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# WASTE EGGSHELL AND SAWDUST AS REINFORCEMENTS FOR SUSTAINABLE POLYESTER COMPOSITES: MECHANICAL CHARACTERIZATION AND ENVIRONMENTAL DURABILITY ASSESSMENT

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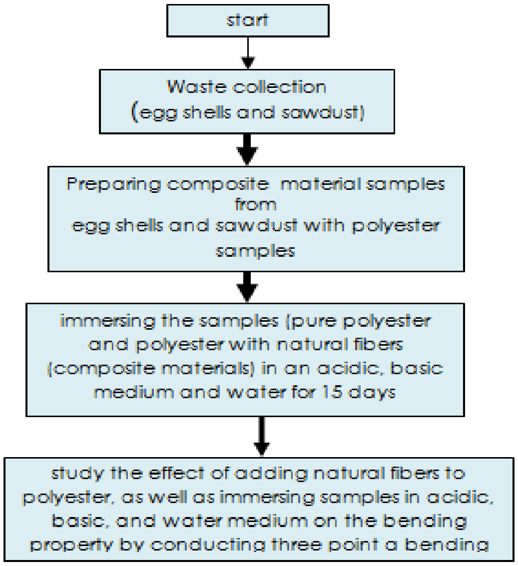
## Graphical abstract



## Abstract

This study investigates the mechanical and environmental properties of polyester composites reinforced with 35 wt.% eggshell powder and sawdust. The research focuses on promoting sustainability by utilizing waste materials. Specimens were fabricated using hand lay-up and compression molding techniques. Environmental exposure, including water, acidic, and basic media, was assessed for its impact on mechanical performance. Results showed significant improvements in mechanical properties, with bending strength increased by 140% for sawdust and 75% for eggshell, and tensile strength improved by 13% and 10%, respectively. However, environmental exposure caused property degradation. Water immersion reduced tensile strength by 63% for sawdust and 3% for eggshell composites, while acidic media caused reductions of 58% and 23%, respectively. Basic media led to a 170% reduction in tensile strength for eggshell composites and a 44% reduction for sawdust. Finite Element Analysis (FEA) simulations supported the experimental findings by illustrating stress distribution, deformation patterns, and potential failure mechanisms under flexural loading. The study highlights the necessity for protective measures or material modifications to enhance the durability of these eco-friendly composites under varying environmental conditions.

*Keywords*: Waste, eggshell, tensile properties, natural fibers, composite materials

## 1.0 INTRODUCTION

The pursuit of ecological preservation and resource optimization has given rise to a significant objective: the development of sustainable materials that are environmentally friendly [1], [2], [3]. Natural fiber-reinforced polymer composites have emerged as a promising solution that has garnered significant attention [4], [5], [6], [7]. These provide significant advantages in comparison to conventional synthetic fiber composites. Renewable, biodegradable, and environmentally friendly, they reduce strain on the environment [7]. Many natural fibers have- been studied, using waste material like eggshells and sawdust as fillers is an attractive solution to utilize waste- items and practice a circular economy.

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Eggshells and sawdust are not useful on their own. However, they can be mixed into other materials as reinforce-ments[8], [9], [10]. Such methodologies that are adopted for life-cycle reusing and other renewable energy applications are extremely beneficial [11], [12]. This gives new life to waste products, it is a novel solution that benefits the environment [11].

During this era, power reinforcement in polymer composites such as natural waste fibers has emerged. Aside from their low cost and eco-friendliness, enhancing mechanical qualities make the fibers attractive. For instance, the view of eggshells, sawdust, banana fibers, pineapple leaf fibers, coir fibers, and rice straw fibers as reinforcements of the polymer composites have been undertaken. These kinds of research underscore attempts to develop value from waste resources. Their processing can be utilized as excellent deliverables to be blended with polymers for composite fabrication. These natural waste fibers, including eggshells and scattered wood dust, combined incrementally within petroleum-based polyester, gave rise to the report by Adil *et al*. [13] , evincing, according to their experimentation, that the bending strength increased in the product obtained in the form of composites. Naik *et al*. [14] reported that mechanical behaviors in tensile and flexural properties of reinforced thermosetting composites by bio-fillers, such as orange peel particulates, show a considerable improvement. Mirza Mohammadi et al. [15] then took a different approach, treating the effect of hybridizing natural fibers and incorporating montmorillonite nanoparticles on the impact and bending properties of green metal/composite laminates. By intelligently interfacing these reinforcements with the highly involved metallic matrixes, appealing mechanical properties and hyperfunctions of natural fiber reinforcement are usually made familiar, while ancient determination of the wave's enigmatic interface states such as higher tensile, interlaminar shear, and compressive strength are deciphered.

Hamdan *et al*. [16] investigated the mechanical properties, including compression stress, of recycled natural composite materials made from walnut peels, sawdust, and polyester. They found that adding 10% of these natural fibers improved the elastic modulus of polyester. In another study [17], they examined the effect of acids, salts, and water on natural composite materials, reporting a reduction in compression stress and changes in hardness after immersion. Gómez *et al*. [18] conducted a comparative study on the mechanical and vibratory properties of composites reinforced with fique (natural fiber) and E-glass fibers. They observed higher stiffness and strength in the E-glass fiber composite but noted poor fiber-matrix adhesion in the fique composite, affecting its overall performance. Pani and Mishra [19] studied the mechanical properties of natural fiber-reinforced hybrid polymer composites, while Sienkiewicz *et al*. [20] reviewed the potential of natural fillers as modifying agents for epoxy compositions. Bhaskar et al. [21]investigated the physical and mechanical properties of banana and palmyra fiber-reinforced epoxy composites, reporting improvements in mechanical properties with fiber addition up to 30%.

Furthermore, the mechanical properties of natural fiber-reinforced polymer composites [22], [23] have been the subject of extensive research pertaining to the impacts of water absorption, acidic alkaline environments, and additional environmental factors. These influences manifest as dimensional instability, water absorption, and potential fiber-matrix interface damage in these composites when subjected to diverse environmental conditions. Highlighted are the challenges that are associated with them. Dhakal *et al*. [22] in his research, he investigated the effect of water absorption on the mechanical properties of hemp fiber-reinforced unsaturated polyester composites, reporting a reduction in mechanical properties due to fiber swelling and weakening of the fiber-matrix interface. Also, research introduced by Aziz and Ansell [24] studied the impact of alkalization and fiber alignment on the mechanical and thermal properties of kenaf and hemp bast fiber composites with a polyester resin matrix, observing changes in properties due to the chemical treatment and fiber orientation. Nóbrega *et al*. [23]developed a model to simulate water absorption in unsaturated polyester composites reinforced with caroá fiber fabrics, providing insights into the kinetics and mechanisms of moisture uptake.

Banerjee and Patel [25] conducted a comparative study on the effects of distilled water, NaCl-water mixtures and seawater on the properties of fiber-reinforced polymer (FRP) composites, and revealed the degradation in different environments.

In recent years, other methods, in addition to experimental work, showed the use of computer modeling and simulation in the form of micromechanical models and finite elements analysis (FEA) [26], [27]. These FEA analyses were used to understand the behavior of natural fiber-reinforced polymer composites and to predict at an early stage the mechanical properties and failure modes of such materials [28]. These methods of computation propose information with insight regarding the design and optimization process of natural fiber-reinforced polymer composites with supplementation from experimental studies [29]. Calculate the porosity and stiffness of plant fiber composites by computational modeling while considering variables like fiber properties and their volume fraction in the composites that dictate the overall composite performance. The use of computational methods permeating: A critical review on the tensile properties of natural fiber-reinforced polymer composites by Ku *et al*. [30] discusses computational models for mechanical behavior prediction and support for material selection and design. This work investigates comparatively the flexural and tensile properties of polyester composites reinforced with sawdust particles with waste eggshell powder.

The distinctive aspect of our research resides in the utilization of waste materials as reinforcing agents, which consequently promotes sustainable methodologies, waste reduction, and environmental pollution mitigation. Additionally, the impact of environmental exposure on the mechanical properties of the composite materials is investigated, including exposure to basic, acidic, and water-based environments. The degradation of the environment has been recognized as a significant determinant of the longevity and functionality of natural fiber composites. Utilization of this integrated experimental methodology yields significant findings regarding the design and enhancement of composites that find utility in a wide range of sectors including packaging, construction, and automotive where there is a pressing need for materials that are not only lightweight but also durable and environmentally friendly. This project is entirely dedicated to experimental investigations. A wide range of testing methods are used to describe the mechanical behavior and performance of polyester composites reinforced with used eggshells and sawdust when they are loaded in both bending and tensile ways.

The paper is organized as follows: First, the introduction outlines the research objectives, novelty, and integrated experimental-computational approach. Next, the materials, methods, experimental procedures, and computational modeling techniques are described. The results and discussion section then presents and analyzes the findings, focusing on the effects of waste natural fiber reinforcements and environmental exposure on the mechanical properties, stress distributions, and failure mechanisms of the composites. Finally, the conclusions, future research directions, acknowledgments, and references are provided.

## 2.0 METHODOLOGY

### 2.1 Materials

The composite materials investigated in this study comprise an unsaturated polyester resin matrix reinforced with waste eggshell powder and sawdust particles, derived from agricultural and industrial byproducts, respectively. The utilization of these waste materials as reinforcing agents aligns with the principles of sustainable practices, waste minimization, and environmental pollution mitigation.

**Polyester Resin:** An unsaturated polyester resin (trade name: Ilkester) supplied by a Turkish company was employed as the polymer matrix. The resin was mixed with an ethyl methyl ketone peroxide hardener at a 3 wt% ratio to initiate the curing process, as depicted in Figure 1.

**Eggshell Powder:** Waste eggshells were collected, cleaned, and air-dried to remove any suspended materials. The cleaned eggshells, as shown in Figure 1-A, were then ground into a fine powder using an electric mill and sieved to obtain a consistent particle size distribution, as illustrated in Figure 1-B.

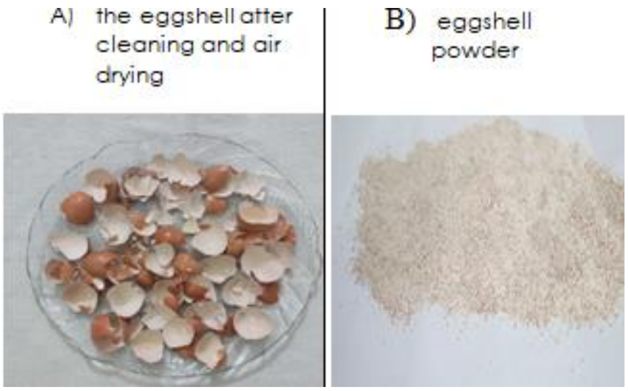

**Figure 1** Eggshell powder obtained after grinding and sieving

**Sawdust Particles:** Sawdust waste, as shown in Figure 2-A, was obtained from a carpentry lab, ground into smaller particles using an electric mill, and sieved to achieve a uniform particle size range, as depicted in Figure 2-B.

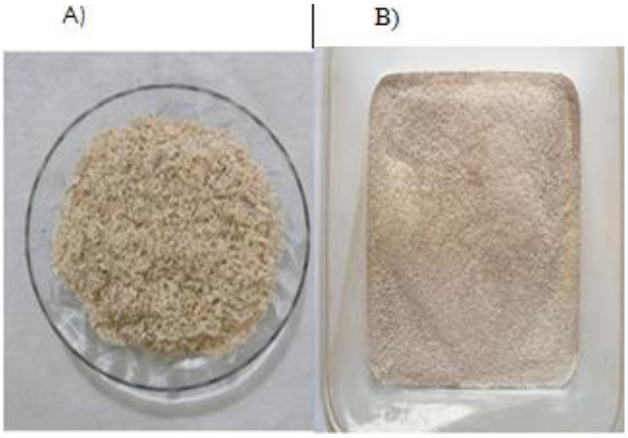

**Figure 2** A) Sawdust waste before processing, B) Sawdust after grinding and filtering

### 2.2 Composite Fabrication and Sample Preparation

The composite samples were fabricated using a hand lay-up technique followed by compression molding, which is a widely adopted method for manufacturing fiber-reinforced polymer composites [28], [29]. The unsaturated polyester resin and hardener were first mixed thoroughly in a glass beaker, ensuring a homogeneous mixture. The eggshell powder and sawdust particles were then added separately to the resin mixture at a weight fraction of 35% and mixed uniformly using a mechanical stirrer to ensure homogeneous dispersion of the reinforcements within the matrix.

The resulting mixtures (polyester + eggshell powder and polyester + sawdust) were carefully degassed in a vacuum chamber to remove any entrapped air bubbles, which can act as potential defects and stress concentration sites, compromising the mechanical properties of the composites [30].

The degassed mixtures were then carefully poured into a glass mold (50 cm × 50 cm × 0.5 cm) coated with a release agent to facilitate easy removal of the castings after curing. The mold was covered with a glass plate to ensure a smooth surface finish and minimize the formation of surface defects. The castings were allowed to cure at room temperature for 72 hours, followed by a post-cure treatment at an elevated temperature (typically 80°C for 2 hours) to ensure complete curing and crosslinking of the polyester resin [28], [29], [30]. Figure 3 show the plate of the composite material fabricated in this study.

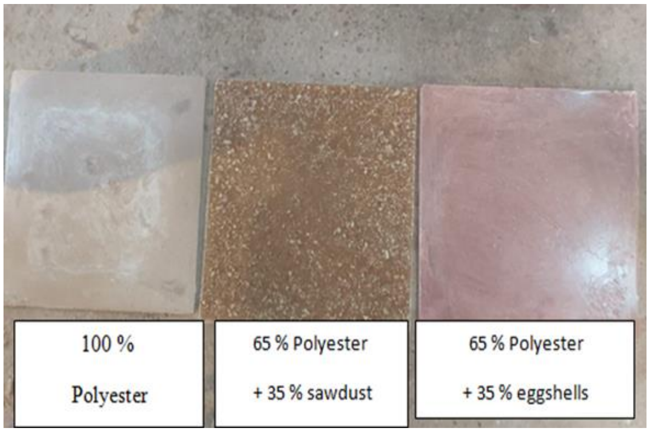

**Figure 3** Castings after molding.

After the curing process, the composite castings were machined using a CNC machine to obtain bending and tensile test specimens according to ASTM standards Figure 4 illustrates the process of cutting the cured composite plates into the required specimen dimensions using a precision machining device. The precision of this cutting process guaranteed that the test specimens were uniform and devoid of defects, the dimensions were 100 mm × 10 x 4 mm, conforming to ASTM D790 [31]for flexural properties of unreinforced and reinforced plastics.

The samples were classified into three main groups: unreinforced polyester (G1), polyester with 35% sawdust (G2), and finally polyester with 35% eggshell (G3). Each group was further classified into subgroups that illustrated the effect of the environment on the mechanical behavior of the materials, as detailed in Table 1.

**Table 1** the samples groups

| Samples groups | Components |
|---|---|
| G1 | 100 % Polyester |
| G2 | 65 % Polyester + 35 % sawdust |
| G3 | 65 % Polyester + 35 % eggshells |
| G1OH | 100 % Polyester immersion in basal medium |
| G2OH | 65 % Polyester + 35 % sawdust immersion in basal medium |
| G3OH | 65 % Polyester + 35 % eggshells immersion in basal medium |
| G1PH | 100 % Polyester immersion in acidic medium |
| G2PH | 65 % Polyester + 35 % sawdust immersion in acidic medium |
| G3PH | 65 % Polyester + 35 % eggshells immersion in acidic medium |
| G1W | 100 % Polyester immersion in water |
| G2W | 65 % Polyester + 35 % sawdust immersion in water |
| G3W | 65 % Polyester + 35 % eggshells immersion in water |

**Figure 4** The cutting by device

The tensile test specimens were prepared with a gauge length of 50 mm and a cross-sectional area of 19 mm × 3 mm, adhering to ASTM D638 [32] for tensile properties of plastics. The specimen dimensions and geometries were carefully selected to ensure proper stress distribution and minimize the influence of edge effects during mechanical testing [33]. Figure 5 show the tensile and flexural sampled prepared for test in this study.

A) Flexural test

b) Tensile Test

**Figure 5** Bending and tensile samples

## 2.3 Environmental Exposure:

The next stage of this investigates study the influence of environmental exposure on the mechanical properties of the composites, the bending and tensile test specimens from each composite group (G1, G2, and G3) were further divided into four subgroups:

- Control group: Samples without any environmental exposure, serving as a baseline for comparison.
- Water immersion group: Samples immersed in distilled water at room temperature for 15 days to simulate the effects of moisture absorption.
- Acidic medium group: Samples immersed in a 5% acetic acid (CH3COOH) solution at room temperature for 15 days, representing acidic environmental conditions.
- Basic medium group: Samples immersed in a 3.5% sodium chloride (NaCl) solution at room temperature for 15 days, mimicking basic or saline environmental conditions.

The immersion periods and solution concentrations were selected based on previous studies [34], [35] that investigated the effects of environmental exposure on the durability and mechanical properties of natural fiber-reinforced polymer composites. Figure 8 from the attached file illustrates the immersion of samples in the acidic, basic, and water media.

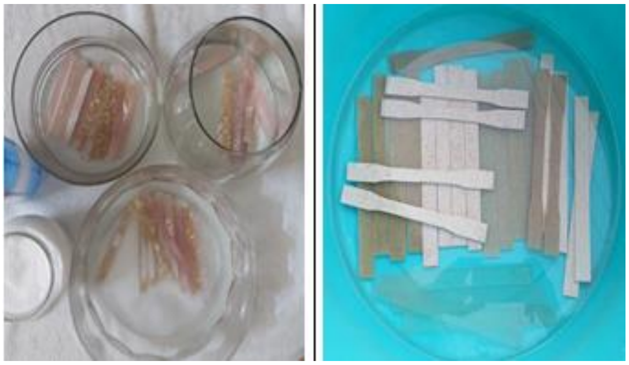

**Figure 6** Immersing samples in acidic, basic, and water media

After the immersion period, the samples were carefully removed from the respective media, rinsed with distilled water, and gently dried with absorbent paper to remove excess surface moisture. The dried samples were then subjected to mechanical testing under bending and tensile loading conditions within 24 hours to minimize the effects of moisture re-absorption [35].The influence of environmental exposure on the mechanical performance of the composite materials was evaluated by comparing the results with the control group samples, providing insights into the effects of water absorption, acidic conditions, and basic/saline environments on the bending and tensile properties of the waste natural fiber-reinforced polyester composites.

## 2.3 Experimental Test

### *2.4.1 Tensile Testing for Property Prediction of the Samples*

The mechanical properties of the waste natural fiber-reinforced polyester composites were examined through tensile testing. The tests followed the ASTM D638 standard [32] to ensure consistency. Specimens were prepared with the required dimensions. Uniaxial tensile tests were conducted on a universal testing machine, with at least five valid tests per material composition to account for variations. The specimens were loaded at a constant crosshead rate of 1.0 mm/min, allowing for accurate measurements while avoiding excessive strain rates that could affect the material behavior. All tests were carried out at an ambient temperature of 25°C to eliminate any influence of temperature variations on the mechanical properties. The failed specimens were visually examined to determine the cause of their failure following testing. Illustrative of the specimens' reaction to the applied tensile load, Figure 7 presents a photograph of the specimens subsequent to testing at the failure point. The utilization of this graphical depiction facilitates the examination and delineation of the performance attributes of the substances.

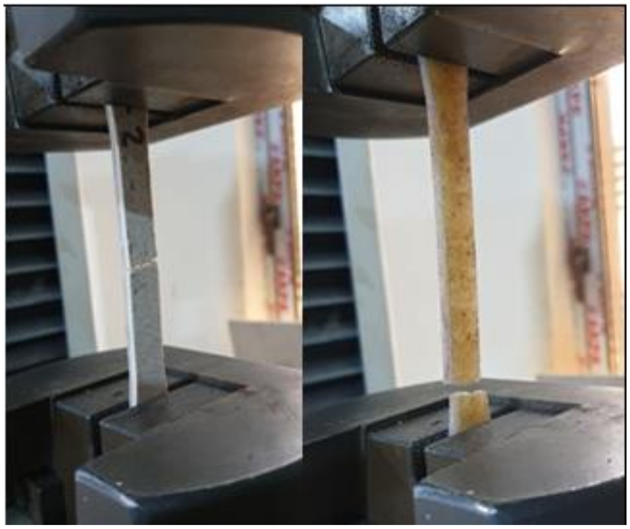

**Figure 7** Sample under tensile test

### 2.4.2 Three-Point Bending Flexural Testing

A three-point flexural test was conducted in order to estimate the modulus of flexural, flexural strength and stress-strain response of composite materials. These properties are important because they help in understanding how materials tend to behave when subjected to bending loads and the kind of structures they can be used for. For the flexural test specimens, the dimension according to ASTM D790 [31]. Failure occurs when the strain or elongation exceeds the material's limits. Experimentally three-point bending tests were conducted using a universal testing apparatus equipped with a three-point bend fixture and an instrument control panel. The maximum stress applied to the specimen during bending was calculated. The specimens were placed on two supporting spans, with a 50 kg load applied at the midpoint through a crosshead moving at a rate of 2 mm/min. The control panel facilitated the recording of the maximum stress experienced by the specimen, ensuring that excessive bending loads were avoided and no fractures occurred during testing. The results of the three-point bending tests are presented in Figures 8.

**Figure 8** Three-point bending tests

In the next part of this work, the results of the experimental study will be presented and discussed in detail, and the effect of potato powder and sawdust reinforcement on the mechanical properties of polyester blends and the effect of environmental absorption on their performance will be given.

## 2.5 Numerical Analysis (FEA for Flexural)

The FEA approach was applied to support the experimental results and receive an understanding of the flexural behavior of heterogeneous materials [28], [36], [37]. To conduct the numerical modeling, the commercial FEA package Abaqus/CAE is applied.

### 2.5.1 FEA Modeling Approach

A three-dimensional solid modeling has been done for representative composite specimens to model appropriately. The composite geometry is prepared in the dimensions of the standard ASTM D790 for flexural experiments, which has a 100 mm length, 10 mm wide, and 4 mm thick, as depicted closely in the Figure 9.

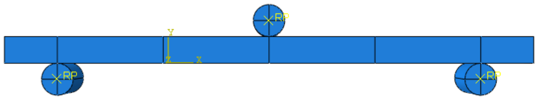

**Figure 9** three-point sample ASTM790

The composite models were meshed using linear hexahedral elements (C3D8) with a structured mesh pattern. A mesh convergence study was conducted to ensure an appropriate mesh density, balancing computational efficiency and accuracy[38], [39] . The final mesh consisted of 27,054 nodes and 22,576 elements, with a refined mesh in critical regions, such as the loading and support points, to capture stress concentrations accurately.

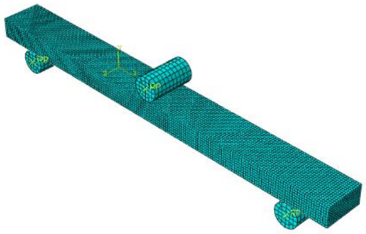

**Figure 10** Mesh distribution

The material properties of the composite constituents, including the unsaturated polyester matrix, eggshell powder, and sawdust particles, were assigned to the FEA model. These properties encompassed elastic moduli, Poisson's ratios, and other relevant parameters obtained from experimental characterization or literature data.

### *2.5.2 Loading and Boundary Conditions*

To simulate the three-point bending test conditions, appropriate loading and boundary conditions were applied to the FEA model. The specimen was supported at two points, maintaining a support span-to-specimen length ratio of 16:1, as recommended by ASTM D790. The supports were modeled as rigid analytical surfaces, constraining the vertical displacement at the contact points.

At the midpoint of the specimen, a concentrated load was applied to simulate the bending moment experienced during the flexural test. Figure 11 illustrates the loading configuration, showcasing the applied load and boundary conditions utilized in the simulation. The load was applied as a distributed pressure over a small region to mimic the contact area of the loading nose used in the experimental setup.

The composite layup sequence and reinforcement distribution were accurately represented in the FEA model, allowing for the investigation of reinforcement effects on the flexural behavior.

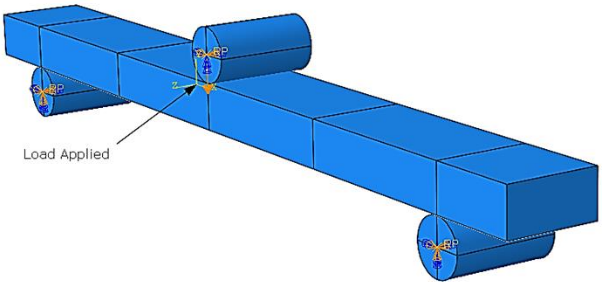

**Figure 11** load applied and boundary condition

### *2.5.3 Failure Criteria and Post-Processing*

An adequate set of failure criteria for the composite has then been adopted to predict the failure behavior and to assess flexural strength within the FEA model. These were maximum stress or strain criteria or a combination of both derived from experimental data and existing failure theories for composites. The FEA results were post-processed for looking at stress and strain distributions in the composite specimens, their deformation patterns, and possible failure initiation sites under a flexural load. A selection of some contour plots and deformed shape representations superimposed with deformed shapes in quantitative terms got an overall impression of how the flexural behavior and, hence, validation of the experimental results proved its immense value of FEA to propose the stress distributions, deformation mechanisms, and possible failure modes, both in individual and comparative terms, with the loading of the waste natural fiber-reinforced polyester composites. The computational results augmented experimental data, thus giving an all-encompassing assessment regarding the composite materials.

## 3.0 RESULTS AND DISCUSSION

The objective of this study was to investigate the impact of incorporating waste eggshell powder and sawdust particles as reinforcements in polyester on the tensile and flexural characteristics of the composites. Furthermore, an assessment was conducted to determine the impact of environmental exposure to water, acidic, and basic media on mechanical performance. The findings demonstrated notable improvements in properties as a result of the incorporation of natural fiber reinforcements, as well as the degradation effects induced by the prevailing environmental conditions.

### 3.1 Tensile Test Results

Figure 12 shows the tensile stress-strain behavior of unreinforced polyester (G1) and composites reinforced with sawdust (G2) and eggshell powder

(G3) under tensile loading. In the case of the unreinforced G1 group, immersion in water (G1W) resulted in a 55% reduction in tensile strength compared to the control G1 sample, as depicted in Figure 13. This reduction can be attributed to moisture absorption and plasticization effects, which disrupt the polymer matrix and weaken the interfacial adhesion, as reported by Dhakal *et al*. [35] for natural fiber composites. Similarly, tensile strength was reduced by 55% and 47% due to immersion in acidic (G1PH) and basic (G1OH) media, respectively, owing to potential hydrolytic degradation and debonding of the fibers from the matrix caused by chemical interactions with the media. [24], [25].

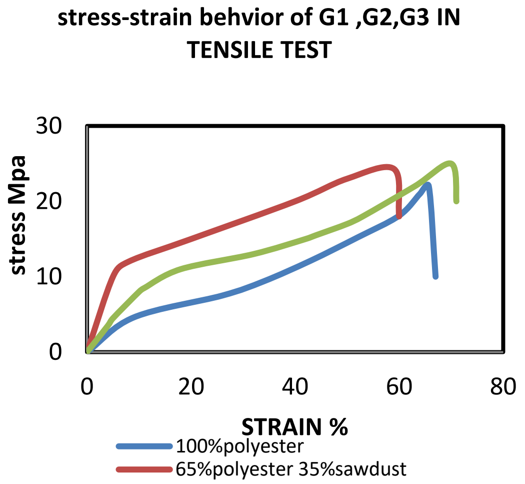

**Figure 12** Sstress-strain behavior of G1 ,G2,G3 in tensile test

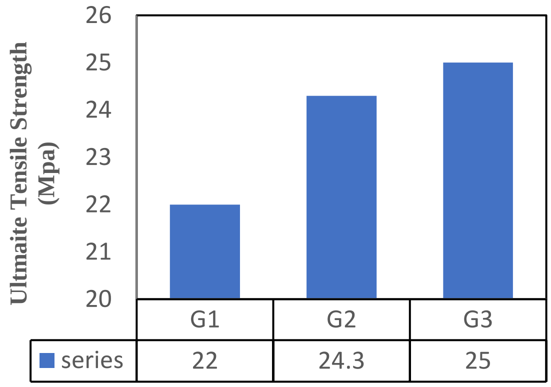

**Figure 13** Ultimate tensile strength for the samples

For the sawdust-reinforced G1 group, the addition of sawdust particles enhanced the tensile strength by 13% compared to unreinforced polyester (Figure 14), owing to the reinforcing effect of the lignocellulosic fibers [14] [19]. However, environmental exposure diminished this improvement, with the G1W (water), G1PH (acid), and G1OH (base) samples exhibiting tensile strength reductions of 63%, 58%, and 44%, respectively, relative to the control G1 sample (Figures 14 and 15). These reductions can be attributed to fiber swelling, matrix plasticization, and potential fiber degradation induced by the respective media, as reported in previous studies [34], [40].

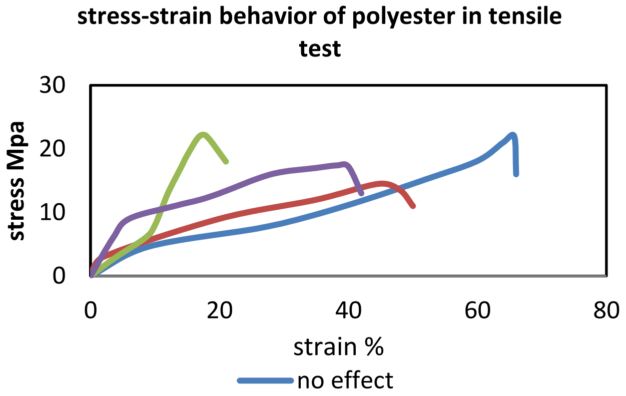

**Figure 14** Ultimate tensile strength for G1 for different medium

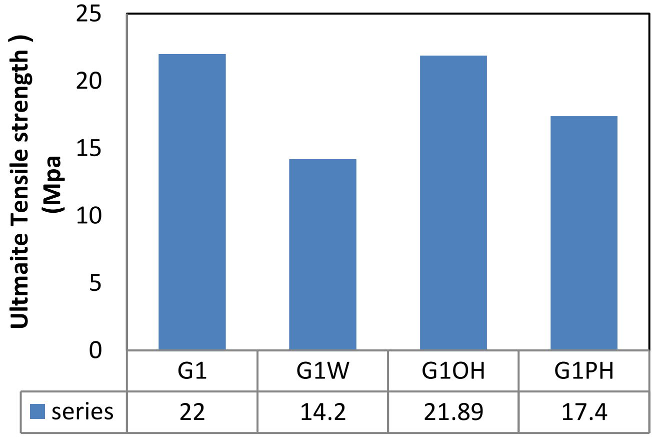

**Figure 15** ultimate tensile strength for G2 for different medium

The eggshell powder-reinforced G3 group displayed a 10% increase in tensile strength compared to unreinforced polyester (Figure 16), owing to the reinforcing effect of the eggshell particles [5], [13]. However, immersion in water (G3W) and acidic media (G3PH) resulted in tensile strength reductions of 3% and 23%, respectively (Figures 16 and 17). Notably, immersion in the basic medium (G3OH) caused a significant 170% decrease in tensile strength, suggesting substantial degradation of the eggshell reinforcement and fiber-matrix interface in this environment, as observed in similar studies [24], [34].

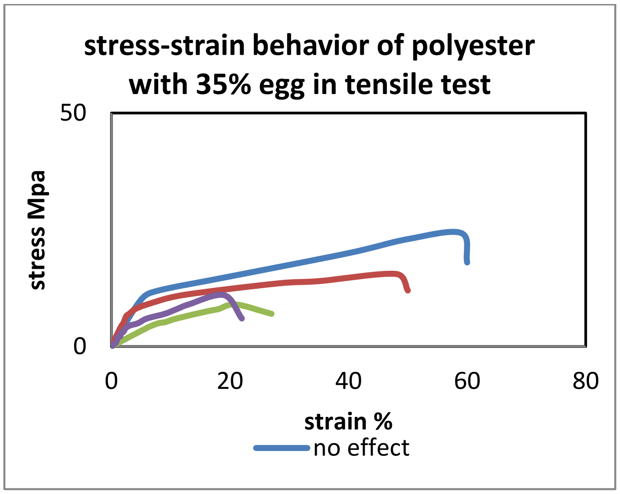

**Figure 16** stress-strain behavior of G3 polyester with 35% egg in tensile test

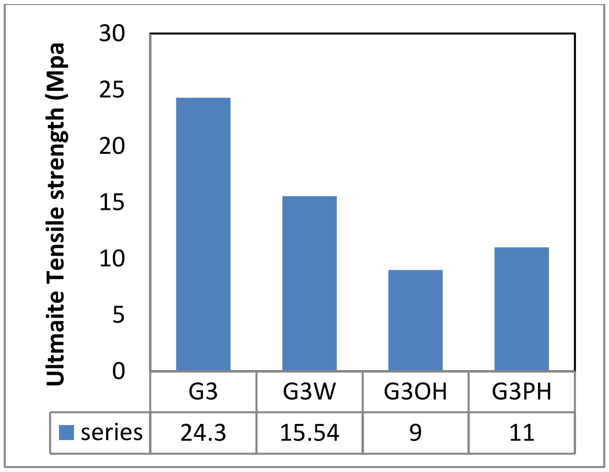

**Figure 17** ultimate tensile strength for the G3

The observed reductions in tensile strength after environmental exposure can be attributed to several factors. Firstly, moisture absorption can lead to plasticization of the polymer matrix, reducing its stiffness and load-bearing capacity [10]. Additionally, the ingress of water molecules can cause swelling and degradation of the natural fibers, weakening their reinforcing effect [34]. Furthermore, the acidic and basic media can induce chemical reactions, such as hydrolysis and leaching of reinforcement constituents, compromising the fiber-matrix interfacial adhesion and load transfer mechanisms [17], [25] .

These findings are consistent with previous studies investigating the effects of environmental exposure on natural fiber-reinforced composites. Aziz and Ansell [22] reported changes in mechanical and thermal properties of kenaf and hemp fiber composites due to alkalization and fiber alignment. Nóbrega *et al.* [34]developed a model to simulate water absorption in unsaturated polyester composites reinforced with caroá fiber fabrics, providing insights into the kinetics and mechanisms of moisture uptake. Banerjee and Patel [15] conducted a comparative study on the effects of distilled water, NaCl-water solution, and seawater on the characteristic properties of fiber-reinforced polymer (FRP) composites, highlighting the varying degrees of degradation in different environments.

## 3.2 Flexural Test Results

The flexural stress-strain behavior of the unreinforced polyester (G1) and the composites reinforced with sawdust (G2) and eggshell powder (G3) is illustrated in Figure 18. Under flexural loading, the addition of sawdust particles (G2) and eggshell powder (G3) led to substantial improvements in the flexural strength of polyester, with increases of 140% and 75%, respectively, compared to the unreinforced G1 group (Figure 19). This enhancement can be attributed to the reinforcing effect of the natural fibers, which can effectively transfer loads and improve the overall strength and stiffness of the composite, as reported in numerous studies [6], [7], [13], [41], [42]

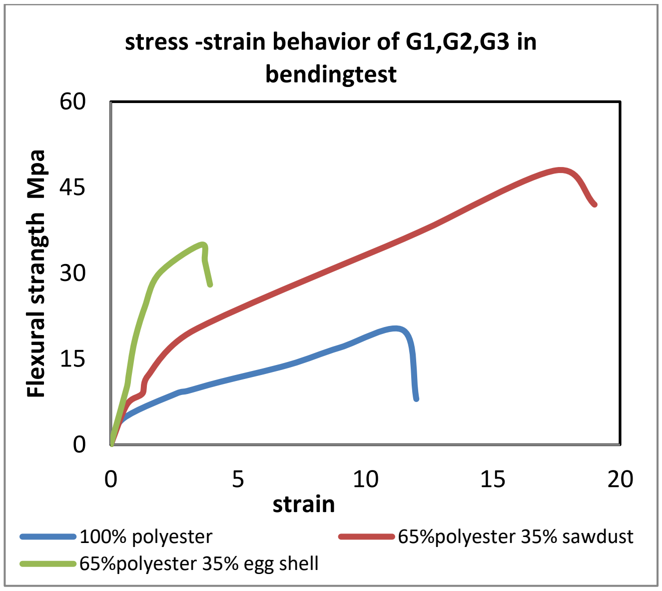

**Figure18** Flexural strength for no effect

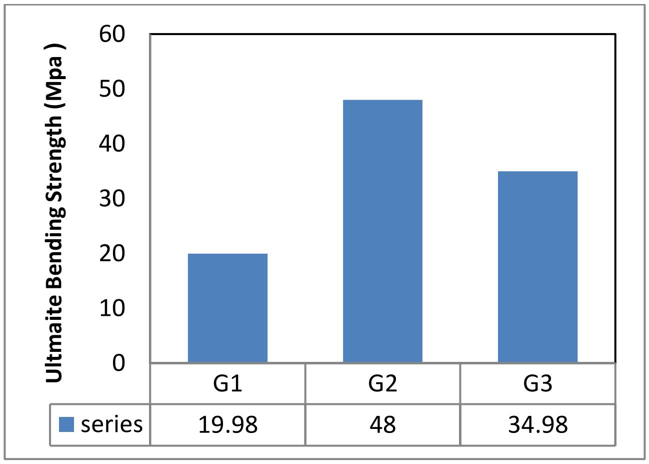

**Figure 19** Maximum flexural strength

Environmental exposure, however, had detrimental effects on the flexural properties. For the G1 group, immersion in water (G1W), acidic (G1PH), and basic (G1OH) media resulted in flexural strength reductions of 55%, 55%, and 47%, respectively, compared to the control G1 sample. Figure 20 explains that the mechanical behavior of composites is affected by different environmental media under all three conditions; there is a noticeable weakening. Figure 21 estimates the flexural strength of all G1 samples, highlighting the significant effects of water, acidic, and basic exposures on composite properties. These reductions can be linked to matrix plasticization, hydrolytic degradation, and potential fiber-matrix debonding caused by the respective media, as observed in previous studies [34] .

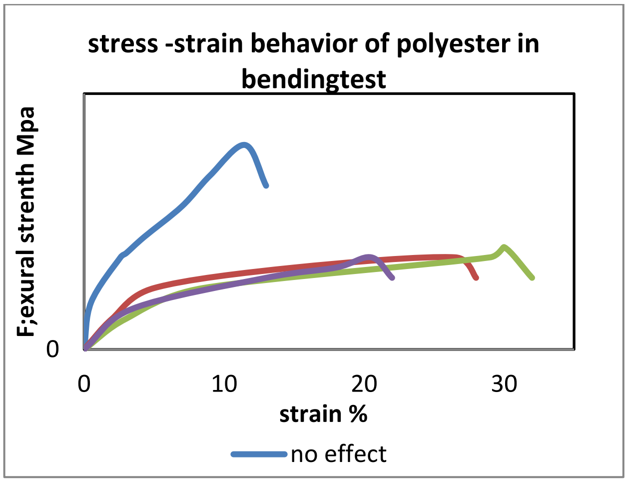

**Figure 20** flexural strength for G1immeresed with different medium

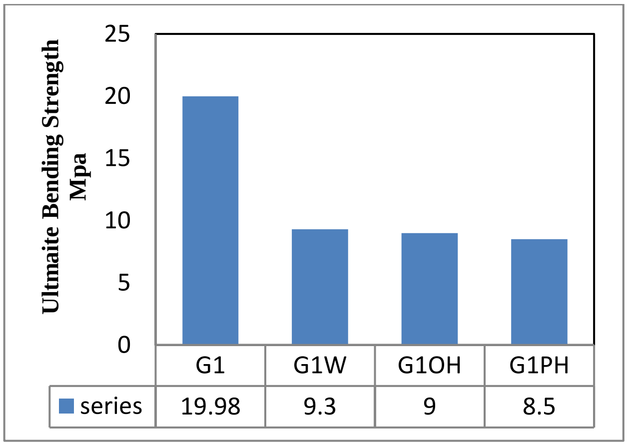

**Figure 21** flexural strength for G1

The sawdust-reinforced G2 group exhibited substantial decreases in flexural strength after environmental exposure, with reductions of 63% (G2W), 58% (G2PH), and 44% (G2OH) compared to the control G2 sample (Figures 22 and 23). These decreases can be attributed to fiber swelling, matrix plasticization, and potential fiber degradation induced by the respective media, as reported in earlier studies [34], [35].

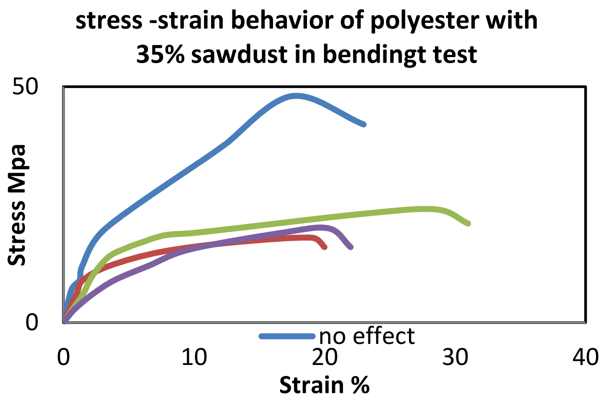

**Figure 22** stress -strain behavior of polyester with 35% sawdust in bendingt test

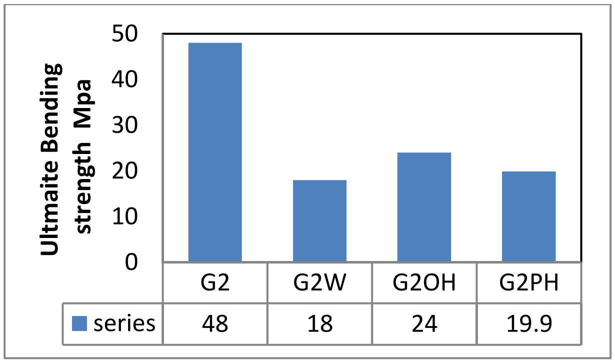

**Figure 23** maximum ultimate strength for G2

For the eggshell powder-reinforced G3 group, immersion in water (G3W) resulted in a marginal 3% decrease in flexural strength, while exposure to acidic media (G3PH) led to a 23% reduction (Figure 24 and Figure 25). However, immersion in the basic medium (G3OH) caused a significant 6% decrease in flexural strength compared to the control G3 sample, suggesting substantial degradation of the eggshell reinforcement and fiber-matrix interface in this environment, consistent with observations reported in similar studies [24], [25].

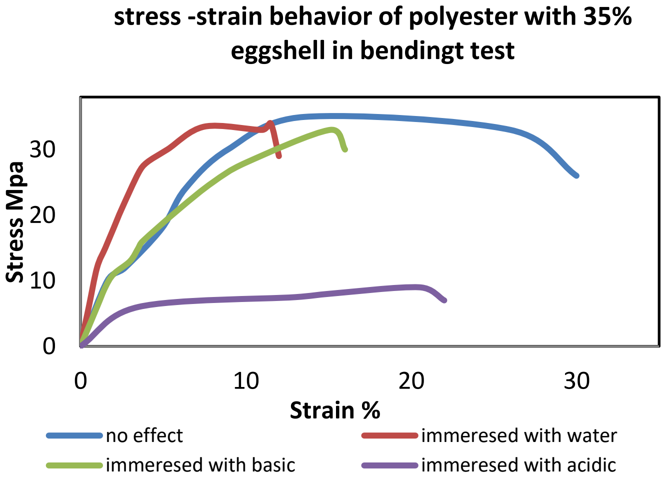

**Figure 22** Stress -strain behavior of polyester with 35% G3

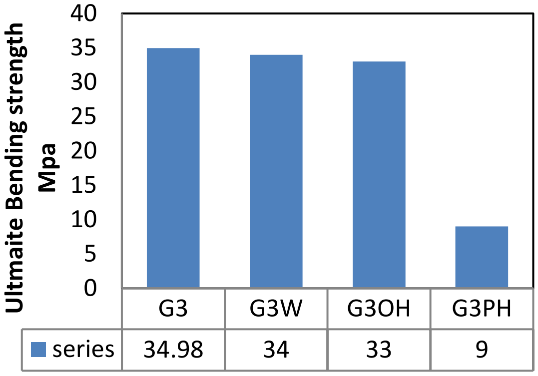

**Figure 23** ultimate tensile strength for G3

The observed reductions in flexural strength after environmental exposure can be attributed to similar mechanisms as discussed for the tensile properties. Moisture absorption and plasticization of the polymer matrix can compromise its load-bearing capacity and interfacial adhesion with the reinforcements [35]. Additionally, swelling and degradation of the natural fibers due to water ingress can weaken their reinforcing effect [23], [25]furthermore, chemical interactions between the acidic and basic media and the composite constituents can lead to hydrolytic degradation, leaching of reinforcement components, and compromised fiber-matrix interfacial bonding [17], [24].

These findings align with previous studies investigating the effects of environmental exposure on natural fiber-reinforced composites. Mirza Mohammadi *et al.* [15] studied the effect of hybridizing natural fibers and adding montmorillonite nanoparticles on the impact and bending properties of eco-friendly metal/composite laminates, observing improvements in these properties. Hamdan *et al.* [4] investigated the mechanical properties, including compression stress, of recycled natural composite materials made from walnut peels, sawdust, and polyester, finding improvements in the elastic modulus with the addition of natural fibers. However, they also reported a reduction in compression stress and changes in hardness after immersion in acids, salts, and water [5].

Table 2 presents a comparison of advanced mechanical properties and damage effects observed in the present study with those reported in previous work. The table highlights the potential of natural fiber waste as a reinforcing agent to improve the mechanical properties of polyester blends while emphasizing the need for appropriate safety measures or material modifications in order to emphasize the longevity of these complex composites in different operating environments.

**Table 2** Comparison of mechanical property enhancements and degradation effects with previous studies

| Property | Present Study | Previous Studies |
|---|---|---|
| Tensile Strength Enhancement | 13% (sawdust), 10% (eggshell powder) | Ku *et al.* [36]: Reported improvements in tensile properties with natural fiber reinforcements |
| Flexural Strength Enhancement | 140% (sawdust), 75% (eggshell powder) | Mirzamohammadi *et al.* [13]: Observed improvements in impact and bending properties with natural fibers and nanoparticles <br> Hamdan *et al.* [14]: Reported improved elastic modulus with natural fiber addition |
| Water Immersion Effect | Tensile strength reduction: 55% (unreinforced), 63% (sawdust), 3% (eggshell powder) <br> Flexural strength reduction: 55% (unreinforced), 63% (sawdust), 3% (eggshell powder) | Dhakal *et al.* [20]: Reported reductions in mechanical properties due to fiber swelling and interface weakening <br> Nóbrega *et al.* [34]: Developed a model to simulate water absorption and its effects |
| Acidic Medium Effect | Tensile strength reduction: 55% (unreinforced), 58% (sawdust), 23% (eggshell powder) <br> Flexural strength reduction: 55% (unreinforced), 58% (sawdust), 23% (eggshell powder) | Banerjee and Patel [23]: Observed varying degrees of degradation in different environments, including acidic media |
| Basic Medium Effect | Tensile strength reduction: 47% (unreinforced), 44% (sawdust), 170% (eggshell powder) <br> Flexural strength reduction: 47% (unreinforced), 44% (sawdust), 6% (eggshell powder) | Aziz and Ansell [22]: Reported changes in properties due to alkalization and fiber alignment <br> Hamdan *et al.* [15]: Observed reductions in compression stress and hardness after immersion in salts |

## 3.3 FEA Results and Discussion

### *3.3.1 Stress Distribution and Deformation Patterns*

The finite element analysis (FEA) simulations provide valuable insights into the stress distribution and deformation patterns of the composite specimens under flexural loading. Figure 24 illustrates the von Mises stress contours and deformed shape for the unreinforced polyester (G1) specimen. The maximum stress concentrations occur at the mid-span, consistent with the applied bending moment. The deformation plot shows the expected bending profile with maximum deflection at the center.

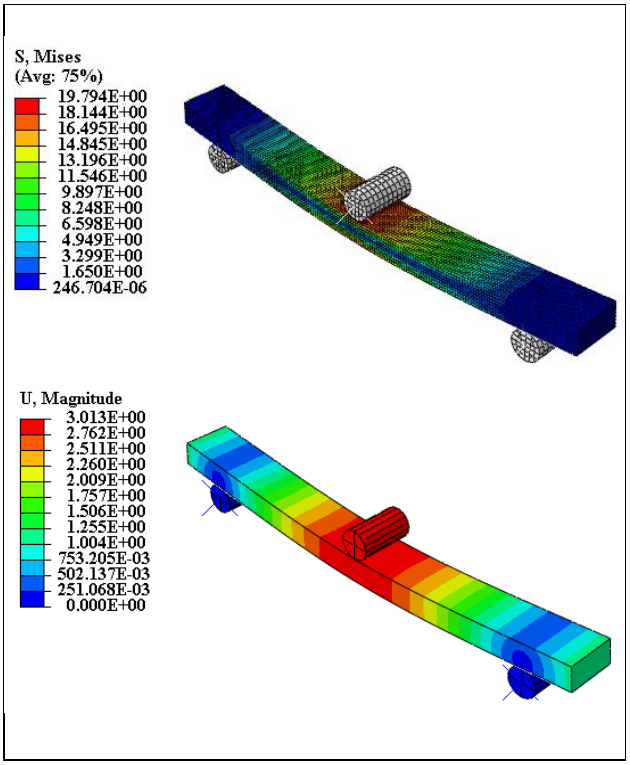

**Figure 24** Von Mises stress and deformation for unreinforced polyester (G1)

For the sawdust-reinforced composite (G2), Figure 8 depicts a more uniform stress distribution with lower peak stresses compared to the unreinforced case. The reduced deflection indicates improved flexural stiffness imparted by the sawdust reinforcement. Similarly, the eggshell powder-reinforced composite (G3) in Figure 25 exhibits a favorable stress state and deformation response due to the reinforcing effects of the eggshell particles. On the other hand, Figure 26 highlights the composite's improved structural integrity under flexural loading, proving the reinforcement strategy works.

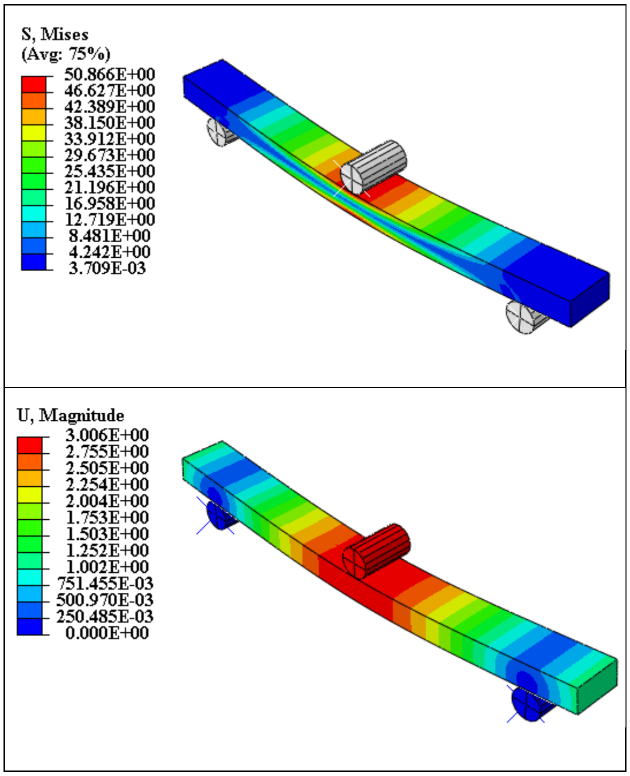

**Figure 25** Von Mises stress and deformation for sawdust composite (G2)

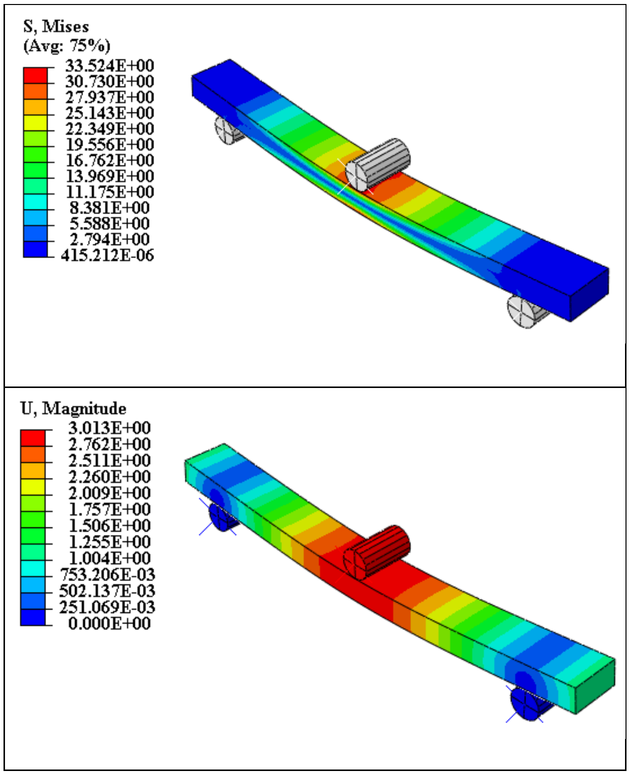

**Figure 26** Von Mises stress and deformation for eggshell composite (G3)

### 3.3.2 Comparison with Experimental Results

The FEA results corroborate the experimental findings regarding the reinforcing effects of sawdust and eggshell powder on the flexural properties. The simulations accurately capture the enhancements in flexural strength observed experimentally, as evident from the reduced maximum stresses and improved flexural stiffness predicted for the reinforced composites.

Furthermore, the stress concentration patterns and deformation modes align with the expected failure mechanisms and locations observed during the three-point bending tests. This correlation between FEA and experiments facilitates a deeper understanding of the underlying mechanics and failure modes in these sustainable composites.

### 3.3.3 Environmental Exposure Effects

To investigate the effects of environmental exposure on the flexural behavior of the composites, additional FEA simulations were conducted, incorporating the degradation of material properties observed in the experimental studies. The material properties of the composite constituents were adjusted based on the experimental data to account for the effects of water immersion, acidic media exposure, and basic media exposure.

Figure 27 shows the von Mises stress distribution and deformed shape of the sawdust-reinforced composite (G2W) specimen after water immersion.

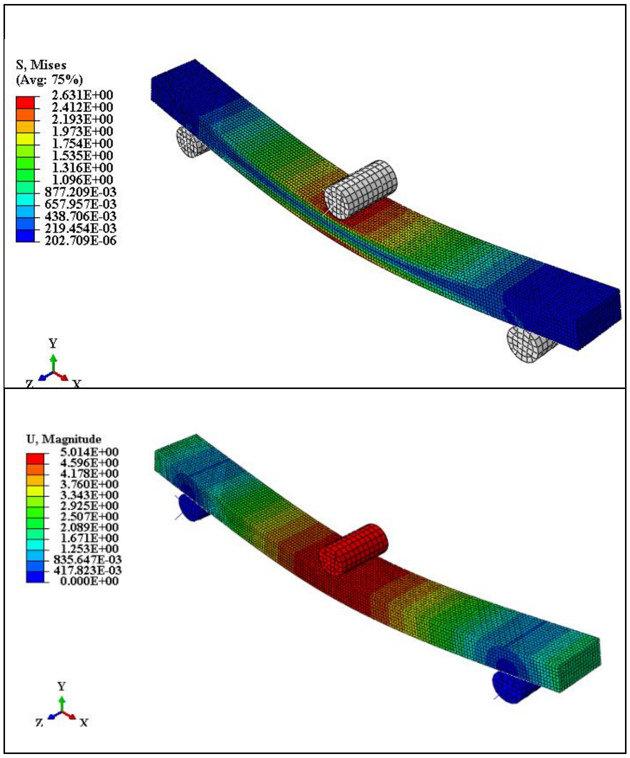

**Figure 27** Von Mises stress distribution and deformed shape of the sawdust-reinforced composite (G2W) specimen after water immersion

Compared to the unexposed condition, the stress contours indicate higher stress concentrations, particularly at the mid-span region. Additionally, the deformed shape exhibits increased deflection, suggesting a reduction in flexural stiffness due to the detrimental effects of water absorption on the composite's mechanical properties.

Figure 28 gives the distribution of von Mises stress and the deformed shape of eggshell powder-reinforced composite G3PH specimen after exposure to acidic media. As in the case of water immersion, the higher concentrated stress regions to be attributed compared with the center-span region are shown to be attributed by higher strains. An altogether deformed form has much more deflection, suggesting the decrease in flexural stiffness and strength due to the harmful effect of acid on constituent materials of the composite and their interface bonding.

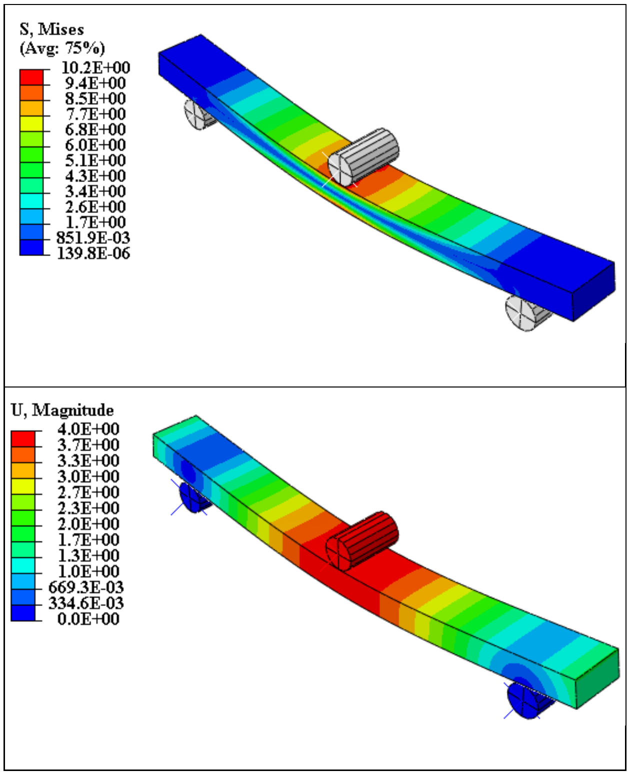

**Figure 28** Von Mises stress distribution and deformed shape of the eggshell powder-reinforced composite (G3PH) specimen after acidic media exposure

There is sufficient consistency between the applied experimental exposure of composites and FEA results of the environmental degradation of the mechanical properties of composites' samples. The simulations effectively reflected increased stress concentration and deformations, corresponding with reduced flexural strength and stiffness observed in the quantified experiments. These show how valuable the findings were in unmasking phenomena that cause marginal property decline in environmentally exposed sustainable composites. They also pinpoint, from the results of the FEA simulation, all critical areas of possible failures in the proposed subcomponents of the composites when exposed to the processes of environmental degradation. Such information could provide guidelines for developing methods to cope with the deleterious effect of environmental exposure through protective coatings, material modifications, or design optimization toward better long-term durability of such composite eco-materials in the service environment.

## 4.0 CONCLUSION

This work aims to relate experimental investigation into the mechanical properties and environmental sustainability of polyester blends formulated with incremental quantities of egg waste powder and sawdust particles. As reinforcing materials, waste videotex and sawdust were used and assessed in polyester composites, thus contributing to a good sustainable practice of waste reduction. Mechanical properties were examined for tensile to compression molding and flexural to hand lay-up for manufactured composite samples with the allocations of these waste materials in a fraction of 35 wt.%. The experimental characterization of the effects of exposure to different environments, such as water and acidic and elemental media immersion, on the composite's mechanical performance was conducted.

The addition of waste natural fibers significantly enhanced the mechanical properties of polyester composites observed the results as the following:

- Bending strength increased by 140% with sawdust reinforcement and 75% with eggshell powder reinforcement.
- Tensile strength improved by 13% with sawdust reinforcement and 10% with eggshell powder reinforcement.
- Environmental exposure led to varying degrees of mechanical property degradation:
- Water immersion reduced tensile strength by 63% for sawdust composites and 3% for eggshell composites. Flexural strength decreased by 63% for sawdust composites and 3% for eggshell composites.
- Acidic medium exposure caused a 58% reduction in tensile strength and flexural strength for sawdust composites, and a 23% reduction for eggshell composites.
- Basic on the medium immersion observed when the sample a striking 170% decrease values of tensile strength and a 6% decrease in flexural strength for eggshell composites. For sawdust composites, tensile and flexural strengths declined by 44%.

These results suggest that protective measures or material modifications must be developed to enhance long-term durability during the service of such eco-friendly composites. To this end, FEA simulations helped complement the experimental investigations further by providing information beneficial to understanding the stress distributions, the deformation mechanisms, and hence, the possible failure modes of the waste natural fiber-reinforced polyester composite under flexural loading conditions. The experimental and computational results capture the effects of reinforcements by sawdust and eggshell powder and environmentally induced degradation. This way, the experimental-computational approach led to a detailed understanding of the flexural response and failure behavior of such sustainable composites to inform the optimization of composite designs and extended service life for a wide range of applications. That is, the abstract changed to focus on the application of FEA along with the supporting computational methodology, but the conclusion was revised to indicate the experimental results experimentally obtained that were validated in practice by the respective FEA simulations and revealed the additional understanding of the flexural behavior and failure mechanisms for such composites.

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## Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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