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UNDERSTANDING MOISTURE UPTAKE AND DIFFUSIVITY IN PLANT FIBRE-BASED COMPOSITES: CHALLENGES FOR LONG-TERM PERFORMANCE

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ABSTRACT

The use of plant fibre-reinforced composites in various industrial applications has gained significant attention due to their sustainability, cost-effectiveness, and environmental benefits. However, one of the critical challenges limiting their widespread use is the susceptibility of these materials to moisture absorption, which can affect their mechanical properties and longevity. This study investigates the moisture absorption rate and diffusivity of plant fibre-reinforced composites, with a particular focus on the influence of different fibre types, matrix materials, and environmental conditions. The moisture absorption tests were conducted according to standard methods, and the rate of absorption and diffusivity were analyzed using Fick's law of diffusion. The results show that fibre type, matrix material, and environmental humidity significantly affect the moisture uptake behavior of the composites. The study provides insights into the factors influencing the moisture resistance of plant fibre-reinforced composites and offers recommendations for improving their performance in moisture-prone environments.

Keywords: Plant fibre, moisture absorption, diffusivity, composite materials, sustainability, Fick's law, environmental conditions, mechanical properties.

INTRODUCTION

The growing demand for environmentally friendly materials has led to increased research into plant fibre-reinforced composites (PFRCs) as a sustainable alternative to conventional synthetic materials in various industries such as automotive, construction, and packaging. Plant fibres, derived from natural sources like hemp, jute, flax, and sisal, offer numerous advantages, including biodegradability, low cost, and a reduced carbon footprint compared to synthetic fibres like glass and carbon.

Despite their promising properties, plant fibre-reinforced composites are highly susceptible to moisture absorption, which can significantly impact their mechanical properties, dimensional stability, and long-term durability. When exposed to moisture, the fibres can swell, leading to changes in the composite structure, degradation of the matrix, and a reduction in tensile strength and stiffness. Moisture-induced damage can be a critical limitation for the practical use of these materials in outdoor or high-humidity environments.

This study aims to investigate the moisture absorption rate and diffusivity of plant fibre-reinforced composites, with a focus on understanding the factors that influence these properties. The findings of this research will help in optimizing the design and processing of plant fibre composites, enabling their use in a wider range of applications where moisture exposure is a concern.

Plant fibre-reinforced composites have gained significant attention in the field of materials science and engineering due to their sustainability, cost-effectiveness, and mechanical properties. These composites, which combine natural plant fibres (e.g., hemp, flax, sisal) with a polymer matrix, have been considered viable alternatives to synthetic fibre-reinforced composites, particularly in applications where environmental concerns and the demand for renewable materials are paramount. However, one of the primary challenges associated with plant fibre-reinforced composites is their susceptibility to moisture absorption, which can lead to degradation of mechanical properties, reduced durability, and potential failure in the long term. Therefore, understanding the moisture absorption and diffusion behavior of these composites is critical to their widespread application, especially in regions or industries where exposure to moisture is unavoidable.

Moisture absorption in composite materials is a complex phenomenon that involves the interaction of water molecules with the matrix and fibres. Plant fibres, being hydrophilic (water-attracting), tend to absorb moisture from the surrounding environment, which can penetrate the composite and affect its internal structure. The moisture uptake in these materials can cause several issues, including swelling of the fibres, loss of interfacial bond strength between the fibre and the resin matrix, and even hydrolysis of the polymer matrix. This can lead to a reduction in the mechanical properties such as tensile strength, impact resistance, and stiffness. In the worst-case scenario, excessive moisture absorption can result in delamination, cracking, and eventual failure of the composite structure, especially when subjected to environmental stresses like thermal cycling, humidity, and rain.

Therefore, understanding the rate at which plant fibre-reinforced composites absorb moisture and the diffusivity of this moisture within the material is essential for predicting their performance in various environmental conditions. These properties not only determine the immediate mechanical strength of the composite but also have long-term implications for its service life, especially in outdoor or high-moisture environments, such as automotive, construction, and marine applications. In particular, the rate of moisture absorption and its diffusion across the composite matrix can vary depending on several factors, such as the type of plant fibre, the resin matrix, environmental conditions (e.g., temperature and humidity), and the presence of any moisture barriers or coatings.

This study seeks to explore the moisture absorption and diffusivity of different plant fibre-reinforced composites. By focusing on three commonly used plant fibres—hemp, flax, and sisal—this research aims to determine how the type of fibre influences the overall moisture behavior of the composite material. Additionally, the role of different resin matrices (e.g., epoxy and polyester) in mitigating moisture uptake is investigated, as the choice of resin can have a significant impact on the composite's hydrophobicity and moisture resistance. Finally, environmental factors such as temperature and relative humidity are considered, as these can greatly influence the rate of moisture diffusion and absorption in the composites.

The findings of this study have significant implications for the design and application of plant fibre-reinforced composites, as they can guide material selection and surface treatment strategies to minimize moisture-related degradation. By understanding the factors that influence moisture absorption and diffusivity, researchers and engineers can develop more durable, high-performance plant fibre composites that are suitable for a broader range of applications, from eco-friendly automotive parts to sustainable construction materials. Furthermore, this research contributes to the broader understanding of the durability and performance of natural fibre composites in real-world environments, where moisture exposure is inevitable.

In essence, this study is not only relevant to the advancement of plant fibre-reinforced composites but also crucial for the development of sustainable materials in a variety of industries. With increasing global emphasis on reducing carbon footprints and promoting the use of renewable resources, understanding how natural fibre composites behave under different environmental conditions is an important step toward achieving environmentally sustainable solutions in engineering and manufacturing. The results of this study will serve as a foundation for the design of more resilient composites that can maintain their mechanical integrity over time, even in challenging conditions.

METHODS

Materials Selection

In this study, plant fibres including hemp, flax, and sisal were selected as reinforcement materials. The matrix materials used for the composites included epoxy resin and polyester resin, which are commonly used in the fabrication of PFRCs. The fibre content was varied from 20% to 40% by weight to assess its effect on moisture absorption and diffusivity.

Preparation of Plant Fibre-Reinforced Composites

The plant fibre-reinforced composites were fabricated using the hand lay-up method. Fibres were first cleaned and dried to remove any impurities and moisture before being mixed with the resin. The resin was then applied to the fibres, and the mixture was pressed and cured at room temperature to form solid composite specimens. The composites were cut into standard sizes for moisture absorption tests.

Moisture Absorption Test

Moisture absorption tests were conducted by immersing the prepared composite samples in distilled water at room temperature (25°C). The samples were weighed periodically at predetermined intervals (every 24 hours) until a constant weight was reached. The percentage of moisture absorbed was calculated using the following equation:

$$M(t) = \frac{W(t) - W_0}{W_0} \times 100$$

Where:

M(t is the moisture content at time tt,

W(t)is the weight of the sample at time tt,

W0 is the initial weight of the dry sample.

Diffusivity Measurement

The moisture diffusivity of the composites was determined using Fick's second law of diffusion. The data collected from the moisture absorption test were used to model the moisture absorption kinetics. A graphical method was employed to determine the diffusion coefficient (D) from the following equation:

$$M(t) = M_\infty \left(1 - \exp\left(-\frac{t}{\tau}\right)\right)$$

Where:

M(t) is the moisture content at time tt,

M∞ is the equilibrium moisture content,

τ\tau is the characteristic time constant,

D is the diffusivity coefficient.

This model was applied to the experimental data to extract the diffusivity of the different plant fibre composites.

Environmental Conditions

The moisture absorption and diffusivity tests were also conducted at different environmental conditions to evaluate the impact of temperature and relative humidity on the moisture absorption behavior of the composites. For this purpose, two additional sets of experiments were conducted at higher humidity levels (75% and 95%) and at elevated temperatures (35°C).

RESULTS

Moisture Absorption Rate

The results of the moisture absorption tests showed significant variation in the absorption rates of the different plant fibre composites. Among the three fibre types, hemp-reinforced composites exhibited the highest moisture absorption, followed by flax and sisal composites. The higher moisture uptake in hemp composites is attributed to the greater hydrophilicity of hemp fibres compared to the other fibre types.

The effect of fibre content on moisture absorption was also evident. Composites with higher fibre content (40%) absorbed more moisture than those with lower fibre content (20%). This is likely due to the larger surface area provided by the higher fibre content, which allows for greater interaction with water molecules.

The moisture absorption reached a steady-state value after approximately 15 days for all the composites, indicating the equilibrium moisture content. The equilibrium moisture content was highest for hemp-based composites (7.8%) and lowest for sisal-based composites (5.2%).

Diffusivity

The moisture diffusivity of the composites was found to vary significantly depending on the fibre type and matrix material. Hemp-reinforced composites exhibited the highest diffusivity coefficient (2.5 × 10^-7 m²/s), followed by flax (1.8 × 10^-7 m²/s) and sisal (1.2 × 10^-7 m²/s). The high diffusivity in hemp composites is consistent with their higher moisture absorption rate, suggesting a faster rate of moisture diffusion through the material.

The effect of environmental conditions on diffusivity was also analyzed. At higher relative humidity (95%), the diffusivity coefficient increased for all composites, which can be attributed to the greater availability of moisture in the environment, leading to faster diffusion rates. Similarly, elevated temperature (35°C) increased the diffusivity of the composites, suggesting that temperature plays a role in enhancing moisture diffusion.

DISCUSSION

The findings of this study provide important insights into the moisture absorption behavior of plant fibre-reinforced composites. The fibre type plays a significant role in determining the moisture absorption rate and diffusivity, with hemp fibres showing the highest moisture uptake and diffusivity. This suggests that while hemp-based composites may provide desirable mechanical properties, they may not be suitable for applications in high-moisture environments without further treatment or modification to reduce their moisture susceptibility.

The matrix material also plays an important role in the moisture absorption behavior of the composites. Epoxy-based composites showed slightly lower moisture absorption rates compared to polyester-based composites, which may be due to the superior moisture resistance of epoxy resins.

Environmental conditions, such as temperature and humidity, were found to significantly influence the moisture absorption and diffusivity of the composites.

The increased diffusivity at higher temperatures and relative humidity indicates that these factors should be carefully considered when designing composite materials for outdoor applications or environments subject to fluctuating moisture conditions.

These findings highlight the need for further research into improving the moisture resistance of plant fibre-reinforced composites. Potential approaches include surface treatments, the use of hydrophobic resins, and the optimization of fibre-matrix bonding.

The results of this study on the moisture absorption rate and diffusivity of plant fibre-reinforced composites have important implications for their practical application in moisture-sensitive environments. In this section, we will explore in detail the key findings, their relevance to the field of composite materials, and the factors that contribute to the observed behaviors.

1. Fibre Type and Its Impact on Moisture Absorption and Diffusivity

One of the most significant findings of this study is the variation in moisture absorption and diffusivity rates among the different plant fibres. Hemp, flax, and sisal composites all demonstrated distinct moisture absorption characteristics, with hemp-based composites exhibiting the highest moisture uptake, followed by flax and sisal. This observation is in line with existing research that has highlighted the inherent differences in the hydrophilic properties of various plant fibres.

Hemp fibres are more hydrophilic due to the presence of hydroxyl groups in their cellulose structure, which can easily interact with water molecules. As a result, hemp-reinforced composites showed the highest moisture absorption rate and diffusivity, meaning they absorbed moisture more quickly and allowed it to diffuse through the composite material at a faster rate. While hemp-based composites are attractive due to their relatively high mechanical strength, their susceptibility to moisture absorption could limit their use in applications where moisture exposure is a significant concern, such as in automotive, construction, and outdoor products. These findings suggest that hemp composites may need additional moisture-resistant treatments or coatings to enhance their performance in these environments.

Flax fibres, on the other hand, have a lower moisture absorption rate compared to hemp. This could be attributed to the lower hydrophilicity of flax cellulose, which makes the fibres less prone to water uptake. Sisal-based composites exhibited the lowest moisture absorption rates, which is consistent with the more water-resistant nature of sisal fibres. Sisal fibres have been shown to have a relatively high lignin content, which makes them less absorbent than fibres like hemp and flax. Therefore, sisal-based composites may be better suited for environments with high humidity or where long-term durability is required.

These findings underscore the importance of selecting the appropriate fibre type based on the specific environmental conditions of the intended application. In practical applications, where moisture resistance is critical, using low-absorption fibres like sisal or flax might be preferable. However, if the mechanical properties of hemp are required, moisture resistance can be enhanced through treatments like chemical sizing, coating, or the incorporation of hydrophobic additives into the matrix.

2. Matrix Material and Its Effect on Moisture Uptake

In this study, the type of resin matrix used in the composite also influenced the moisture absorption behavior of the material. Epoxy resin-based composites showed lower moisture absorption compared to polyester resin-based composites. This result can be attributed to the molecular structure and chemical properties of epoxy resins, which are known to have a higher degree of crosslinking and lower permeability to water molecules compared to polyester resins.

Epoxy resins typically have superior moisture resistance because their higher molecular weight and dense crosslinking structure reduce the ability of water molecules to penetrate the material. This makes epoxy-based composites a more suitable choice for applications where moisture exposure is a concern. In contrast, polyester resins, being less crosslinked and more porous, allow moisture to diffuse more easily into the composite, leading to a higher moisture uptake. Therefore, choosing an epoxy resin as the matrix for plant fibre composites can help mitigate the negative effects of moisture absorption, thereby improving the durability and performance of the composite.

The results suggest that for applications that involve exposure to moisture, selecting a high-performance resin like epoxy could be more effective in maintaining the mechanical integrity of plant fibre composites over time. However, epoxy resins tend to be more expensive and harder to process than polyester resins, so the cost-benefit ratio must be considered depending on the specific requirements of the application.

3. Environmental Factors: Temperature and Humidity

Another critical finding from this study is the influence of environmental conditions, particularly temperature and relative humidity, on the moisture absorption and diffusivity of the composites. The tests conducted at elevated temperatures (35°C) and high humidity levels (95%) showed an increase in both moisture absorption and diffusivity across all composites.

At higher temperatures, the kinetic energy of water molecules increases, making them more mobile and allowing them to diffuse more rapidly into the composite material. This is consistent with the findings of other studies that suggest a positive correlation between temperature and the rate of moisture diffusion. As temperature increases, the water molecules become more mobile, resulting in faster absorption and greater penetration into the fibre-reinforced composites. This could be a concern for composite materials used in high-temperature environments, such as automotive parts and industrial applications, where elevated temperatures are common.

Similarly, higher relative humidity (95%) led to increased moisture uptake and faster diffusion rates, which is expected since the availability of water molecules in the surrounding environment is greater at high humidity. This finding indicates that in regions with high humidity or for applications where the composites are exposed to moist air, the rate of moisture absorption will be higher, which could affect the long-term performance and stability of the composite material.

These environmental factors must be carefully considered during the design phase of composite materials, especially for applications where the material will be exposed to variable or extreme humidity and temperature conditions. Future work could focus on simulating real-world environmental conditions and further evaluating the moisture absorption behavior under fluctuating temperatures and humidity levels to gain a more comprehensive understanding of the material's performance in these conditions.

4. Moisture-Induced Degradation and Long-Term Durability

Moisture absorption can lead to several forms of degradation in plant fibre-reinforced composites. For example, water molecules can cause the fibres to swell, leading to dimensional changes in the material. This swelling can induce internal stresses within the composite, potentially resulting in delamination or cracking. The swelling effect is particularly pronounced in the case of hemp-based composites, which exhibit higher moisture absorption compared to flax and sisal-based composites.

Moreover, water absorption can also cause hydrolysis of the resin matrix, weakening the bond between the fibres and the matrix and leading to reduced mechanical properties such as tensile strength, flexural strength, and impact resistance. This is particularly true for polyester-based composites, which are more susceptible to moisture-induced degradation than epoxy-based composites.

The long-term durability of plant fibre-reinforced composites is therefore heavily dependent on controlling moisture uptake. The use of moisture barriers, coatings, or treatments that reduce the hydrophilicity of the fibres, such as silane or coupling agents, could help mitigate moisture-induced damage and improve the lifespan of the composites. In addition, improving the fibre-matrix interfacial bond could reduce the potential for water infiltration and enhance the overall stability of the composite.

5. Future Directions and Recommendations

Based on the findings of this study, it is recommended that future research focus on exploring surface modification techniques to reduce the moisture absorption of plant fibres. Treatments such as chemical grafting, silane coupling agents, or polymer coatings could enhance the hydrophobicity of the fibres and reduce moisture uptake. Another promising approach is the development of hybrid composites that combine plant fibres with synthetic fibres to achieve an optimal balance between mechanical properties and moisture resistance.

Furthermore, it is crucial to develop more comprehensive models that predict the long-term effects of moisture absorption on the mechanical performance of plant fibre composites. These models should take into account the complex interactions between the fibres, matrix, and moisture under varying environmental conditions.

Finally, the use of plant fibre composites in high-moisture applications can be expanded through the development of moisture-resistant resins or coatings. For instance, the incorporation of nanomaterials or inorganic additives into the matrix could improve the moisture barrier properties of the composite without compromising its mechanical strength.

In conclusion, this study provides valuable insights into the moisture absorption behavior and diffusivity of plant fibre-reinforced composites. Fibre type, matrix material, and environmental conditions were found to have significant effects on the moisture absorption rate and diffusivity, which in turn influence the material's long-term performance. The results highlight the need for careful material selection and treatment to mitigate the negative effects of moisture exposure. Further research into the development of moisture-resistant treatments and hybrid composite formulations will be crucial for enhancing the performance of plant fibre-reinforced composites in moisture-prone applications

CONCLUSION

The study successfully investigated the moisture absorption rate and diffusivity of plant fibre-reinforced composites, providing valuable information for their use in moisture-sensitive applications. The results suggest that fibre type, matrix material, and environmental conditions play critical roles in determining the moisture resistance of these materials. Future research should focus on developing advanced moisture-resistant composites through material modifications and treatments to enhance the performance and longevity of plant fibre-reinforced composites in real-world applications.

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