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ASSESSING THE IMPACT OF ARTIFICIAL UV AGING ON THE MECHANICAL PERFORMANCE OF EPOXY COMPOSITES REINFORCED WITH FLAX: EXPLORING TENSILE STRENGTH PROPERTIES

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ABSTRACT

This research investigates the impact of accelerated weathering, specifically exposure to ultraviolet (UV) light and humidity, on the chemical, and mechanical properties of flax/epoxy composite materials manufactured using the compression molding technique. Two distinct stacking arrangements of these composites, Unidirectional (UFE) and Quasi-Isotropic (QFE), commonly used in industries, were studied. The composites were subjected to 1200 hours of exposure to UV light and moisture in an accelerated weathering chamber by Q-Lab, USA. After exposure, the composites exhibited various chemical and physical changes, including surface roughness and color changes, indicating significant surface degradation. This degradation was evaluated using visual analysis, infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). Our analysis revealed that weathering affected not only the chemical and physical characteristics but also caused notable degradation in mechanical properties. This was evident from tests such as tensile. In tensile testing, after 1200 hours of exposure, the UFE configuration showed a reduction of 11.56% in Young's Modulus, a 12.12% decrease in stress, and a 9.90% decrease in strain. The QFE configuration displayed a 10% decrease in Young's Modulus, a 17.64% decrease in stress, and an 18.59% decrease in strain. For a comprehensive discussion of the methodology, detailed results, and further implications of these findings, see in the longer version.

1 INTRODUCTION

Natural fiber composites have emerged as a promising alternative to traditional synthetic composites across various industrial applications due to their sustainable and environmentally friendly characteristics **[1]**. Flax fibers have garnered significant interest because of their superior mechanical properties, low carbon footprint, cost-effectiveness, and biodegradability. The mechanical properties of flax fibers are primarily attributed to their intrinsic constituents, including cellulose, hemicellulose, wax, lignin, and pectin. Cellulose, hemicellulose, and lignin are especially crucial in determining the physical attributes of the fibers, with cellulose being the stiffest and most robust organic component **[2]**. When integrated with epoxy resin, a commonly used matrix material, flax/epoxy composites offer high mechanical strength, are lightweight, and are ecologically sustainable **[2]**.

However, the long-term durability of natural fiber composites, particularly when exposed to environmental factors such as ultraviolet (UV) radiation and moisture, needs careful consideration **[3]**. Prolonged exposure to these elements can significantly diminish the mechanical properties of the composites **[4]**, an effect compounded by the low lignin content in flax fibers. For lignocellulose fibers like flax, aging or degradation occurs through several mechanisms, including UV radiation absorption by lignin, the formation of quinoid structures, Norrish reactions, and photo-yellowing in lignin **[5]**. Additionally, the inherent hydrophilicity of flax fibers due to surface hydroxyl groups leads to higher moisture absorption, which can accelerate hemicellulose degradation **[6]**. Moisture exposure can also cause the epoxy resin to undergo detrimental changes like chain crosslinking, making it brittle or weakening it through chain scission. Elevated temperatures can exacerbate the deterioration of epoxy resins **[7]**.Given these challenges, comprehensive testing of flax/epoxy composites is essential for ensuring their long-term application. However, conducting tests over extended periods like years is impractical and can hinder product development. Accelerated weathering methods, which simulate long-term degradation within a shorter timeframe, are thus a valuable approach. These tests can replicate the degradation that occurs over months or years in a matter of weeks, allowing for the evaluation and quantification of each degradation factor (humidity, UV, etc.).

Numerous studies have explored the durability of natural fiber composites under these conditions. L. Yan et al. **[8]** observed a degradation in both tensile and flexural properties of flax fabric-reinforced epoxy composites after 1500 hours of combined UV and humidity exposure. S.C. Das et al. **[9]** reported significant discoloration and a decrease in flexural properties due to photo-degradation from accelerated weathering on natural fiber-reinforced recyclable polymer composites compared to glass fiber composites. K. Senthilkumar **[10]** found reductions in tensile and flexural strengths in weathered sisal, hemp, and hybrid sisal/hemp composites, although their impact resistance increased. Similarly. However, the effects of low-velocity impacts on flax/epoxy composites that have been exposed to UV light and humidity have been less studied, yet they are crucial for evaluating structural integrity. **[11-12]**.

Our study aims to address this significant gap by analyzing the mechanical properties of weathered flax/epoxy composites under tensile loads and low-velocity impact conditions, combined with insights from FTIR and SEM observations and X-ray tomography.

2 Experimental procedure

2.1 Materials and Specimens

Composite plates made from 16 layers of flax/epoxy prepreg were produced via compression moulding. These plates were manufactured in two stacking sequences: unidirectional and quasi-isotropic, with an average thickness of approximately 3.47 mm. Specimens for tensile and impact testing were cut using an abrasive water jet method, following ASTM standards.

2.2 Accelerated Weathering

An accelerated weathering experiment was conducted using the QUV/SE apparatus, involving cycles of UV exposure and condensation to simulate aging over a total of 1200 hours according to ASTM G154-23 **[13]**.

2.3 Fourier Transform Infrared (FTIR) Spectroscopy and Scanning Electron Microscope (SEM)

FTIR and SEM analysis were performed to examine the chemical and microstructural changes in the composite samples over time, using a Nicolet™ iS™ 10 FTIR spectrometer and VP-SEM Hitachi SU1510.

2.4 Tensile Tests

Tensile tests on the composites were conducted using an Instron electromechanical testing machine, adhering to the ASTM D3039 **[14]** standard. Each set of conditions was tested on three samples to ensure reliability.

2.5 Low-velocity Impact Tests

Drop weight impact tests were carried out with a specific impact energy to examine the damage threshold. The testing followed ASTM D5628-18 **[15]** standards, using a hemispherical impactor and an anti-rebound system to maintain specimen stability.

2.6 X-ray Micro-tomography

X-ray tomography, a non-destructive method, was used for detailed characterization of the internal structures of the composites, particularly to assess damage phenomena like microcracking and delamination.

The experimental procedure is summarized in **Figure 1.**

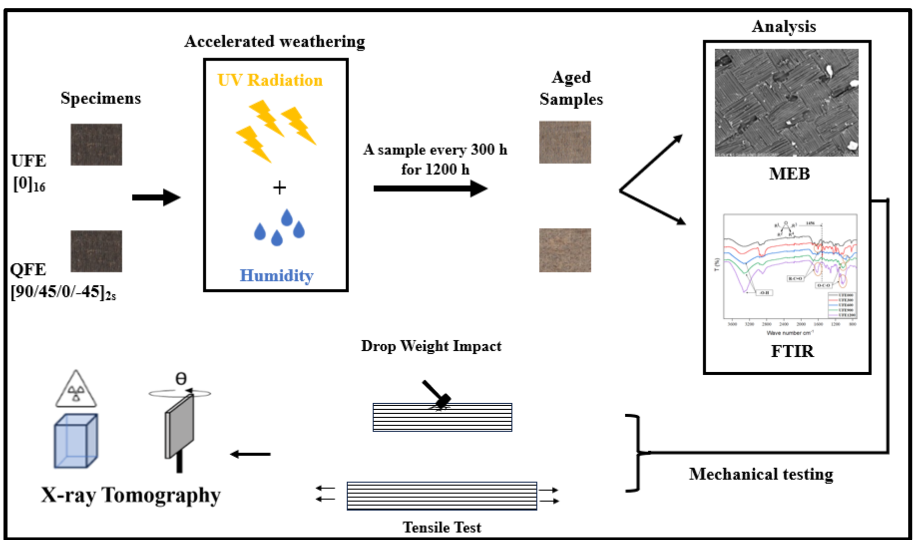

Figure 1. Experimental procedure.

3 Results analysis

3.1 Visual aspect

Figure 2 shows the change in colour of the flax/epoxy composite specimens with time, specifically after 0, 300, 600, 900, and 1200 h of exposure. This change is characterized by yellowing of the specimen surfaces, signifying alterations in their physical and chemical properties. The discoloration is likely attributed to the photodegradation of the epoxy matrix and the flax fibres and the erosion of the polymer matrix.

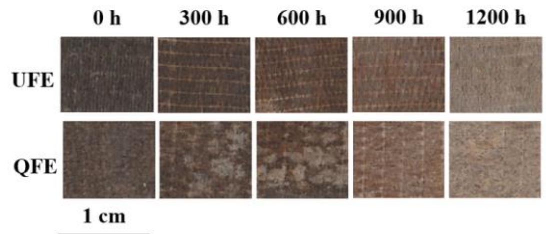

Figure 2. Color change as function of weathering time.

3.2 FTIR and SEM analysis

Figure 3 shows the SEM and FTIR images of the weathered UFE and QFE samples. According to the SEM images, all the configurations exhibited signs of matrix erosion, micro-cracks, and fiber/matrix debonding, with the appearance of fibers on the surface of the composites. The FTIR spectroscopy analysis of the aged flax/epoxy composites reveals significant degradation of the epoxy matrix, evidenced by changes in chemical structure including the formation of carbonyl and ester groups and increased hydroxyl groups from exposed flax fibers. These chemical alterations suggest a decrease in material performance over time.

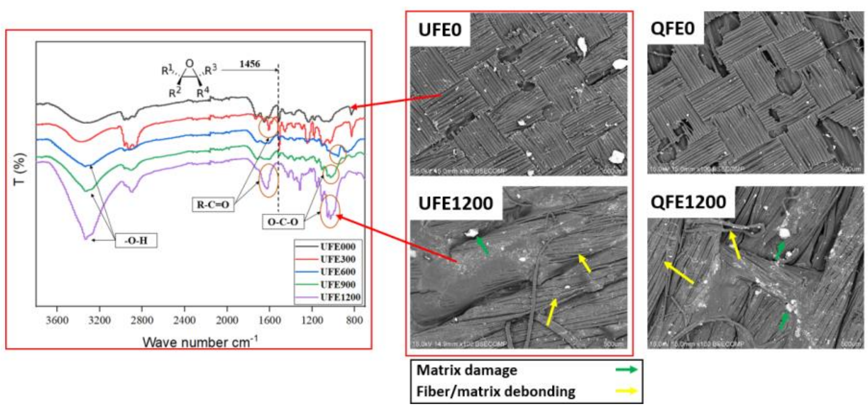

Figure 3. FTIR and SEM images of the UFE and QFE samples before and after 1200 h of weathering time.

3.3 Tensile test

Figure 5 illustrates the stress-strain behavior of specimens subjected to tensile tests before and after exposure to various aging durations (0, 600, and 1200 hours). All configurations exhibited a brittle response, with both stress and strain decreasing as aging time increased. Prolonged exposure to UV radiation leads to matrix degradation in the specimens, causing the formation of voids and micro-cracks that jeopardize the structural integrity of the material. Additionally, the exposed fibers undergo photo-oxidation, exacerbating the degradation of the biocomposite. Among the tested configurations, the UFE (Unidirectional Flax/Epoxy) showed the highest resistance due to its fiber alignment along the loading direction, which enhances stress transfer. The QFE (Quasi-isotropic Flax/Epoxy), with its varied fiber orientations, allows for a more uniform stress distribution but remains vulnerable to weathering effects, particularly matrix degradation and moisture-induced damage due to fiber orientation at 45° and -45°.

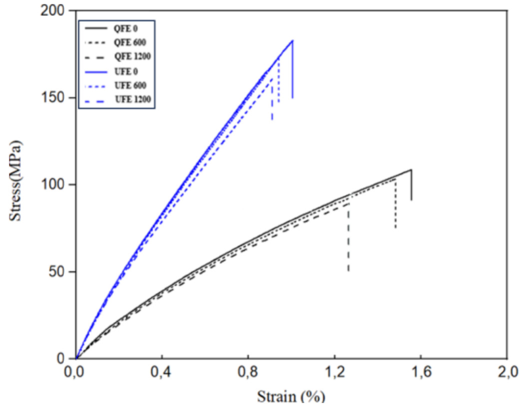

Figure 4. Stress-Strain curves for the UFE and QFE configurations at 0, 600 and 1200 h of weathering time.

3.4 Drop-Weight-Impact test

Flax/epoxy composites with various ply orientations underwent low-velocity impact tests at an energy level of 3 J, which represents 20% of their perforation threshold. Figure 8 displays the load-displacement curves for these composites at 0 and 1200 hours of weathering time. All curves formed a closed loop, showing a linear increase due to elastic behavior until the point of crack initiation, indicated by the first significant drop in the curve due to delamination and matrix cracking. The QFE samples exhibited the highest maximum impact load, followed by UFE. As weathering time increased to 1200 hours, the impact loads decreased by 5.86% and 9.69% for QFE and UFE respectively. This reduction in impact resistance is attributed to superficial microcracks that enhanced damage during impact, increasing both maximum displacement and absorbed energy, as shown by the area inside the bell-shaped curves. The X-ray tomography showed a high presence of delamination in the case of the UFE configurations after 1200 hours of weathering.

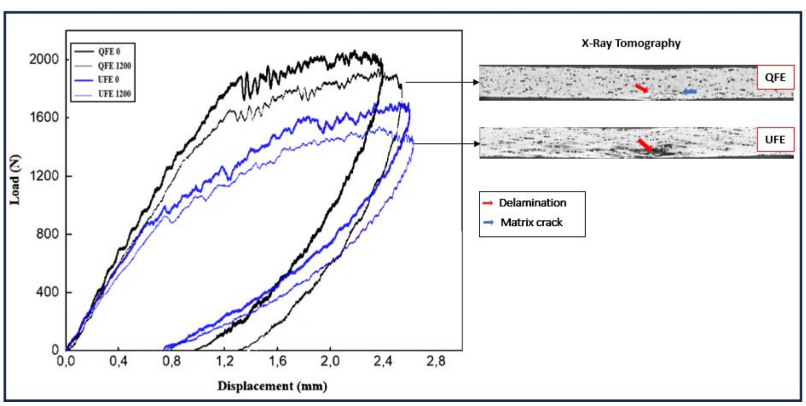

Figure 5. Drop-Weight-Impact and X-ray Tomography of the QFE and UFE configurations.

4 Conclusion

In this investigation, flax/epoxy composite plates with distinct stacking sequences (UFE and QFE) underwent accelerated aging to assess the impact on their mechanical properties and microstructure. Accelerated aging caused visible surface discoloration and microstructural changes, such as matrix erosion and micro-cracks, detected by SEM; these were attributed to the hydrophilic nature of flax fibers and UV-induced matrix degradation. FTIR spectroscopy identified significant chemical changes, including the disappearance of original epoxy peaks and the appearance of new ones, indicating matrix degradation and fiber exposure. Tensile tests revealed a decline in the elastic modulus, stress, and strain with increased weathering, with UFE showing the greatest resistance. Impact testing demonstrated reduced impact loads due to superficial microcracks, with QFE initially displaying the highest resistance.

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