

Experimental and Numerical Analysis of Vinyl Ester Composites Reinforced with Coconut and Glass

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Article Info	Abstract
Received 30/08/2025	Vinyl ester composites reinforced with treated coconut (shells and fibers) and glass (powder and fibers) have been investigated using numerical, experimental, and statistical methods. Tensile and bending tests were applied. Numerical simulation was conducted using the Finite Element Method (FEM) with the ABAQUS CAE 2019 program for tensile and flexural samples. Experimental values were analyzed using the statistical analysis from the Minitab Statistical Software 2022 program. The simulation results illustrate the great convergence between numerical and experimental values. By analyzing the experimental results, the 30% and 40% filler ratios prevailed in all the vinyl ester composites reinforced with coconut and glass. The strength values obtained from the simulation did not exceed the experimental laboratory values by more than 5% in the tensile test and 10.6% in the bending test. Additionally, scanning electron microscopy (SEM) has demonstrated improved adhesion in synthetic fiber, displaying holes formed by the removal and pulling of fibers and particles from the polymer. The mechanical properties of these composites encourage their further study, as they can be used in many structural industries.
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1. Introduction

Composite materials occupy a wide area of structural industries in the world, in various uses such as automobiles, furniture, construction, etc. For composite materials, this also includes failure analysis tools, helping industries like aerospace, automotive, and marine engineering develop stronger and lighter structures.

Many researchers have supported the use of coconut waste in composites with synthetic materials, including Windyandari et al. [1], who designed a finite element FA simulation to assess damage to the bow structure of a fishing boat hull caused by a front collision load, using a hybrid coconut/glass fiber composite material. The mechanical properties of four hybrid composite laminates were measured experimentally to evaluate their differences in fiber type, layer number, and orientation angle. The hybrid composite material was created utilizing a hand lay-up lamination technique, which is commonly used in shipyards to create fiberglass ship hulls. The mechanical characteristics test yielded satisfactory results for each type.

The simulation at various crash speeds and lamination types revealed that the collision bulkhead was intact for all forms of laminated composite. As a result, it could be stated that composite can be used as a substitute hull material. Also, Hussain et al. [2] aimed to reduce the weight of the car by replacing the steel leaf spring with the treated coir-reinforced polyester composite leaf spring by stabilizing the load and comparing the relative values and errors by designing it using UG NX -10.0 and analyzing it using ANSYS 18.1. The results showed the composite's lightness compared to steel and, conversely, reduced stress resistance by 40.6%. The results are considered within acceptable ranges, as composite leaf springs can be used in lightweight vehicles.

To increase the mechanical properties of composites reinforced with natural fibers, a form of synthetic reinforcement must be substituted; Jani et al. [3] looked at the mechanical characteristics of treated coconut shell fibers and the effect of shell fillers on the composites. The composites were made of epoxy and coconut/Kevlar fibers at one orientation, with and

without coconut shell fillers; the proportion of Kevlar to coconut being 3:2. The addition of a small quantity of coconut shell filler in these composites increased the tensile and bending properties of the composite, demonstrating a beneficial hybrid effect. The hybridization and surface treatments of bio-fibers reduced the water absorption tendency of composites. Thus, hybrid composites with filler fiber reinforcements encourage mechanical properties, which could extend the usability of these composites in the automotive and building products industries. Also, Kai et al. [4] created a hybrid polymer composite using epoxy resin with treated fibers of sugarcane bagasse and coconut, employing a hand lay-up method. To improve the mechanical performance of composite materials, nano-silica was also incorporated. In terms of mechanical performance, coconut fiber outperformed sugarcane bagasse fiber among all single natural fiber-reinforced epoxy resin composites. Among all the different weight fractions of hybrid polymer composites, the 2.5% sugarcane bagasse and 12.5% coconut hybrid composite samples had the best mechanical performance. Furthermore, Ekpechi et al. [5] created five composite samples with varying fractions of coconut fiber of city solid waste, aluminum oxide, silicon carbide, and epoxy using a hand-layup and compression molding production procedure. Mechanical, thermal, and water absorption tests were performed on the produced specimens. When fibers were introduced into the composition, they increased the mechanical and thermal properties of the polymer material. Natural and synthetic materials have demonstrated enhanced thermal and mechanical properties, as evidenced by comparisons with specimens lacking these materials.

1.1. Mechanical Properties of Glass and Coconut Fiber Composites

Looking into the mechanical properties of glass and coconut fiber composites, Hemanth et al. [6] employed epoxy and polyester resins using a hand layup method to prepare 18:82 fiber-to-polymer composites, with fiber lengths of 5-6 mm. Mechanical characteristics were improved in glass/epoxy composites; tensile strength was 40.53 MPa, bending strength was 177.37 MPa, and impact strength was 5.75 J in glass/epoxy composites. The results of coconut composites cannot be overlooked, and the analysis revealed the potential application of coconut composites with good stiffness. Also, Dhas and Pradeep [7] sandwiched composites within a polyester resin and contained a nanoparticle coconut shell filler. Fibers from oil palm, coconut, palm, and raffia leaves were used and treated with a potassium permanganate solution to improve their quality. Four distinct plates were created using a hand lay-up method with a 30% fiber percentage. According to experimental results, the polymer composite made from palm leaf stalk fiber and treated with alkali performs significantly better than the other specimens. As a result, the created composite can be suggested for use in manufacturing automotive parts. Likewise, Rahman et al. [8] manufactured coconut fiber epoxy composites using a hand lay-up process. Coconut fiber demonstrated good strength in tensile and compression tests. The weight and strength of coconut coir were boosted when it was combined with glass fiber. These may be ideal for structural applications in automobiles and aircraft.

Untreated and alkali-treated coir/glass and (Pineapple Leaf Fiber) PALF/glass hybrid epoxy-based composites were created by Mittal and Chaudhary [9] with a fiber Vf of 30% and length of 20 mm, using a hand lay-up method. The 30% PALF/glass hybrid composite had greater tensile and bending performance when compared to the other hybrid formulations. The bending strength of the alkali-treated 30% PALF/glass composite was 35.13% higher than that of the glass composite. The mercerized 30% coir/glass composite had the highest impact strength and resistance to water molecules of all the developed materials. In addition, the goal of Mawardi et al. [10] study was to determine the impact properties of epoxy composite hybrids by multi-reinforcing. Therefore, they created the coconut/glass/fabric/rubber hybrid composites in three different ways, with the first layer in each variation being coir/epoxy/alumina, using a hand-layup technique with a coconut fiber length of 10 to 20 mm. The results revealed that fiber fibrillation treatment can improve the mechanical properties of a composite. Fiber fibrillation for 10 minutes produced the maximum impact and bending strength, 24.45 kJ/m² and 87.91 MPa, respectively. The hybrid composite with coconut/glass/fabric/rubber had the highest impact strength of 58.02 kJ/m². Rubber reinforcement could improve the impact strength of hybrid composites. Brittle fracture was the type of fracture that occurred in hybrid composites. Fabric and rubber reinforcement could boost impact strength by up to 137%.

Looking at how untreated and treated coconut husk particles affected the mechanical characteristics of vinyl ester composites, Livingston et al. [11] used a hand lay-up technique to create composite plates with Wf at 5, 15, 25, 35, 45, and 55%. The alkali treatment eliminated natural and manufactured contaminants while also altering the surface morphology of the particles. The results showed that the mechanical characteristics of the composites rose at 35% with the addition of coconut shell particles and then decreased at both settings. When compared to untreated composites, the treated composites have higher mechanical property values. In this composite, the ideal particle content for the best combination of mechanical qualities is 35%. Moreover, Navaneethakrishnan et al. [12] investigated the tensile characteristics of a vinyl ester composite reinforced with Roselle fiber and coconut shell powder, using a hand lay-up technique with 10, 20, 30, 40, and 50% Wf and a constant fiber length of 8 mm. The density of composites decreased, and the volume proportion of voids increased as the roselle fiber loading increased; also, the tensile strength values increased. The tensile strength of the composites improved with fiber loading up to 40%, then decreased. 27 trials were performed on composite specimens with the same fiber/particulate loading of 40 %, fiber length of 6 mm, and sizes of 150, 20, and 3 mm for statistical analysis, and the associated tensile strength values were recorded. When comparing the predicted value to the measured average, the variation was quite minor (0.29%). Like Livingston et al. [11], Girish et al. [13] presented the creation and mechanical characterization of composites based on coir fiber of vinyl ester polymers; a hand layup method was used to prepare the composites with 70% untreated and treated coir fibers. The fibers were treated with a 10% concentrated NaOH solution and uniformly cut into 8 ± 1 mm lengths. The chemically treated coir fiber composite samples outperformed the untreated coir fiber composite samples in terms of tensile

and bending strength. Morphological tests also showed that the treated fibers adhere better to the vinyl Ester matrix, contributing to better outcomes as compared to untreated samples

This study aims to promote environmental sustainability through the manufacture of vinyl ester composites, reinforced with natural materials (coconut shells and fibers), synthetic materials (glass powder and fibers), and by hybridization of both, in proportions from 20% to 50%. One of the most important purposes of this research is to make the most of coconut in terms of the use of fiber and external cortex in the composite, as well as to research the possibility of replacing it with glass material. To reach this conclusion, experimental values of tensile strength were analyzed to identify composites with higher values. The process was similarly done for bending strength, and then both strengths were analyzed to choose the most appropriate composites from each group. The statistical analysis was conducted to identify higher-efficiency composites reinforced by natural and hybrid materials, highlighting tensile and bending strengths. FE Method is considered the best in terms of accuracy and is the most used by several simulation programs. The simulation program ABAQUS CAE 2019 was used to draw and simulate the tensile and bending test samples according to standards. The numerical results are compared with the experimental results from the laboratory.

2. Materials and Methods

2.1. Preparation of Materials for Fabrication

Brown coconut fruit (outer husks and fibers), E-glass fiber, and glass powder are the materials used in this work as a reinforcement. A type of vinyl ester resin (Polives 701 TA Bisphenol-A Epoxy Vinyl Ester Resin) was used to bind the reinforcement material. Bisphenol-A is a thermosetting polymer that is based on epoxy and has a moderately high reactivity vinyl ester resin. The hardener used is Butanox M50, which has a density of 1.18 g/cm³. Industrial materials like glass fibers, powder, and vinyl ester polymer with hardener were obtained from Poliya Company in Turkey, while coconut shells and fiber waste were obtained from Kajo Baghdad's sweet factory in Iraq. For chemical processing, which is done in the laboratory, coconut fibers and shells are dipped fully into a 5% sodium hydroxide solution for 24 hours, washed, and dried in water before and after soaking.

Six shapes of materials were reinforced with the composites: glass fiber and coconut fiber (30 mm), chopped glass (5mm), coconut shell particles (4.75 – 2.36 mm), and glass and coconut shell powder (< 75 µm). The materials were thoroughly combined with resin using the (SCARLETT ENGLAND / Model SC-510) mixer. The hardener was added at 2% of the resin. Pour the mixture into a 25 x 25 cm acrylic mold and press it at 5 MPa; leave to dry for 24 hours, and cut plates into samples as per ASTM (American Society for Testing and Materials) for tests with a CNC machine (Accuway UM85, Taiwan); tensile samples according to ASTM D638 and bending samples according to ASTM D790. To ensure accuracy and reliability, the average values were reported after conducting tests on five specimens per composite type with a universal testing machine (LARYEE), performed at the Technological University,

Department of Applied Sciences. Also, the Scanning Electron Microscopy (SEM) test was performed using (Thermo Scientific, Axia Chemi SEM, USA), after coating with gold. This test was carried out at Al-Khora Laboratory, Al-Khora Company for General Trade, Baghdad.

2.2. Statistical Analysis of Experimental Results

Design of Experiments (DOE) is a systematic method of conducting experiments aimed at determining the relationship between inputs (factors) and outputs (responses) in a system. DOE's main goal is to improve processes and products by analyzing the different effects of factors and how they interact. Taguchi Design Method is a specific method of experimental design developed to lower expenses and raise quality. It is especially helpful in industries because it depends on effective experimental designs that reduce the quantity of tests needed. The principles of the Taguchi Method are reducing variability, the loss function, and the use of orthogonal arrays [14].

Tensile strength obtained from experimental results is analyzed by the Taguchi Method. Composites are analyzed based on the type of reinforcing materials (natural and hybrid) and reinforcement ratios (20, 30, 40, and 50%). Repeat the process to analyze bending strength once; then the values are analyzed for both strengths to prefer the composites with the best and highest efficiency for tensile and bending strengths.

Statistical analysis was employed using a Taguchi design with two factors and 4 levels (controllable and uncontrollable). The Minitab analysis settings are shown in Fig. 1

The optimal conditions are determined using the Signal-to-Noise (S/N) ratio, which is the logarithmic element of the desired yield. This aids in information examination and forecasting of ideal outcomes. The standard S/N ratio used in this work is as in (1), where y is the response to the given factor level blend and n is the number of reactions in the factor level blend. The response type used for response variables (tests) was [15]:

Larger is better;

$$S/N = -10 \times \log \left(\frac{1}{n} \sum (1/y^2) \right) \quad (1)$$

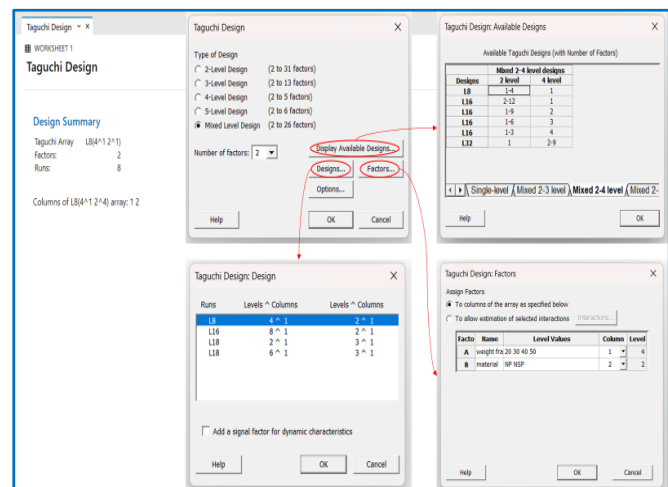


Figure 1. The Taguchi design array example creation.

2.3. Modelling and Simulations of Experimental Tests

The experimental results of the tensile and bending tests are simulated in the ABAQUS program and compared with the outputs of the program while ensuring that the difference between numerical and experimental values does not exceed 20% [16]. The drawing is done using the drawing feature in ABAQUS, specifying the required dimensions according to the standards. The tensile test is simulated for samples according to ASTM D638, and the bending test is simulated for samples according to ASTM D790. As shown in Figs. 2 and 3, the 2D tensile and bending samples.

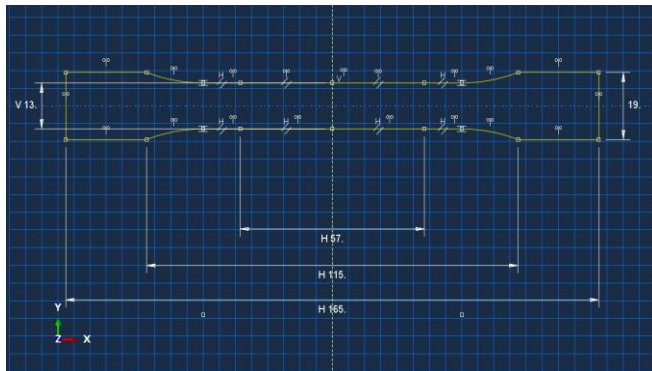


Figure 2. The 2D geometry of the tensile sample.

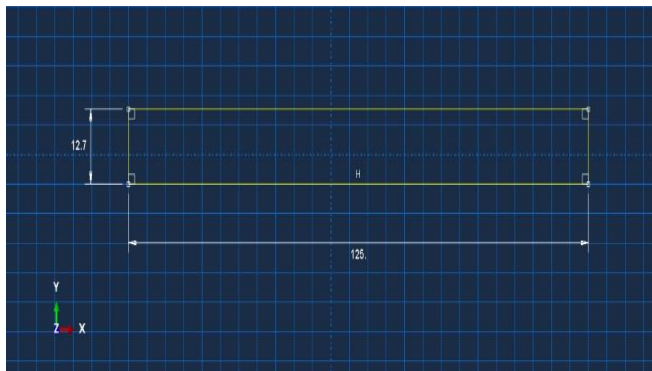


Figure 3. The 2D bending sample.

The deformable parts are also divided into several parts using the partition feature to execute other commands and perform the simulation correctly and in a manner closest to the conventional tests. An additional rigid part is drawn for the bending test, which consists of pillars to stabilize the ends of the sample and shed the force downwards in the center of the sample, as shown in Figs. 4 and 5.

Materials are identified according to their physical and mechanical properties, such as density, modulus of elasticity, Poisson's ratio, etc. Young modulus ranges from 1 to 4 GPa, while Poisson's ratio ranges from 0.29 to 0.32. The input values are taken from the experimental studies by Ngah et al. [17]. The type of material is applied to the part by changing the color of the part from grey to green, thus identifying the part as the required material. It should be noted that the additional part is rigid and does not need a defined material. The parts assembly for the bending test execution contains two parts.

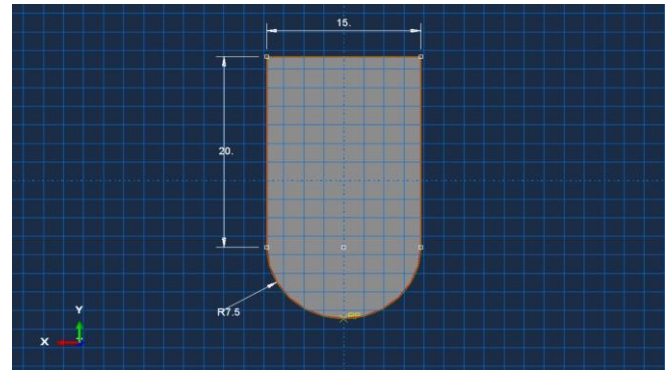


Figure 4. The 2D rigid part for the bending test.

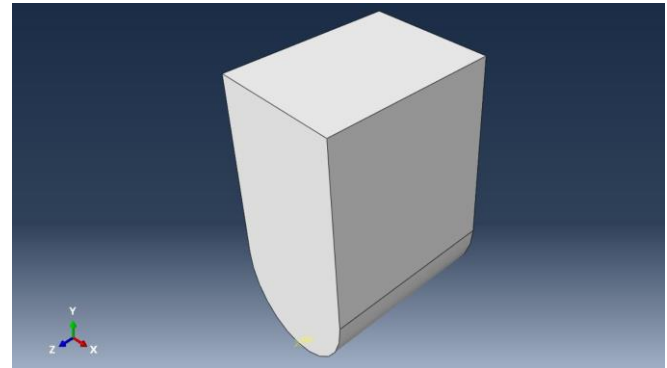


Figure 5. The 3D rigid part for the bending test.

To perform the simulation, steps must be put in place to show the dynamic state of the sample according to the test. According to the tensile test, the sample is initially placed in a state of rest (initial) by the program itself, and then the sample is placed in a state of increased length and distance (loading step). Boundary conditions were applied to the samples (fixed and motion) as shown in Figs. 6 and 7.

A sample's mesh, as seen in Figs. 8 and 9, was created using linear hexagonal element shapes of type C3D8R (an 8-node linear brick reduced integration hourglass control), with sizes and element counts of 2.3 mm and 1152 for the tensile sample and 1 mm and 6552 for the bending sample. The rigid part of the bending test meshed with the R3D4 (a 4-node 3d bilinear rigid quadrilateral) element's shape type, with size 2mm and element count 649. The last stage in the simulation is to create a Job and show the results.

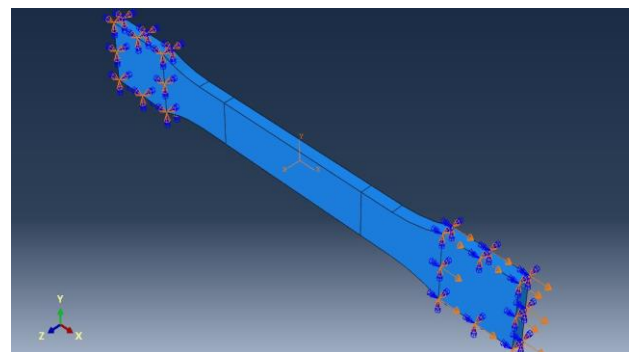


Figure 6. The boundary conditions of the tensile sample.

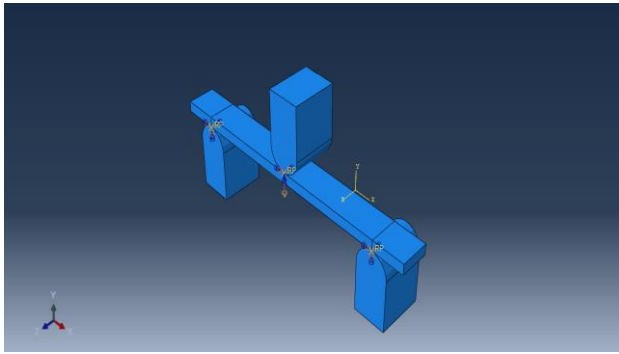


Figure 7. The boundary conditions of the bending sample.

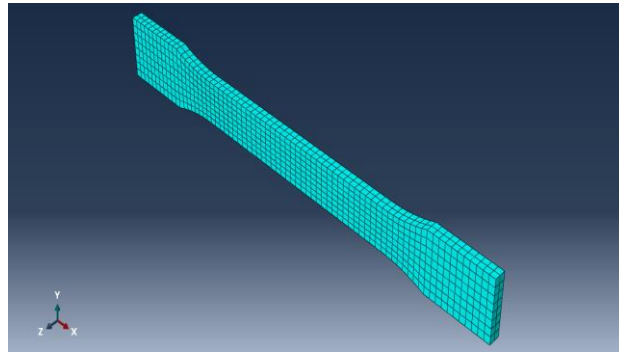


Figure 8. The mesh of the tensile sample.

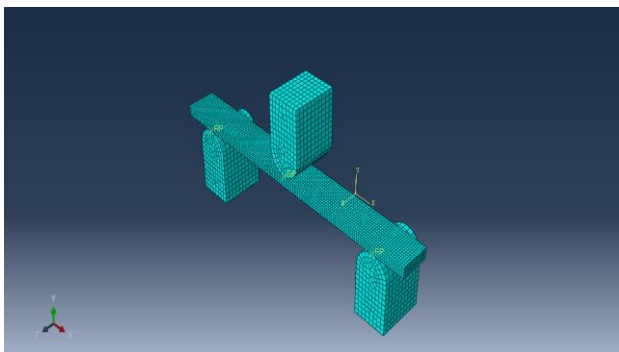


Figure 9. The mesh of the bending sample.

3. Results and Discussion

3.1. Taguchi Results

The analysis results of the Taguchi method review the experimental results of the tensile and bending tests, as shown in Figs. 10 – 12. Hybrid powder composites NSP demonstrate 20%, 30%, and 40% gain in the tensile strength values compared with natural powder composites NP, with an acceptable slope. Fig. 10 shows that the 30% NSP composites outperformed them in terms of tensile and bending strength values when analyzed separately. Hybrid powder composites with NSP reinforcement at a 30% filler ratio also showed superior values, followed by the 40% filler ratio.

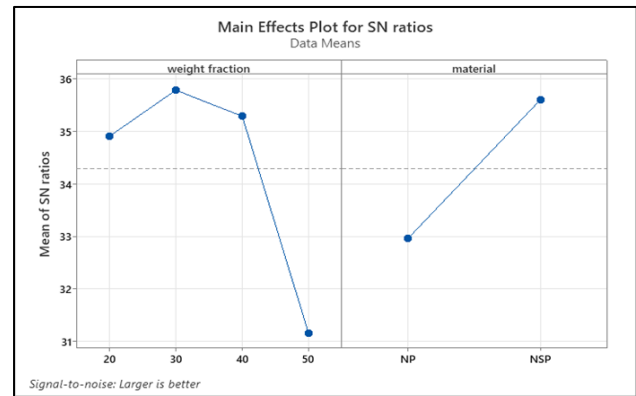


Figure 10. The analysis of tensile and bending strength results by the Taguchi method for natural NP and hybrid NSP powder composites.

Fig. 11 shows a comparison between (Natural Chopped) NCH composites, which are chopped coconut shells with reinforcement ratios of 20, 30, 40, and 50%, and hybrid (Natural Synthetic Chopped) NSCH composites from chopped coconut shells and chopped glass fiber with the same previous ratios, showing that the hybrid coconut and glass chopped NSCH composites are significantly superior to the coconut shells chopped NCH composites for tensile and bending strengths. Fig. 11 explains the rising and exceeding 50% then 40% filler ratio for NSCH composites at the expense of NCH composites, when analyzing both values of tensile and bending strengths.

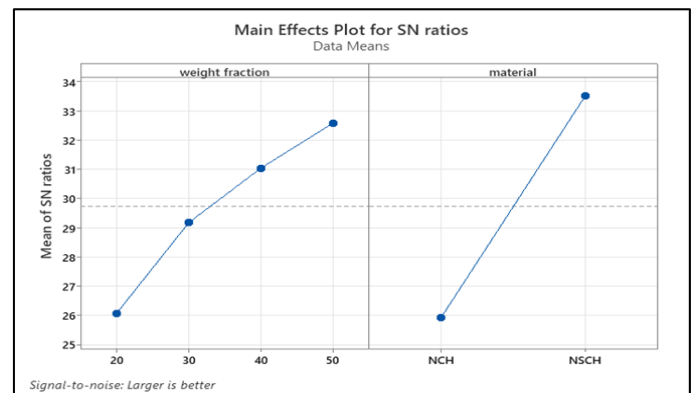


Figure 11. The analysis of tensile and bending strength results by the Taguchi method for natural NCH and hybrid NSCH chopped composites.

The comparison between composites reinforced with (Natural Fiber) NF, composed of coconut shell fiber, and composites reinforced with (Natural Synthetic Fiber) NSF, composed of coconut shell fiber and glass fiber, is illustrated in Fig. 12. The hybrid coconut and glass fiber composites NSF are similar to NSCH composites in their superiority over their natural fiber NF and natural chopped NCH composites. When analysing the values of both tensile and bending strengths, the 30% and 40% fiber filler ratios of hybrid composites NSF were higher, confirming that they were the most suitable in terms of tensile and bending properties.



Figure 12. The analysis of tensile and bending strength results by the Taguchi method for natural NF and hybrid NSF fibre composites.

Although the forms and types of reinforcements of composites vary, filler ratios between 30% and 40% have the best enhancement. The 30% and 40% hybrid filler ratios prevailed in all the vinyl ester composites reinforced by coconut and glass, ensuring improved toughness while maintaining strength and moisture resistance. This combination offers a compromise between natural fiber sustainability and the superior mechanical properties of glass, making it ideal for applications like automotive panels or construction materials. This is logical based on many factors, including the appropriate filler percentage, which reduces the agglomeration of the materials, and a good soaking of the reinforced materials with a sufficient amount of resin. Reinforcement materials impose their properties on the composite, including high stiffness, load-bearing capacity, and stress transfer. These ratios also reduce the agglomeration of materials and their gathering relative to the matrix, resulting in poor interconnectedness between surfaces. In addition, the amount of the resin provides sufficient infiltration and adequate wetting of reinforcement materials, thereby enhancing the attachment and coherence between the matrix and the reinforced materials.

3.2. ABAQUS Simulation Results

The following Fig. 13 shows the values of experimental results from the laboratory and numerical results from the ABAQUS simulation for the tensile strength test of powder composites, as an example, with other values in Table 1, showing that the numerical values are remarkably close to the experimental values, with a slight difference. They showed that the difference between the values resulting from the simulation and the experimental tests does not exceed 5%. The absence of superiority of the numerical values over the experimental values in the tensile test is clear and logical due to applying the maximum tensile strength of the composite that the program cannot exceed.

It is observed from the analysis of the tensile strength results of NP composites reinforced with coconut shell powder that the tensile strength increases with the increase of the percentage of reinforcement from 20% to 30% and peaks in NP30 and NP40. However, at NP50, the tensile strength drops considerably. This reduction is caused by the excessive presence of powder, which weakens the interfacial bonding in the polymer matrix and creates weak points that reduce the ability of the material to

withstand stress. Note that the numerical and experimental values are in good agreement; this means that the numerical model is able to capture the real behavior of the material. For the NCH composites reinforced with chopped coconut shells, the tensile strength increases consistently with the increase in percentage of reinforcement. The tensile strength of NCH20 is relatively low, but it increases gradually with the reinforcement level, reaching the highest value in NCH50. Thus, the chopped coconut shells contribute significantly to the mechanical performance of the composite by acting as short fibers to help distribute the stress more efficiently within the material. The numerical results are in good agreement with the experimental results; although there are some differences, they are small, which means that the numerical predictions can reflect the actual material behavior relatively accurately. For NF composites reinforced with coconut fibers, the tensile strength increases with the increase of fiber content, and the highest value is obtained for NF30. But there is a gradual decline in strength after this, with a more evident reduction at NF50. The overabundance of fibers, which causes an uneven distribution within the polymer matrix, is probably the cause of this decline. Weak zones are produced by this unequal dispersion, which has an adverse effect on the composite's overall performance. Although there is often fair agreement between numerical and experimental results, differences become more apparent at greater levels of reinforcement, indicating additional complexity in the dispersion of fibers within the polymer at these concentrations.

The tensile strength of glass powder-reinforced SP composites first rises from SP20 to SP30 before progressively decreasing from SP40 to SP50. This implies that while a modest amount of glass powder reinforcement improves the mechanical properties, an excessive amount could result in weak bonding between the particles and the matrix, which would lower the tensile strength. The correctness of the numerical model in predicting the behavior of SP composites is confirmed by the close match between the experimental and numerical data. The tensile strength of SCH composites, which have chopped glass reinforcements, steadily rises from SCH20 to SCH50. The highest results are found at SCH50, suggesting that because chopped fibers can more efficiently disperse stresses inside the polymer matrix, they greatly enhance tensile strength. The usefulness of chopped glass reinforcements in improving the mechanical performance of the composite is further validated by the numerical model, which yields results that are in good accord with the experimental data. Tensile strength is significantly increased for SF composites, which are reinforced with continuous glass fibers, especially between SF20 and SF40. The maximum strength is reached at SF40; however, there is a discernible decline at SF50. Fiber clustering or poor interfacial adhesion may be the cause of this reduction at greater reinforcement levels, which could result in stress concentration spots and early failure. The model's accuracy in describing the tensile behavior of the composite is reinforced by the numerical findings, which exhibit the same trend as the experimental data.

The tensile strength of the NSP composites in Fig. 13, which are reinforced with a mixture of glass and coconut shell powder, increases from NSP20 to NSP30, peaking at NSP30 and NSP40. A small drop is seen at NSP50, though, suggesting that

too much powder reinforcement may result in poor dispersion and reduced interfacial interaction within the polymer matrix. Strong correlations between the numerical and experimental data verify that the numerical model appropriately captures the behavior of the composite. The tensile strength of NSCH composites, which are reinforced with chopped glass and coconut shells, increases steadily from NSCH20 to NSCH50. The combined effect of both reinforcements in chopped form improves load transfer and stress distribution, as indicated by the maximum value measured at NSCH50. The simulation's accuracy in simulating real-world material performance is further supported by the numerical predictions' strong agreement with the experimental results. When compared to powder or chopped reinforcements, the tensile strength of NSF composites-which are reinforced with both glass and coconut fibers- shows a notable improvement. From NSF20 to NSF40, the strength gradually increases, with NSF40 reaching the maximum tensile strength. However, a decrease is observed at NSF50, which weakens the composite structure and is probably caused by fiber aggregation or poor bonding at higher reinforcement levels. The better reinforcing impact of continuous fibers is highlighted by the fact that NSF composites had the highest overall tensile strength of all tested groups. The numerical model's accuracy in forecasting tensile performance is further validated by the near match between the numerical results and the experimental data.

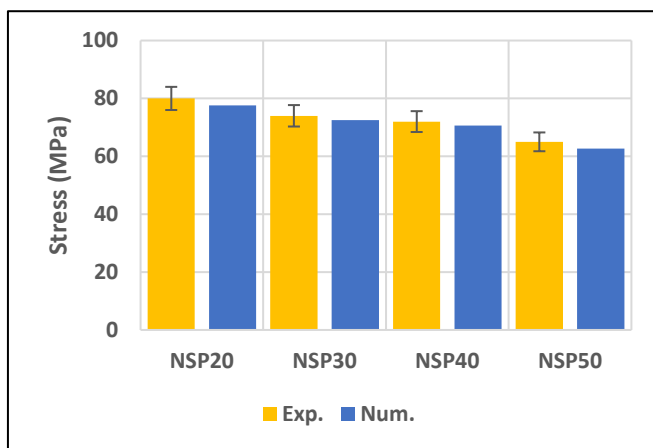


Figure 13. The tensile strength of numerical and experimental tests for NSP composites.

For the bending strength test of powder composites, for instance, Fig. 14 displays the experimental data from the lab and the numerical results from the ABAQUS simulation, with additional values in Table 1. The bending test, where the material reacts variably and the bending strength may be higher or lower, but it stays within the permissible ratios, shows the difference between the simulation results and the laboratory data.

The bending strength of NP composites supplemented with coconut shell powder first rises from NP20 to NP30, peaks, and then progressively declines from NP40 to NP50. This suggests that while a modest amount of coconut shell powder improves the bending capabilities, an excessive amount could cause poor adhesion or particle aggregation, which would degrade the composite structure. The correctness of the numerical

predictions is confirmed by the excellent correlation between the experimental and numerical results. The bending strength of NCH composites, which have chopped coconut shell reinforcement, increases dramatically between NCH20 and NCH40, reaching its maximum value at NCH40. However, a decrease in strength is seen at NCH50, indicating that problems like poor fiber dispersion or matrix saturation may impair bending performance above a particular reinforcement level. The usefulness of chopped reinforcements in enhancing bending properties is supported by the computational results, which closely match the experimental data. The bending strength of NF composites, which are reinforced with natural coconut fibers, rises from NF20 to NF30, when it achieves its maximum, and then either stays reasonably constant or slightly declines for NF40 and NF50. This implies that while coconut fibers offer strong reinforcement, they might not greatly increase bending strength above a certain point. The numerical approach is further validated by the good agreement between the numerical predictions and the experimental data.

The bending strength of the glass powder-reinforced SP composites first rises from SP20 to SP30, peaks, and then progressively declines at SP40 and SP50. This implies that while a modest amount of glass powder improves the bending capabilities, an excessive amount could cause particle agglomeration or poor interfacial bonding, which would lower the mechanical performance of the composite. The experimental data and the numerical results agree quite well. The bending strength of the SCH composites (reinforced with chopped glass) greatly increases from SCH20 to SCH40, with SCH40 showing the maximum bending strength. However, a decrease is shown at SCH50, most likely as a result of stress concentration effects, inadequate dispersion, or fiber aggregation. The numerical model is validated by the good agreement between the numerical predictions and the experimental results. The bending strength of the glass-fiber-reinforced SF composites increases dramatically from SF20 to SF30, peaking at SF30. After this, there is a noticeable drop at SF40 and SF50. According to this pattern, high fiber content may result in poor adhesion between fibers and the polymer matrix, decreasing structural integrity, even if glass fibers greatly improve bending capabilities at ideal concentrations. This observation is supported by the excellent agreement between the computational and experimental results.

The bending strength of the NSP composites (reinforced with glass powder and coconut shell) in Figure 14 peaks at NSP30 before declining at NSP40 and NSP50. This implies that while a high filler content causes poor adhesion and weakens the material, an ideal ratio of glass powder to coconut shell increases strength. The experimental results are in close agreement with the numerical results. The bending strength of the NSCH composites (reinforced with chopped glass and coconut shell) increases dramatically from NSCH20 to NSCH30 and NSCH40, with NSCH40 exhibiting the greatest performance. A slight decrease is seen at NSCH50, which could be the result of more voids or fiber agglomeration. The simulation approach is validated by the good agreement between the numerical and experimental results. The bending strength of the NSF composites (reinforced with glass and coconut fibers) rises until NSF30 before progressively

decreasing at NSF40 and NSF50. This pattern suggests that fiber reinforcement enhances bending qualities to some degree, but too much fiber may lower bonding efficiency and result in poorer performance. The experimental data and the numerical results are in good agreement.

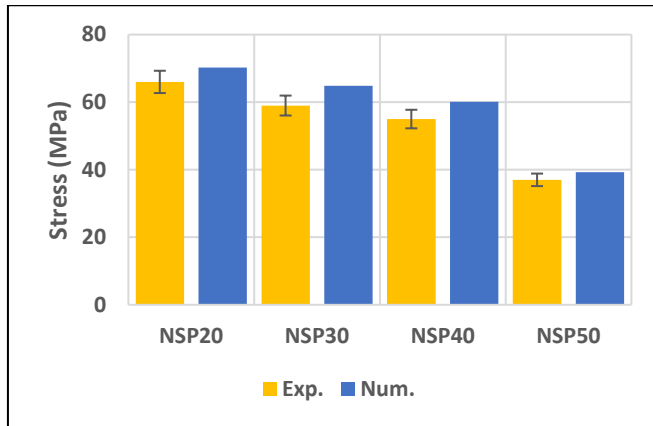


Figure 14. The bending strengths of numerical and experimental tests for NSP composites.

Table 1 presents a comparative analysis of the mechanical characteristics of different vinyl ester composite samples reinforced with glass fibers, coconut shell, and their hybrid combinations. The % discrepancy between experimental and numerical values for bending and tensile strength is the main focus of the analysis. The tensile strength of coconut fiber-reinforced (NF) composites is often lower than that of glass and hybrid composites. Because the numerical model predicts tensile strengths with very little deviation (less than 5%) from experimental values, the mathematical technique is dependable. This is explained by the tensile test's application of homogeneous stress across the material, which reduces the results' susceptibility to chance elements like manufacturing flaws or uneven fiber distribution in the sample. However, some samples, such as NP20, NP30, and NP50, showed variations of about 4%. This could be because the numerical model could not fully account for secondary effects like lateral strains and localized deformations or because the powder distribution was not perfect. The tensile behavior of glass-based materials is more stable than that of coconut shell composites, as seen by the smaller differences observed in samples reinforced with glass fibers, such as SF30 and SF40. Glass fiber-reinforced (SF) composites have the highest tensile strength; SF30 and SF40 achieve values of 176 MPa and 182 MPa, respectively. With variances of less than 4%, the numerical predictions closely match these values. Hybrid composites (SCH, NSCH, and NSF) typically have improved mechanical properties due to the synergistic impact of glass and natural fibers. It is noteworthy that SCH40 has an experimental tensile strength of 131 MPa, which deviates only 1.77% from the numerical value.

The discrepancies between experimental and numerical values for the bending strength test were comparatively greater, sometimes reaching 10.62% (SF50, for example). This can be explained by other elements that influence bending tests, like microscopic cracks, material inhomogeneity, and contact interactions between the sample and testing fixtures. Particularly in high-stress areas, the numerical model might not completely capture all of the material's nonlinear characteristics. For instance, the difference varied between 6% and 8% in samples with hybrid reinforcements of chopped glass and coconut shells (NSCH30 and NSCH40), suggesting that material composition has a direct impact on simulation accuracy. In comparison to single-reinforcement materials like NP or SP, hybrid composites (NSP, NSCH, and NSF) clearly show greater deviations when the general trend of variances between experimental and numerical values is examined. This might be because of the interaction effects between the various materials in the composite, which could result in differences in the distribution of stress and make numerical simulations less accurate in simulating real-world behavior. Furthermore, compared to manufactured materials like glass, natural materials like coconut shells frequently exhibit structural irregularities that result in a less uniform reaction to loads.

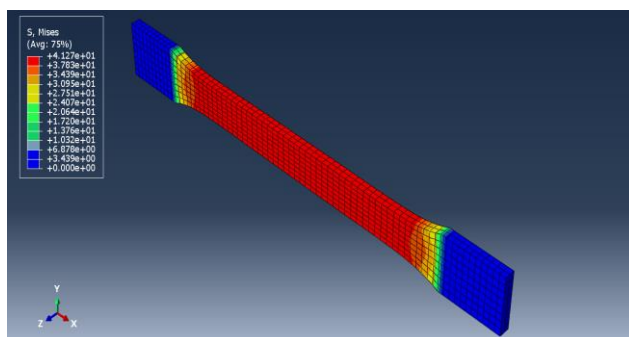
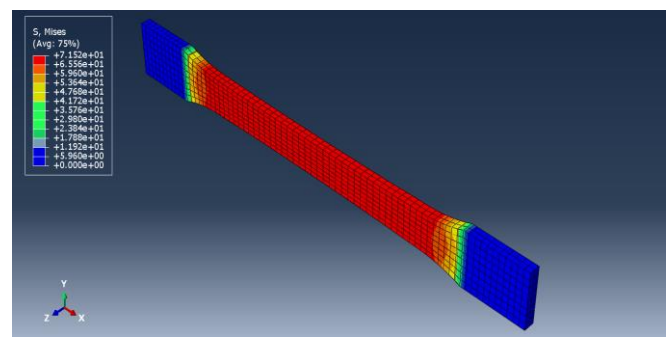
The bending strength of the composites exhibits a similar pattern to that of the tensile strength, with the maximum values produced by hybrid and glass reinforcements. SCH40 and SF30 are hybrid composites that exhibit exceptional bending properties. SF30 has been experimentally measured to reach 215 MPa, which is 5.44% higher than the numerical result. Variations in fibre dispersion, interfacial bonding, and inherent material inconsistencies are likely to account for the increased differences between numerical and experimental results in composites with a higher weight fraction of natural fibres.

In general, the predictive model's accuracy is confirmed within an acceptable error range (mostly below 10%) by the strong correlation between numerical and experimental data. The most even mechanical properties are exhibited by hybrid composites that are reinforced with both coconut shells and glass fibres (SCH, NSCH, NSF) as a result of improved interfacial bonding and reinforcement performance. The research confirms that numerical modelling is capable of accurately predicting mechanical behaviour, despite the fact that minor variations may occur as a result of matrix adhesion properties and fibre distribution.

Figs. 15 to 17 show numerical simulations of 20% powder composites, for example, for tensile testing. Red regions indicate areas of high stress, which are mostly concentrated in the middle of the specimen, as expected in tensile tests. 30% and 40% filler ratios for most composites seem to exhibit a more balanced stress distribution compared to 20% and 50% filler ratios, suggesting an improvement in tensile strength at certain percentages.

Table 1. The numerical and experimental results of mechanical tests and the difference ratio between them.

Sample code	Exp. Tensile strength MPa	Num. Tensile strength MPa	Difference ratio %	Exp. Bending strength MPa	Num. Bending strength MPa	Difference ratio %
NP20	43	41.27	4.19	43	45.43	5.35
NP30	50	47.85	4.49	72	74.71	3.63
NP40	47	46.19	1.75	68	65.78	3.37
NP50	23	22.36	2.86	43	41.37	3.94
SP20	74	71.52	3.47	66	61.53	7.26
SP30	72	69.98	2.89	70	76.18	8.11
SP40	66	65.13	1.34	63	58.75	7.23
SP50	58	56.93	1.88	59	63.3	6.79
NSP20	80	77.63	3.05	66	70.25	6.05
NSP30	74	72.46	2.13	59	64.8	8.95
NSP40	72	70.59	2.00	55	60.12	8.52
NSP50	65	62.72	3.64	37	39.24	5.71
NCH20	10	9.74	2.67	17	18.15	6.34
NCH30	14	13.46	4.01	26	24.85	4.63
NCH40	19	18.37	3.43	58	62.9	7.79
NCH50	28	26.75	4.67	29	27.57	5.19
SCH20	61	59.44	2.62	88	94.6	6.98
SCH30	129	127.18	1.43	132	122.5	7.76
SCH40	131	128.72	1.77	265	251.75	5.26
SCH50	145	140.49	3.21	127	135.9	6.55
NSCH20	30	29.32	2.32	38	41.3	7.99
NSCH30	37	35.54	4.11	81	74.75	8.36
NSCH40	40	38.93	2.75	75	79.8	6.02
NSCH50	59	56.81	3.85	70	65.59	6.72
NF20	25	23.97	4.30	31	31.65	2.05
NF30	39	37.85	3.04	39	41.15	5.22
NF40	33	32.73	0.82	35	36.72	4.68
NF50	20	19.51	2.51	34	35.75	4.90
SF20	76	73.14	3.91	59	62.85	6.13
SF30	176	170.47	3.24	215	203.91	5.44
SF40	182	177.62	2.47	122	113.32	7.66
SF50	119	115.38	3.14	61	68.25	10.62
NSF20	97	96.13	0.91	39	41.85	6.81
NSF30	121	117.85	2.67	60	57.03	5.21
NSF40	143	140.21	1.99	57	55.55	2.61
NSF50	99	95.67	3.48	52	54.2	4.06

**Figure 15.** The simulation tensile test of the NP20 composite.**Figure 16.** The simulation tensile test of the SP20 composite.

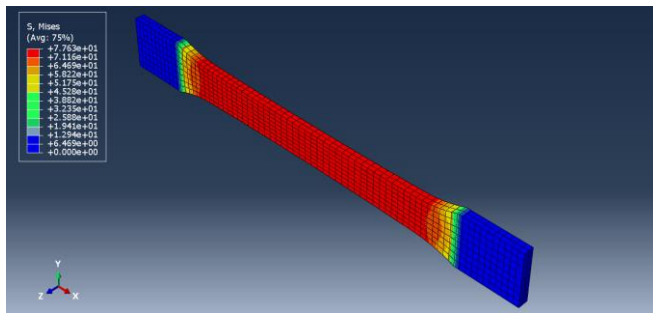


Figure 17. The simulation tensile test of the NSP20 composite.

Figs. 18 to 20 show numerical simulations of 20% powder composites, for example, for bending testing. The red zones indicate regions of maximum stress, primarily located in the middle of the specimen, which is the typical behaviour in bending tests. 30% and 40% filler ratios seem to provide better stress distribution, indicating improved bending performance at these reinforcement levels.

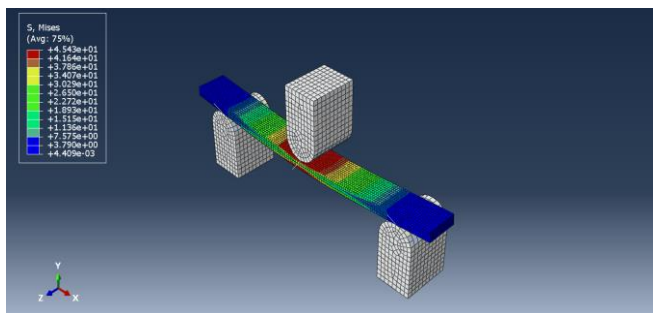


Figure 18. The simulation bending test of the NP20 composite.

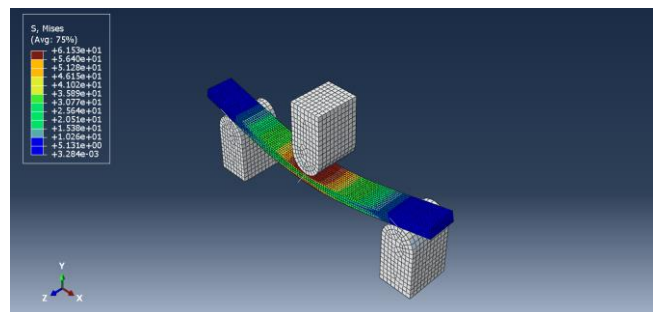


Figure 19. The simulation bending test of the SP20 composite.

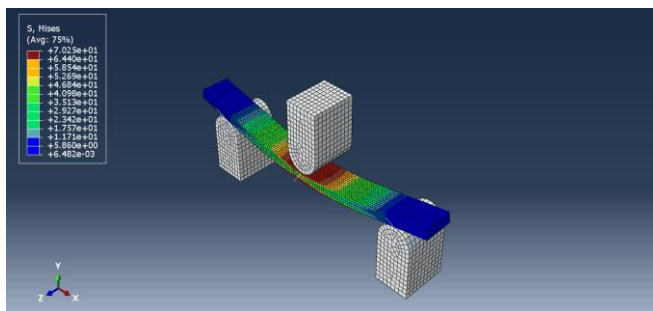


Figure 20. The simulation bending test of NSP20 composite.

3.3. Morphological Analysis

Morphological analysis of samples from Figs. 21 to 26 were obtained for composites that were reinforced at 50% with only natural materials, and hybrids after breaking. Figs. 21 and 22 demonstrate that particle size and shape are crucial in forming bonds and starting cracks in particle-reinforced polymer composites. Regarding the size of reinforced particles in composite materials, the size of the particles is key to obtaining more particles in the same sample and weight fraction. It's obvious that the coherence is greater when compared to the weight fraction of the addition. This point has been supported by more researchers [18], [19]. Small particles have a plastic strain property that makes them less susceptible to cracks. Additionally, the transfer of applied load (stress) to the reinforcements of the polymer is made easier by large-dimensional particles and fibers. SEM photos also show some holes resulting from removing and pulling the particles and fibers from the composites. Note also poor interface bonding that reduces the strength as it begins to diffuse cracks. Fig. 24 shows good adhesion between coconut shell particles and glass chopped in NSCH composites. The residual polymer on fibers indicates stronger adhesion strength, and it was higher in glass fiber and powder than in natural materials. Figs. 25 and 26 illustrate that coconut fibers are hard to remove because of their precise composition, which leads to inclined fractures. Chemical treatment with a diluted NaOH solution, as shown in Fig. 25, produced natural materials with stronger mechanical properties and better-interconnected composites with greater strength, and many researchers agree on this [20].

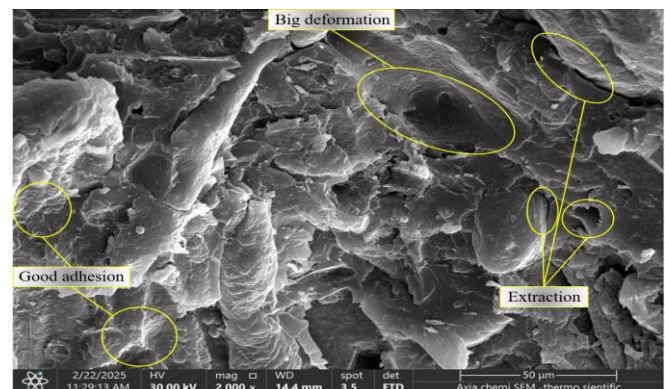


Figure 21. SEM photos of NP composites after fracture.

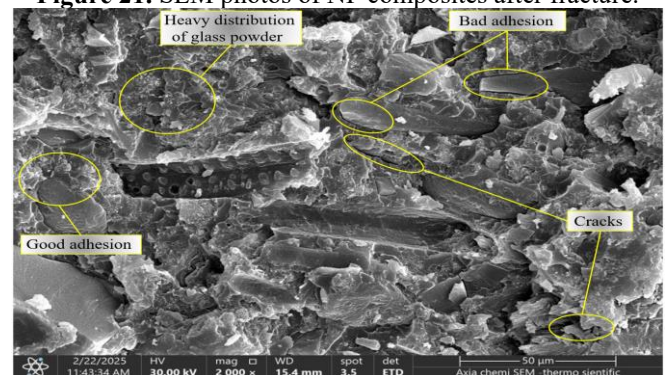


Figure 22. SEM photos of NSP composites after fracture.

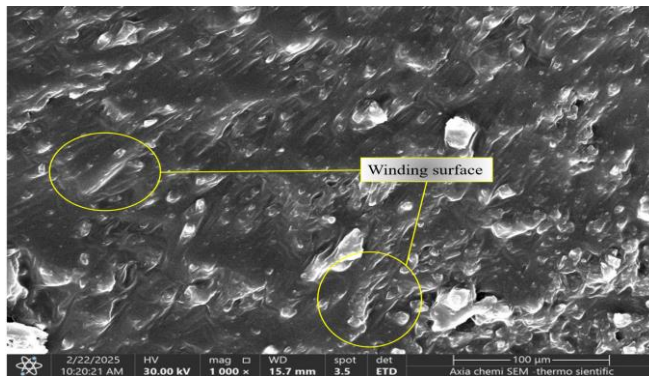


Figure 23. SEM photos of NCH composites after fracture.

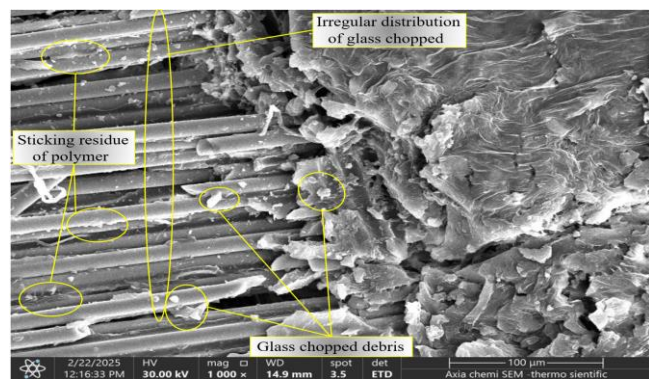


Figure 24. SEM photos of NSCH composites after fracture.

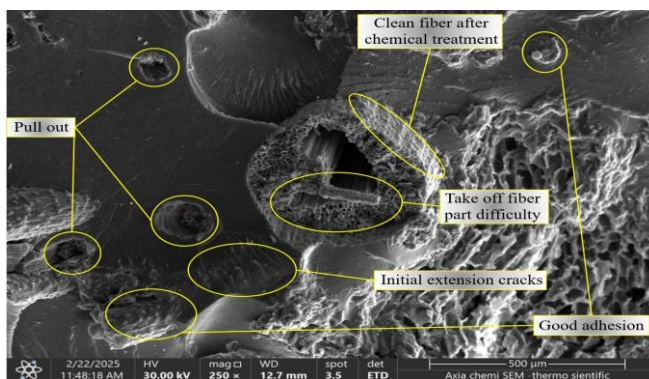


Figure 25. SEM photos of NF composites after fracture.

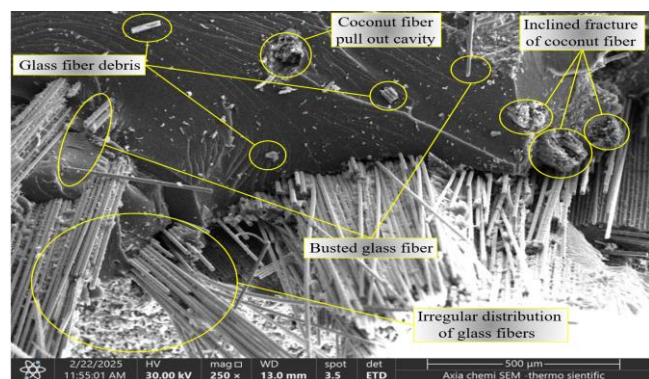


Figure 26. SEM photos of NSF composites after fracture.

4. Conclusions

The results presented can be summarized as the efficiency of mechanical properties (tensile and bending strength) increases by hybridizing coconut shell fiber with glass (chopped and fiber), as in NSCH and NSF composites. NSP composites have higher tensile values than other powder composites, but their bending values are lower. Chopped composites achieve their highest tensile strength values at 50%, and their highest bending strength values are achieved at 30% and 40%. Natural composites with tensile and bending strengths that were the highest ever recorded were NP with 30% values of 50MPa and 72MPa, while NCH with 20% values of 10MPa and 17MPa were the lowest. The tensile performance of hybrid composites was recorded as the highest at 40% with 143 MPa and the lowest at 20% with 30 MPa in NSF and NSCH, respectively. NSCH had the best bending strength at 30% with 81MPa, and NSP had the worst at 50% with 37MPa. The 30% and 40% filler ratios prevailed in all the vinyl ester composites reinforced by coconut and glass. The strength values obtained from the simulation did not exceed the experimental laboratory values by more than 5% in the tensile test and 10.6% in the bending test. The morphological scanning test (SEM) has identified positive and negative points, such as good and poor adhesion in different sections, and voids, which can be avoided with practical experience. The mechanical properties of these composites encourage their further study as they can be used in many structural industries.

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Use of LLM and AI

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Data Availability

The experimental and numerical data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Author Contribution Statement

Duaa Abd Al-Kadhem Foud conducted the experimental work, including mechanical testing, and contributed to the data analysis.

Suhad D. Salman: Conceptualized the research problem, designed the experiments, contributed to the data analysis, and supervised the overall project

Zulkiflle Leman: Developed the theoretical framework and assisted in the interpretation of results.

Munir Faraj Alkbir: Verified the analytical methods, contributed to the experimental design, and provided critical revisions to the manuscript.

All authors discussed the results, provided input on the analysis, and contributed to the final version of the manuscript.

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