6 mm diameter center hole has been prepared from pure bamboo fiber, 10 Vol% TBF, 20 Vol% TBF and 10 Vol% TBF plus corn starch soaking for 30 min treated bamboo fiber/polyester resin composite materials. To capture the stress field distribution around the circular hole during the DIC tensile test, the surface of the specimen was cleaned and painted with black and white paints. In addition to that, the position of the camera has been adjusted at 90° to the surface of a specimen. Subsequently, a continuous video was recorded and saved during the tensile test process [21]. The recorded videos were analyzed in GOM correlate soft-ware strain analysis to calculate the strain fields present in the composite sample specimen materials. The DIC experimental test setup has been represented as shown in Fig. 6 below.

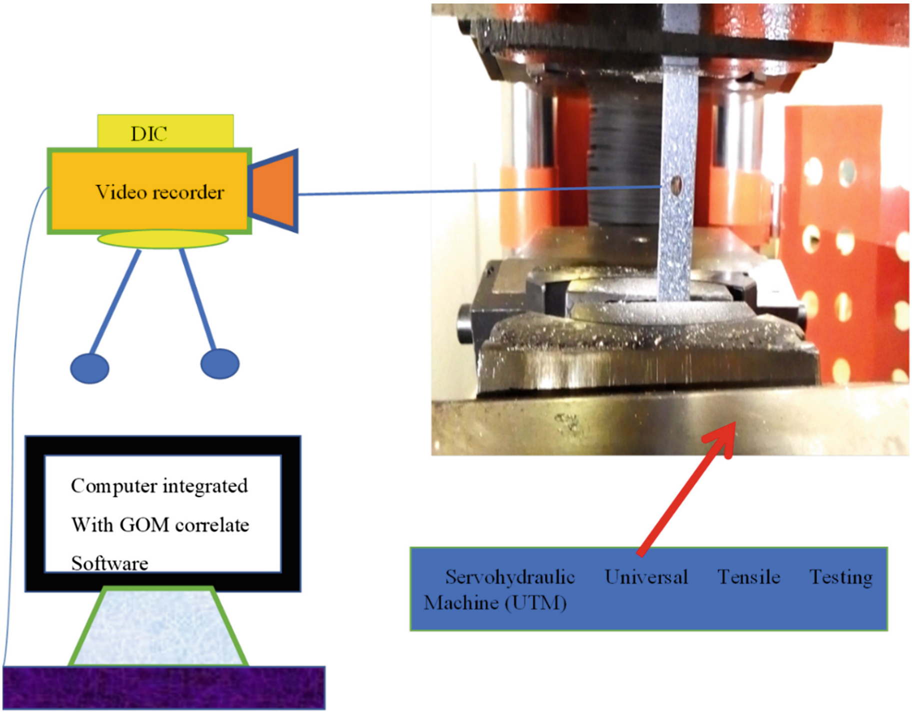

Fig. 6. Schematic representations of DIC experiment tensile test setup.

3 Results and Discussions

3.1 Tensile Test Experimental Measurements and Results

As illustrated in Fig. 7 and Table 1, the mechanical properties of pure bamboo fiber reinforced polyester composite have the maximum values. However, the flexibility and its industrial applications of the as-extracted pure bamboo fiber are very low compared to the processed (treated) bamboo fibers. To exploit the potential applications of bamboo, the bamboo fiber chemical solution treatment is cost-effective and an easy approach. In this study, NaOH solution treatment has been considered to remove the unwanted parts of the bamboo fiber to enhance the required properties. As shown in Table 1 below, the 10 Vol% NaOH plus corn starch soaking for 30 min treatment of bamboo fiber improves the yield strength and elongation properties compared to 10 Vol % NaOH, and 20 Vol% NaOH solution treated bamboo fiber polyester resin composite materials. As observed in Fig. 2, the 10 Vol% NaOH plus corn starch soaked for 30 min treated bamboo fiber surface roughness looks improved compared to the results obtained by 10 Vol% NaOH, and 20 Vol% NaOH solution treated bamboo fibers as shown in Fig. 3 which indicates the significant effect of corn starch to improve the bamboo fiber surface roughness.

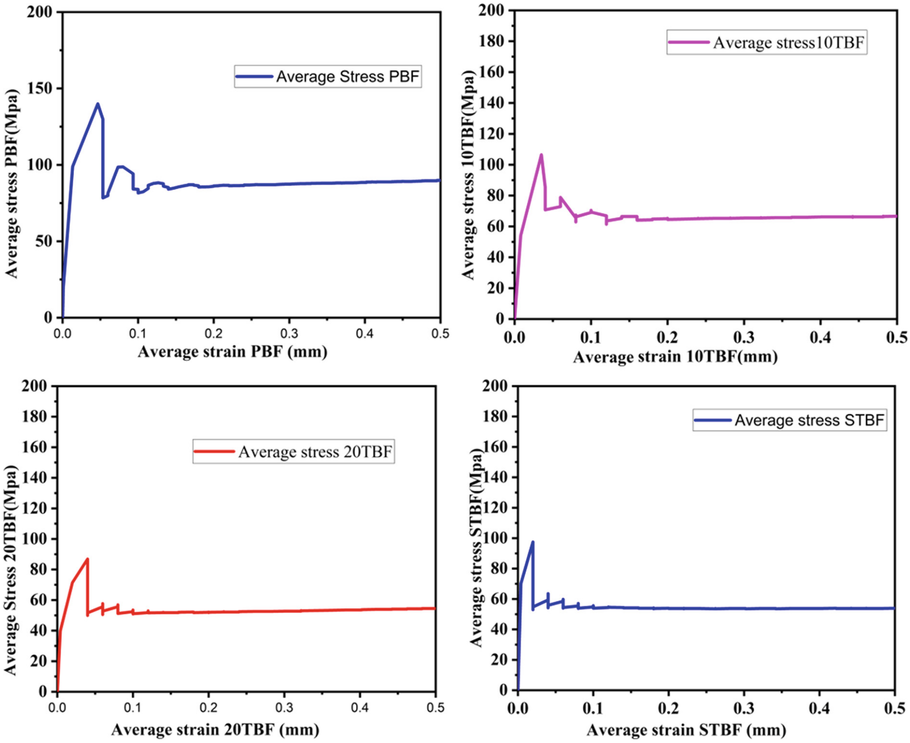

Fig. 7. The stress-strain relations bamboo/polyester composite materials were obtained by experimental tensile test.

The ultimate tensile strength (UTS) and young's modulus of a 10 Vol% NaOH treated bamboo fiber shows the maximum values compared to the 20 Vol% NaOH treated (20TBF) and the 10 Vol% NaOH plus corn starch soaked for 30 min treated bamboo fiber reinforced polyester resin composites. The results obtained from the experimental tensile test lead to the generalization that the use of a higher volume percentage of NaOH reduces the brittleness and rigidity of bamboo fiber. Furthermore, the use of corn starch integrated with NaOH can enhance the ductility and surface roughness of bamboo fiber.

Table 1. Mechanical properties of the average tensile strength of bamboo fiber/polyester resin composite materials

Treatment type	Mechanical properties of composite materials			
	Yield strength (MPa)	Ultimate strength (UTS) (MPa)	% Elongation @ break	Young's Modulus (GPa)
Pure bamboo (PBF)	98.93	139.98	5.56%	14.84
10TBF	54.05	106.43	3.86%	10.68
20TBF	39.81	86.86	3.189%	7.14
Corn starch TBF	70.21	97.5	5.245%	8.78

3.2 Finite Element (FE) Analysis Results Using ABAQUS CAE

The finite element analysis using ABAQUS Software gives similar trends of stress variations with the experimental tensile test results. As shown in Fig. 8 (a), the maximum stress was recorded in the untreated bamboo fiber. Next to the untreated bamboo fiber, the 10 Vol% NaOH solution treated bamboo fiber showed the maximum stress value as shown in Fig. 8 (b). Due to the loss of brittleness and rigidity of fiber, the 20 Vol% NaOH and 10 Vol% NaOH plus corn starch soaking treatment lead to lower stress values compared to the previously described treatment solutions.

3.3 Digital Image Correlation (DIC) Analysis Results

The DIC strain measurement was done by using the GOM correlate software integrated with tensile test experiments. The DIC analysis can give detailed information on the fiber-matrix interface bonding and the effects of surface/subsurface inclusion distributions on the stress-strain distribution patterns. As shown in Fig. 9, the stress field fluctuations are very high, even though the stress field values are maximum at the final recording time. The highest stress field fluctuation in the untreated bamboo fiber reinforced polyester composite indicates the highest mismatch of mechanical properties between the fiber and the matrix. Compared to all the four DIC specimens, the 20 Vol% NaOH treated bamboo fiber reinforced polyester composite shows the uniform stress field distributions as shown in Fig. 11, due to its enhanced surface roughness which can lead to strong bonding between the fiber and matrix interface. Similarly, the fiber surface roughness enhanced by corn starch soaking treatment leads to both stress field uniformity and stress carrying capacity of the composite as illustrated in Fig. 12 (Fig. 10).

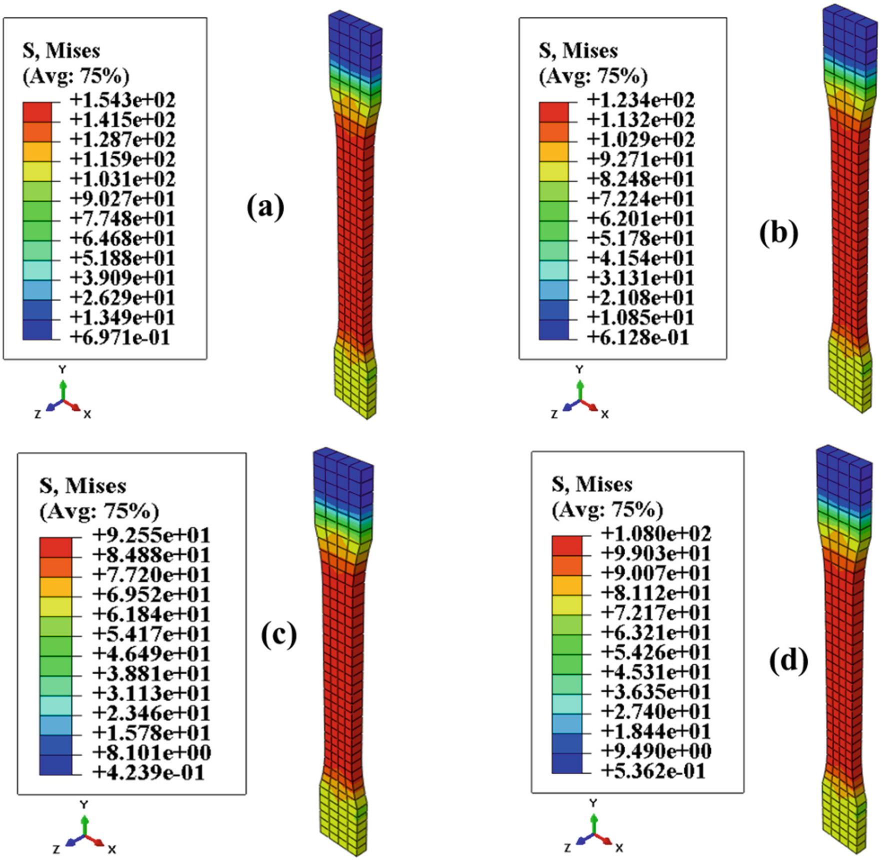

Fig. 8. ABAQUS finite element (FE) analysis results in the contour plot. **(a)** pure, **(b)** 10 Vol% NaOH treated, **(c)** 20 Vol% NaOH treated, and **(d)** 10 Vol% NaOH plus corn starch soak for 30 min treated bamboo fiber reinforced polyester composites

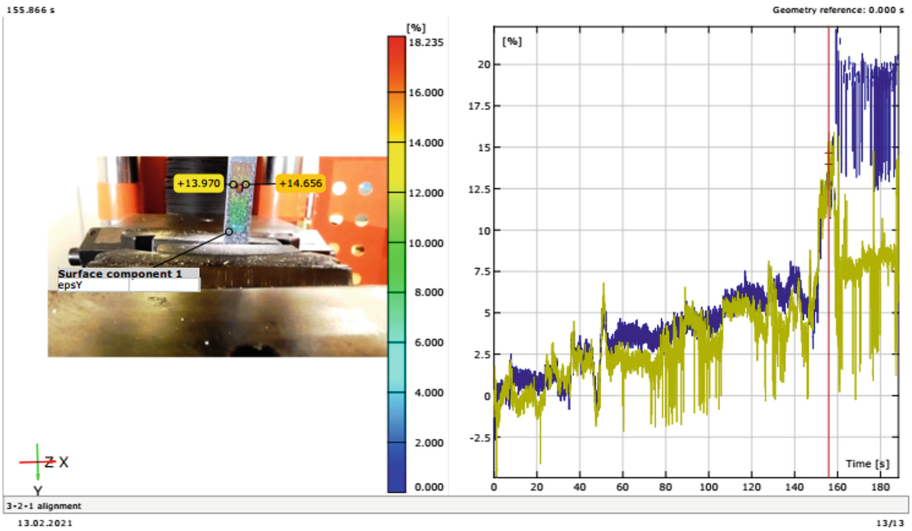

Fig. 9. DIC tensile test strain analysis using GOM correlate software for untreated bamboo fiber

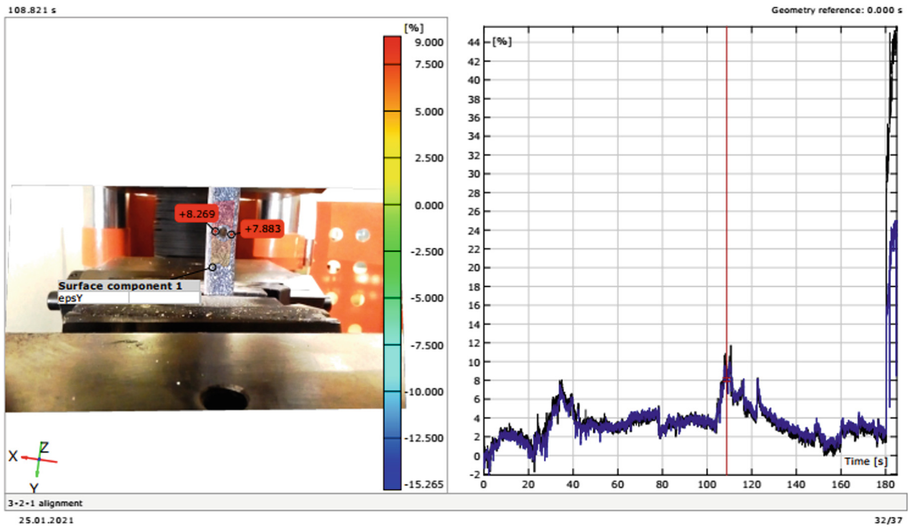

Fig. 10. DIC tensile test strain analysis using GOM correlate software for 10 Vol% NaOH treated bamboo fiber.

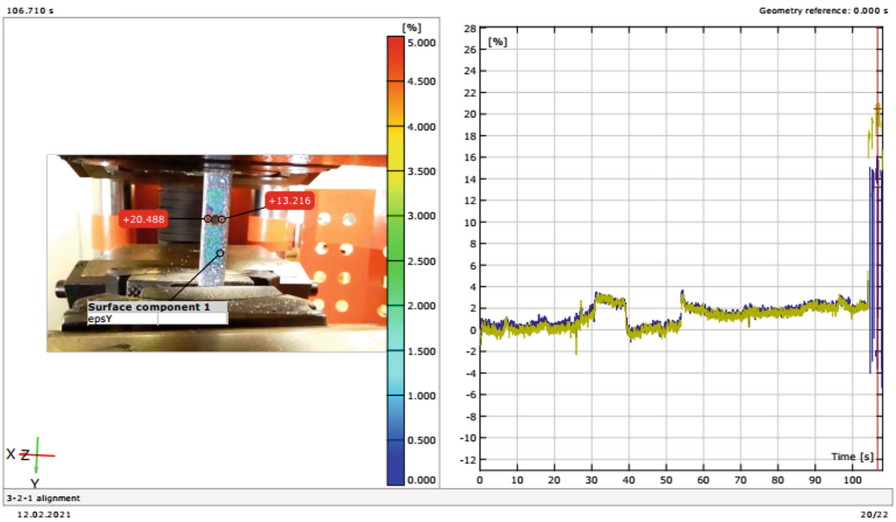

Fig. 11. DIC tensile test strain analysis using GOM correlate software for 20 Vol% NaOH treated bamboo fiber.

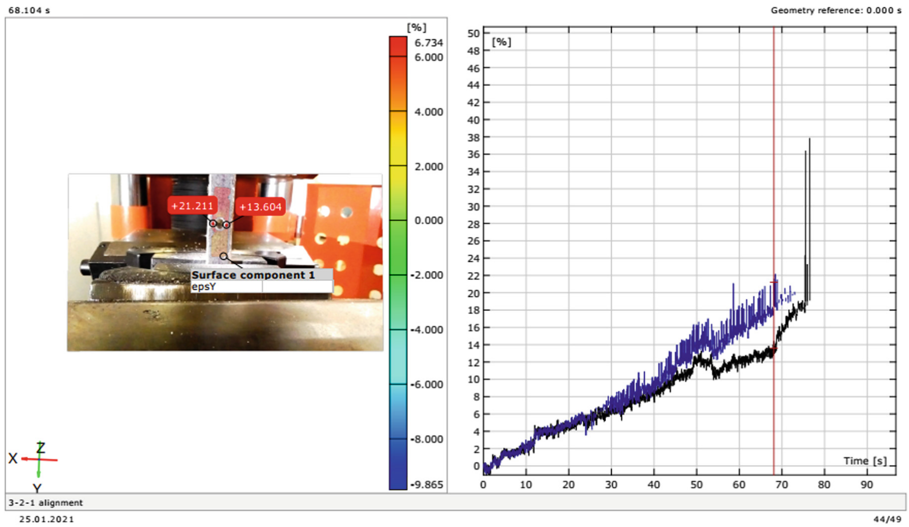

Fig. 12. DIC tensile test strain analysis using GOM correlate software for 10 Vol% NaOH plus corn starch treated bamboo fiber.

4 Conclusions

The results obtained from the experimental and finite element analysis lead to the following conclusions:

- The use of a higher volume percentage of NaOH treatment chemicals leads to improved uniform stress field distributions on the surface of bamboo fiber polyester resin composite materials specimens.
- The untreated bamboo fiber has higher strength, however; the DIC analysis indicated the non-uniformity of stress field distributions which indicates the presence of higher con-tents of inclusions.
- The 10 Vol% NaOH treated bamboo fiber has high strength next to untreated bamboo fiber.
- The 10 Vol% NaOH treated bamboo fiber plus corn starch soaking leads to good elastic and elongation properties compared to other treatment processes.
- In general, the NaOH chemical treatment of bamboo fiber reduces the brittleness of the fiber and improves the surface roughness and its ductile properties.

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