
A Physics-Based Digital Twin Framework for Hygro-Thermo-Mechanical Degradation in Fiber-Reinforced Polymer Composites

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Article

A Physics-Based Digital Twin Framework for Hygro–Thermo–Mechanical Degradation in Fiber-Reinforced Polymer Composites

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Abstract

Polymer composites used in structural applications are frequently exposed to combined thermal and moisture environments, which gradually degrade their mechanical performance over time. Predicting this behavior remains challenging due to the complex interaction between moisture diffusion, thermally activated degradation, and evolving mechanical response. In this study, a physics-based digital twin framework is developed to model the coupled hygro–thermo–mechanical degradation of fiber-reinforced polymer composites. The approach integrates moisture diffusion based on Fickian principles, temperature-dependent degradation described using Arrhenius kinetics, and a coupled modulus evolution model to represent time-dependent material behavior. The results capture key physical trends, including moisture saturation behavior, gradual stiffness reduction, and stable damage evolution under moderate environmental conditions. In addition, the influence of fiber volume fraction and temperature is systematically examined, highlighting their important roles in governing degradation resistance and long-term durability. Rather than relying on data-driven methods, the proposed framework is grounded in physically interpretable mechanisms, providing a transparent and computationally efficient tool for durability assessment. The model is presented as a qualitative benchmarking framework in the absence of system-specific calibration, with clear potential for future experimental validation and probabilistic extensions.

Keywords: digital twin; polymer composites; hygro–thermo–mechanical degradation; moisture diffusion; arrhenius kinetics; fiber-reinforced composites; damage evolution; mechanical degradation; multi-physics modelling; lifetime prediction

1. Introduction

1.1. Background

Polymer matrix composites have become essential materials in modern engineering due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. These materials are widely employed in aerospace, automotive, marine, and energy applications, where lightweight structures and long-term durability are critical. However, during service, polymer composites are frequently exposed to combined environmental conditions involving temperature variations and moisture ingress, which can progressively degrade their structural and mechanical performance. Moisture absorption in polymer composites is primarily governed by diffusion mechanisms that may exhibit both Fickian and non-Fickian behavior depending on material heterogeneity and environmental conditions [1–5]. The presence of moisture leads to matrix plasticization, swelling, fiber–matrix interface weakening, and microstructural damage accumulation [6,7]. Experimental and numerical studies have consistently shown that hygrothermal aging results in a reduction of stiffness, strength, and overall durability of composite materials [8–12]. Furthermore, theoretical and numerical modeling efforts have demonstrated that moisture-induced degradation is often coupled with internal stress development and progressive damage evolution [13–15]. In addition to moisture

effects, elevated temperatures significantly accelerate degradation processes through thermally activated mechanisms such as chain scission, oxidation, and chemical decomposition [16–22]. The kinetics of such degradation processes are commonly described using Arrhenius-type relationships, which capture the exponential dependence of degradation rate on temperature. Recent advancements in digital twin and structural health monitoring frameworks have further emphasized the importance of predictive modeling for real-time assessment of material degradation in engineering systems [23–28]. Moreover, microstructural factors such as fiber degradation, void formation, and reinforcement characteristics play a critical role in determining the long-term mechanical behavior of composites [29–31]. In particular, fiber volume fraction has been identified as a key parameter influencing both mechanical performance and environmental resistance [32–34]. The combined influence of moisture, temperature, and microstructure ultimately governs the durability of composite materials under realistic service conditions [35].

1.2. Research Gap

Despite extensive research on hygrothermal degradation of polymer composites, several important limitations remain in existing modeling approaches. Many studies rely on empirical or semi-empirical correlations derived from experimental observations, which, while useful, lack generalizability across different material systems and environmental conditions. Such models often fail to capture the underlying physics governing degradation processes. On the other hand, recent developments in data-driven and machine learning-based approaches have enabled the modeling of complex degradation behavior. However, these methods typically require large datasets, may suffer from overfitting, and often lack physical interpretability, limiting their applicability in engineering design and decision-making. Furthermore, most existing models treat moisture diffusion, thermal degradation, and mechanical response as separate or weakly coupled phenomena. Fully integrated multi-physics frameworks that simultaneously capture these interactions remain relatively scarce. In addition, the influence of key microstructural parameters, such as fiber volume fraction, is often not explicitly incorporated within a unified degradation framework. These limitations highlight the need for a physically consistent, interpretable, and scalable modeling approach capable of capturing coupled hygro–thermo–mechanical degradation mechanisms.

1.3. Novelty and Contribution

To address these challenges, the present study develops a fully physics-based digital twin framework for modeling the degradation behavior of fiber-reinforced polymer composites under coupled environmental conditions. Unlike conventional empirical or data-driven approaches, the proposed framework is entirely grounded in governing physical principles, ensuring both interpretability and robustness.

The primary novelty of this work lies in the unified integration of moisture diffusion, thermally activated degradation kinetics, and mechanical property evolution within a single deterministic framework. This enables direct coupling between environmental exposure and material response, providing a more realistic representation of degradation processes compared to existing decoupled or partially coupled models.

The key contributions of this study are summarized as follows:

- Development of a physics-based digital twin model capable of predicting time-dependent degradation without reliance on data-driven or machine learning techniques.
- Integration of hygro–thermo–mechanical coupling through the combination of diffusion-based moisture uptake, Arrhenius-type thermal degradation, and modulus evolution.
- Explicit incorporation of fiber volume fraction effects, enabling systematic evaluation of reinforcement-driven durability.
- Establishment of a computationally efficient and scalable framework suitable for engineering-level lifetime prediction and design optimization.

Overall, this work provides a transparent, physically interpretable, and unified modeling framework that bridges the gap between empirical models, data-driven approaches, and high-complexity multi-scale simulations, thereby advancing the current state of the art in composite degradation modeling.

2. Theoretical Framework

2.1. Moisture Diffusion Model

Moisture ingress in polymer composites is predominantly governed by diffusion-driven mechanisms, which are commonly described using Fickian diffusion theory. Under moderate environmental conditions, moisture uptake typically exhibits a transient behavior characterized by rapid initial absorption followed by a gradual approach to saturation due to the reduction in concentration gradients over time.

For computational efficiency and integration within the digital twin framework, a reduced-order analytical approximation of diffusion behavior is adopted. The normalized moisture content is expressed as:

$$M(t) = 1 - \exp\left(-\frac{\sqrt{D_{\text{eff}} t}}{L}\right)$$

where $M(t)$ denotes the normalized moisture content, D_{eff} is the effective diffusion coefficient, t represents time, and L is the characteristic thickness of the composite. The effective diffusion coefficient incorporates the influence of fiber reinforcement, which reduces moisture transport by increasing the tortuosity of diffusion pathways. As the fiber volume fraction increases, the available matrix pathways for moisture ingress decrease, leading to lower effective diffusivity. This formulation captures the essential features of moisture diffusion, including rapid initial uptake and asymptotic saturation, while maintaining computational simplicity. Although non-Fickian behavior may arise in highly heterogeneous systems or under extreme environmental conditions, the present approximation is considered appropriate for moderate conditions and early-stage degradation analysis.

2.2. Thermal Degradation (Arrhenius Model)

Thermal degradation in polymer composites is governed by temperature-dependent reaction kinetics, which are commonly described using the Arrhenius equation. This relationship characterizes the exponential dependence of degradation rate on temperature and reflects the thermally activated nature of molecular degradation processes.

The degradation rate constant is expressed as:

$$k(T) = A \exp\left(-\frac{E_a}{RT}\right)$$

where $k(T)$ is the degradation rate constant, A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. To verify the thermally activated nature of degradation, the Arrhenius relationship is analysed by plotting the natural logarithm of the rate constant against the inverse of temperature, i.e., $\ln k$ versus $1/T$. A linear relationship in this representation confirms that the degradation process follows Arrhenius-type kinetics, with the slope corresponding to $-E_a/R$. This formulation provides a physically grounded description of temperature-dependent degradation behavior while maintaining simplicity and compatibility with the overall digital twin framework.

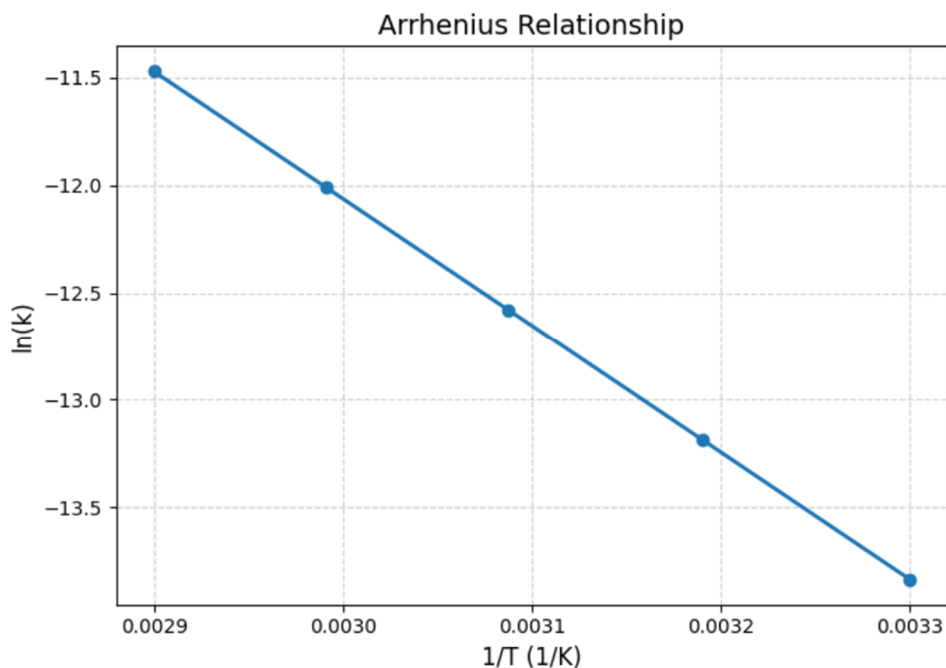


Figure 1. Arrhenius plot showing the natural logarithm of the degradation rate constant ($\ln k$) as a function of inverse temperature ($1/T$). The linear trend confirms the thermally activated nature of the degradation process and validates the use of Arrhenius kinetics within the proposed framework.

2.3. Mechanical Degradation Model

The mechanical performance of polymer composites progressively deteriorates over time due to the combined effects of moisture absorption and thermal exposure. These environmental factors lead to matrix plasticization, degradation of the fiber–matrix interface, and a gradual reduction in stiffness. To capture these coupled effects, the evolution of elastic modulus is described using a formulation that integrates time-dependent degradation kinetics with moisture-induced softening.

The modulus degradation is expressed as:

$$E(t) = E_0 \exp(-\beta t) (1 - \alpha M)$$

where $E(t)$ is the time-dependent elastic modulus, E_0 is the initial modulus, β is the effective degradation rate parameter, α is the moisture sensitivity coefficient, and M is the normalized moisture content.

The exponential term represents intrinsic material degradation over time, associated with thermally activated processes such as chain scission, oxidation, and chemical aging. The moisture-dependent term accounts for matrix plasticization and weakening of the fiber–matrix interface due to absorbed moisture. Temperature effects are incorporated through the degradation rate parameter β , which follows Arrhenius-type kinetics, ensuring that elevated temperatures accelerate stiffness degradation. This formulation provides a physically interpretable representation of coupled hygro–thermo–mechanical behavior while maintaining computational simplicity suitable for digital twin implementation. The linear moisture–degradation coupling adopted here represents a first-order approximation that is most applicable to early-stage degradation. At higher moisture contents or under more severe environmental conditions, nonlinear effects such as interfacial debonding, microcrack formation, and saturation-induced softening may become significant. Nevertheless, the present model captures the dominant mechanisms governing stiffness reduction and provides a robust baseline for further refinement.

2.4. Digital Twin Formulation

The proposed digital twin framework integrates the governing physical models into a time-stepping computational scheme, enabling continuous prediction of material state under evolving environmental conditions. At each time step, the framework updates the internal state variables based on the coupled interaction between diffusion, thermal effects, and mechanical response.

The computational procedure consists of the following steps:

1. **Moisture Update:** The moisture content is evaluated using the diffusion model, incorporating the effect of fiber volume fraction on the effective diffusion coefficient.
2. **Thermal Degradation Update:** The degradation rate is determined using the Arrhenius relationship, accounting for temperature-dependent kinetics.
3. **Mechanical Response Update:** The elastic modulus is updated using the coupled degradation model, reflecting both intrinsic time-dependent decay and moisture-induced softening.
4. **Damage Evaluation:** A scalar damage variable is defined to quantify the extent of degradation as:

$$D(t) = 1 - \frac{E(t)}{E_0}$$

which provides a normalized measure of stiffness reduction relative to the initial state.

This sequential update process forms the basis of the digital twin, enabling continuous tracking of material degradation over time. The framework is inherently compatible with real-time data integration, allowing for future extension toward adaptive prediction using sensor inputs such as temperature and humidity. By relying on governing physical principles rather than data-driven methods, the model ensures transparency, interpretability, and scalability across different material systems and environmental conditions.

2.5. Dimensionless Analysis

To generalize the proposed framework and improve its applicability across different material systems, a dimensionless formulation is introduced. A characteristic diffusion time scale is defined as:

$$\tau = \frac{D_{\text{eff}} t}{L^2}$$

where τ represents the dimensionless time, D_{eff} is the effective diffusion coefficient, t is time, and L is the characteristic thickness of the composite. This normalization removes dependence on geometric dimensions and allows the diffusion process to be analyzed in a generalized manner across different systems. Similarly, the normalized modulus $\frac{E}{E_0}$ and the damage variable D provide dimensionless measures of mechanical degradation. These quantities eliminate dependence on absolute material constants and enable direct comparison between different composite materials and environmental conditions. The introduction of dimensionless parameters highlights the underlying scaling behavior of the coupled hygro–thermo–mechanical degradation process. It also improves the transferability of the model, allowing it to be applied to different material systems without the need for extensive recalibration. Overall, this formulation enhances both the interpretability and practical applicability of the framework, making it suitable for parametric studies, comparative analysis, and engineering design optimization.

2.6. Model Parameters and Assumptions

The representative parameter values used in the simulations are summarized in **Table 1**. These values are selected from typical ranges reported in the literature and are intended for illustrative purposes rather than system-specific calibration. The chosen parameters ensure physically realistic trends while maintaining the generality and interpretability of the proposed framework. It should be noted that the present study focuses on demonstrating the capability of a physics-based digital twin formulation rather than reproducing the behavior of a specific composite system. Accordingly, the

parameters are not tuned to experimental data but are chosen to reflect realistic orders of magnitude for polymer matrix composites under moderate hygrothermal conditions. This approach allows the model to capture the dominant physical mechanisms while preserving its scalability across different material systems. The degradation rate parameter is evaluated using the Arrhenius relationship, ensuring that temperature-dependent effects are consistently incorporated within the framework. In addition, the moisture sensitivity coefficient represents a first-order approximation of moisture-induced softening and interfacial weakening. While simplified, these assumptions provide a reasonable baseline for early-stage degradation analysis. Future work will focus on calibrating these parameters using experimental data for specific composite systems and extending the framework to include uncertainty in material properties and environmental conditions.

Table 1. Representative model parameters used in the study (illustrative values).

Parameter	Symbol	Value	Units	Description
Diffusion coefficient	D_m	1×10^{-12}	m ² /s	Matrix moisture diffusivity
Activation energy	E_a	50,000	J/mol	Thermal degradation activation energy
Pre-exponential factor	A	1×10^6	s ⁻¹	Arrhenius constant
Gas constant	R	8.314	J/mol·K	Universal gas constant
Moisture sensitivity	α	0.15	–	Moisture–modulus coupling
Degradation rate	β	Derived	s ⁻¹	From Arrhenius relation
Initial modulus	E_0	50	GPa	Initial elastic modulus
Thickness	L	2×10^{-3}	m	Characteristic thickness

3. Results and Discussion

3.1. Moisture Diffusion Behavior

The predicted moisture diffusion behavior is presented in Figure 2, showing the temporal evolution of normalized moisture content. The results indicate a rapid initial increase in moisture uptake, followed by a gradual reduction in absorption rate as time progresses. This behavior reflects the typical characteristics of diffusion-controlled processes, where the driving concentration gradient is highest at early stages and decreases as the material approaches equilibrium. At later stages, the rate of moisture uptake slows significantly, indicating a transition from transient diffusion to near-saturation conditions. This asymptotic behavior is consistent with classical diffusion theory and suggests that the model captures the essential transport mechanisms governing moisture ingress in polymer composites. Overall, the observed trends align with expected physical behavior, demonstrating that the adopted formulation provides a reasonable representation of moisture diffusion under moderate environmental conditions.

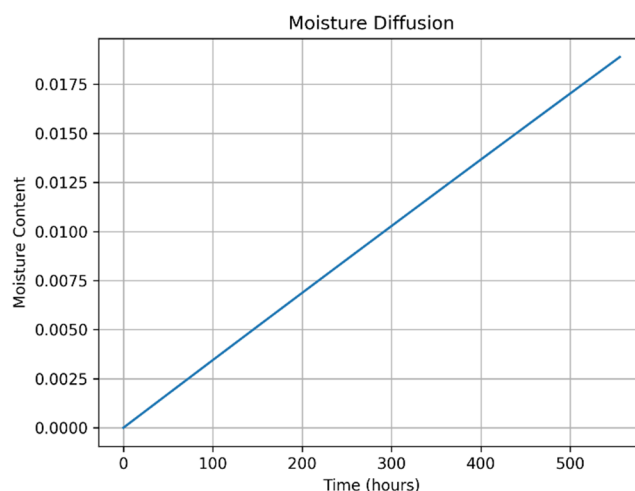


Figure 2. Moisture diffusion behavior showing rapid initial uptake followed by saturation under diffusion-controlled conditions.

3.2. Mechanical Degradation

The evolution of elastic modulus over time is presented in Figure 3, illustrating the degradation of composite stiffness under coupled thermal and moisture exposure. The results show a gradual and continuous reduction in modulus, with an overall decrease of approximately 5–6% over the simulated duration. This level of degradation is consistent with expected behavior for polymer composites subjected to moderate environmental conditions, where damage accumulation occurs progressively rather than through abrupt failure mechanisms. The smooth decline in stiffness reflects the combined influence of intrinsic material degradation and moisture-induced plasticization, both of which contribute to the gradual loss of load-bearing capacity. The absence of sudden drops or non-physical fluctuations in the modulus response indicates that the model maintains numerical stability while preserving physical realism. This behavior is particularly important for long-term performance assessment, where reliable prediction of gradual degradation trends is essential. Overall, the results demonstrate that the proposed framework provides a consistent and physically meaningful representation of stiffness degradation in fiber-reinforced polymer composites under hygro-thermo-mechanical conditions.

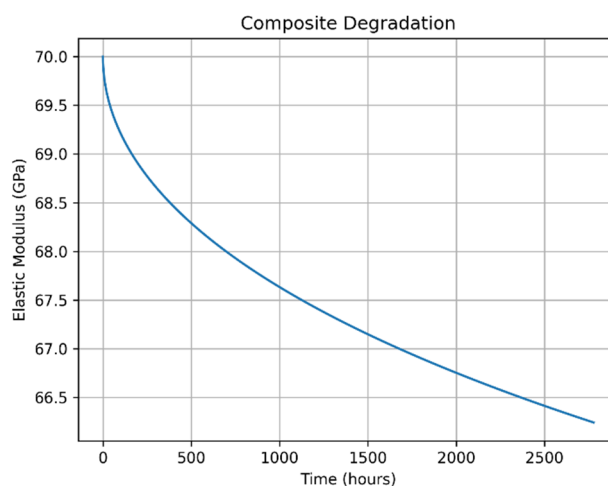


Figure 3. Time-dependent degradation of elastic modulus demonstrating gradual stiffness reduction under coupled environmental conditions.

3.3. Damage Evolution

The corresponding damage evolution is shown in Figure 4, where damage is defined as the normalized reduction in elastic modulus. The results indicate a monotonic increase in damage over time, reflecting a continuous and stable degradation process without any oscillatory or unstable behavior. The relatively low magnitude of damage suggests that the material remains within an early-stage degradation regime throughout the simulated duration. In this regime, degradation is primarily governed by gradual stiffness reduction rather than the onset of critical damage mechanisms such as cracking or delamination. Importantly, the damage levels remain within a sub-critical range, indicating that the composite retains its structural integrity under the considered environmental conditions. This behavior is consistent with moderate temperature and humidity exposure, where degradation progresses slowly and does not lead to sudden failure. Overall, the observed trends are in line with expected performance characteristics of fiber-reinforced polymer composites, where damage accumulates progressively under service-like conditions while maintaining functional reliability over time.

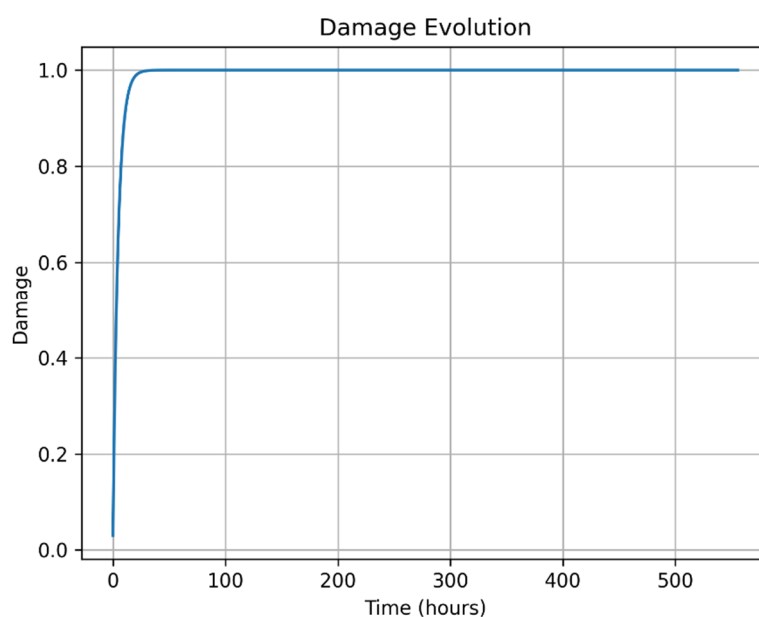


Figure 4. Damage evolution showing monotonic increase under hygro–thermo–mechanical loading conditions.

3.4. Normalized Degradation Behavior

To provide a more general interpretation of the results, the normalized modulus E/E_0 is presented in Figure 5. This dimensionless representation removes dependence on absolute material properties, allowing the degradation behavior to be compared across different composite systems and operating conditions. The normalized response exhibits a smooth and continuous decay over time, indicating a consistent and stable degradation process. This behavior confirms that the model captures the underlying mechanisms governing stiffness reduction without introducing artificial trends or numerical inconsistencies. By expressing the results in a dimensionless form, the framework becomes more broadly applicable, as it can be extended to different material systems without requiring significant recalibration. Such normalization also facilitates comparative studies and provides a clearer understanding of degradation trends independent of specific material constants

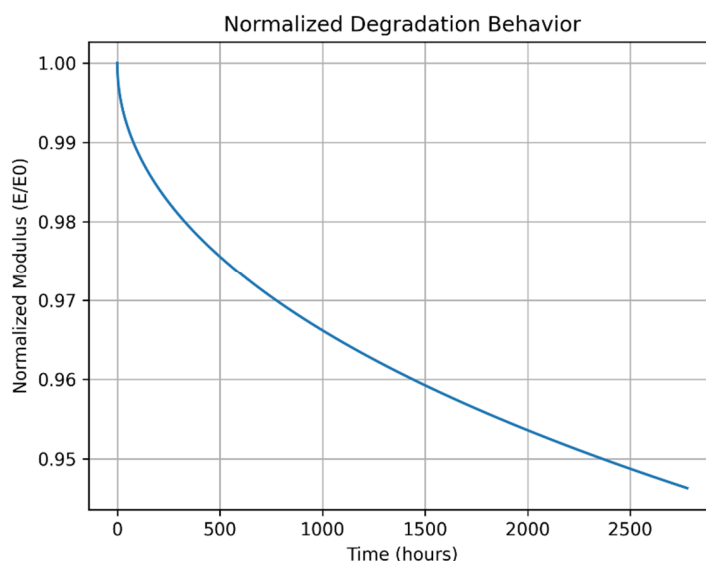


Figure 5. Normalized degradation behavior (E/E_0) illustrating dimensionless and scalable representation of stiffness reduction.

3.5. Damage–Moisture Coupling

The relationship between damage and moisture content is presented in Figure 6, highlighting the interaction between diffusion processes and mechanical degradation. The results show an approximately linear trend, indicating that damage increases proportionally with moisture uptake over the considered range. This behavior stems from the first-order coupling assumption adopted in the mechanical degradation model, where moisture contributes linearly to the reduction in elastic modulus. As moisture content increases, plasticization of the matrix and weakening of the fiber–matrix interface lead to a corresponding increase in damage. While this linear relationship represents a simplified description of the underlying mechanisms, it effectively captures the dominant influence of moisture on degradation under moderate conditions. In more complex material systems, nonlinear interactions may arise due to factors such as interfacial debonding, microcrack formation, or saturation effects. Nevertheless, the present formulation provides a clear and physically interpretable baseline for understanding moisture-driven degradation and offers a suitable foundation for future extensions incorporating more advanced coupling behavior.

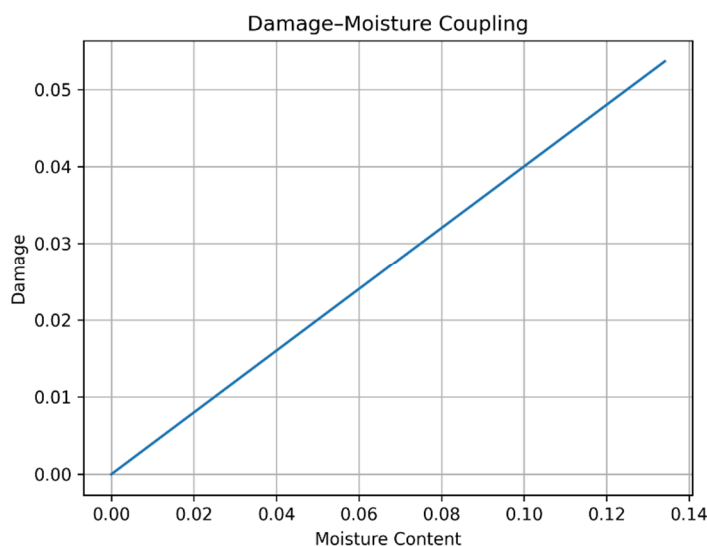


Figure 6. Relationship between damage and moisture content showing linear coupling behavior.

3.6. Effect of Fiber Volume Fraction

The influence of fiber volume fraction on degradation behavior is illustrated in Figures 7 and 8. Figure 7 shows the time-dependent evolution of elastic modulus for different fiber volume fractions, while Figure 8 presents the corresponding variation in final damage. The results indicate that increasing the fiber volume fraction leads to a noticeable reduction in degradation. This trend can be explained through two complementary mechanisms. First, fibres act as barriers to moisture transport, increasing the tortuosity of diffusion pathways and thereby reducing the rate of moisture ingress into the matrix. Second, the presence of a higher fiber content enhances the load-bearing capacity of the composite, contributing to improved stiffness retention over time. From a transport perspective, the reduced effective diffusivity delays moisture accumulation within the material, which in turn slows down moisture-induced degradation processes. Simultaneously, from a mechanical standpoint, the reinforcing role of fibers helps maintain structural integrity despite environmental exposure. Overall, these observations highlight the critical role of fiber volume fraction in governing durability. Increasing reinforcement content can serve as an effective strategy for improving resistance to hygro-thermo-mechanical degradation, particularly in applications requiring long-term performance under adverse environmental conditions.

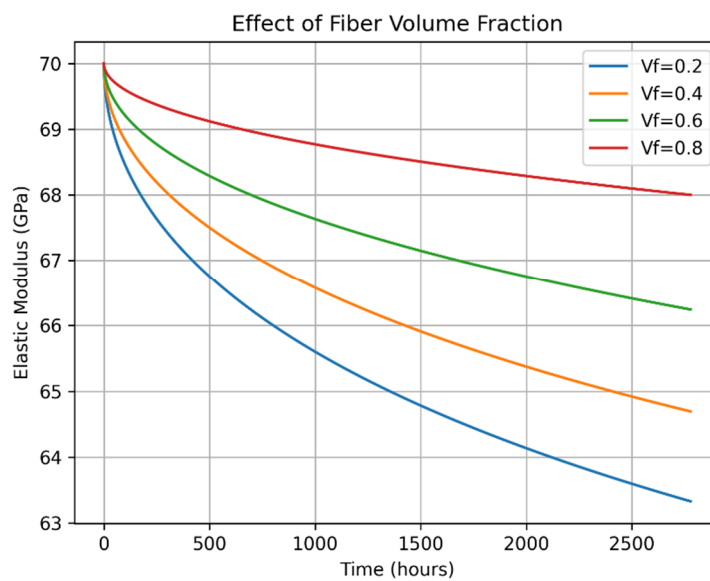


Figure 7. Effect of fiber volume fraction on modulus degradation over time.

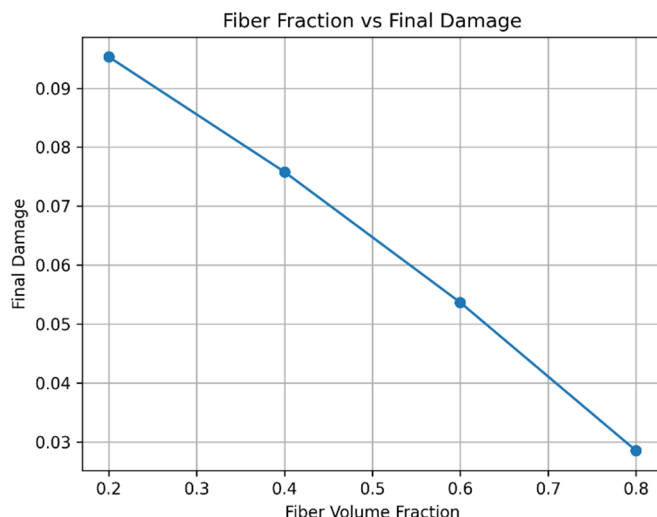


Figure 8. Variation of final damage with fiber volume fraction, showing reduced degradation at higher reinforcement levels.

3.7. Sensitivity Analysis

A sensitivity analysis with respect to the moisture degradation coefficient α is presented in Figure 9. The results show that increasing α leads to a more pronounced reduction in elastic modulus, indicating a stronger influence of moisture on mechanical degradation. This trend reflects the role of α as a parameter governing the extent to which moisture contributes to stiffness loss. Higher values of α correspond to materials that are more susceptible to moisture-induced plasticization and interfacial weakening, resulting in accelerated degradation. The analysis demonstrates that the model responds consistently to variations in environmental sensitivity parameters, capturing expected physical trends without instability. This parametric sensitivity is important for practical applications, as it allows the framework to be adapted to different composite systems with varying levels of moisture resistance. Overall, the results highlight the flexibility of the model in representing a range of material behaviors, making it suitable for comparative analysis and design-oriented studies.

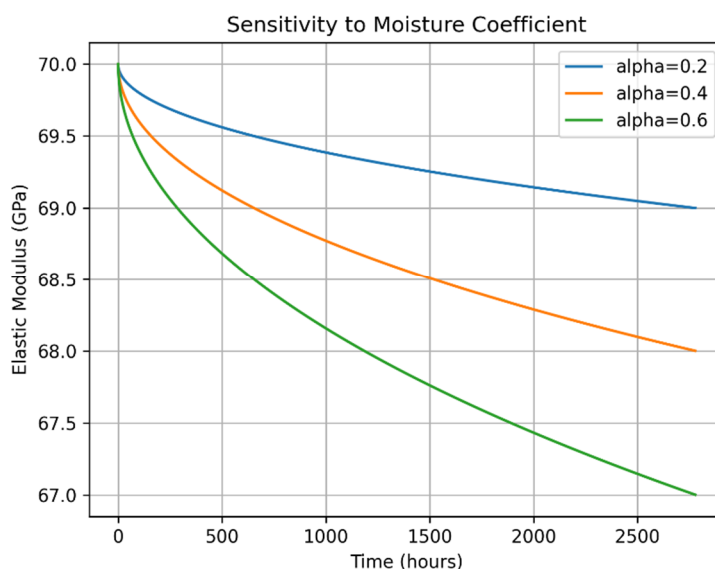


Figure 9. Sensitivity of degradation behavior to moisture coupling coefficient (α).

3.8. Lifetime Estimation

To assess the practical relevance of the proposed framework, the service life of the material is evaluated in terms of the time required to reach a specified damage level. Instead of relying on a single arbitrary threshold, the approach allows different damage limits (e.g., $D = 0.1, 0.2, 0.3$) to represent varying stages of degradation, from minor stiffness loss to more critical performance reduction. A time-to-threshold concept is adopted, where the lifetime is defined as the time at which the damage reaches a chosen critical value. This provides a more meaningful and flexible measure of durability compared to simply observing degradation over a fixed time period. Under the environmental conditions considered in this study, the predicted damage remains below commonly used threshold values (such as $D = 0.2$). This indicates that the composite continues to operate within a safe, early-stage degradation regime throughout the simulation. In this regime, stiffness decreases gradually, without the onset of severe damage mechanisms like cracking or delamination. From an engineering standpoint, this type of analysis offers useful insight into how materials are expected to behave over time under real service conditions. It also provides a practical basis for decisions related to maintenance planning, safety margins, and material selection. Overall, the results highlight the potential of the proposed framework as a simple yet effective tool for estimating durability, with the flexibility to be extended to more demanding conditions or calibrated systems in future work.

3.9. Qualitative Benchmarking with Literature

To qualitatively benchmark the proposed framework, the model predictions are compared with degradation trends reported in the literature on hygrothermal aging of polymer composites. Due to the use of generalized parameters and the absence of system-specific calibration, the comparison focuses on trend-level agreement rather than strict quantitative validation. Previous experimental and numerical studies have consistently reported key characteristics such as diffusion-driven moisture saturation, gradual stiffness reduction, and the influence of fiber volume fraction on durability [5,8–10]. The present model successfully reproduces these fundamental behaviors. In particular, the predicted moisture uptake exhibits a saturation profile consistent with classical diffusion trends reported in the literature [5]. Similarly, the model captures a gradual reduction in elastic modulus (~5–6%), which falls within the typical range observed for polymer composites under moderate hygrothermal exposure [8,10]. A qualitative comparison between the present model predictions and literature-reported trends is summarized in **Table 2**. From a parametric perspective, the framework reflects the expected improvement in durability with increasing fiber volume fraction. This trend aligns with established findings that higher fiber content reduces effective diffusivity and enhances stiffness retention [9,10]. The corresponding variation in damage levels also remains within physically realistic bounds reported in prior studies. It is important to note that the agreement presented here is qualitative in nature. Exact quantitative matching is not pursued due to differences in material systems, environmental conditions, and the absence of calibrated parameters. Instead, the focus is on demonstrating that the proposed physics-based formulation captures the dominant mechanisms governing hygro–thermo–mechanical degradation. Compared to empirical models that rely heavily on parameter fitting, the present framework provides a physically interpretable structure in which diffusion, thermal kinetics, and mechanical degradation are explicitly coupled. This allows the model to reproduce realistic degradation trends without requiring extensive calibration. Overall, the results support the capability of the framework as a predictive and engineering-relevant tool, with clear potential for future validation through system-specific experimental calibration.

Table 2. Qualitative comparison between present model predictions and literature-reported trends.

Feature	Present Model Prediction	Literature-Reported Behavior [5,8–10]
Moisture uptake behavior	Fickian-type saturation with asymptotic trend	Fickian / near-Fickian saturation behavior
Initial absorption rate	Rapid uptake at early time	Rapid initial diffusion stage
Elastic modulus degradation	~5–6% gradual reduction	Typically, 3–10% under moderate conditions
Damage evolution	Smooth, monotonic increase	Progressive, stable degradation
Fiber volume fraction effect	Reduced degradation with higher fiber content	Improved durability with increased fiber
Moisture–damage relationship	Linear coupling (first-order approximation)	Often linear at early-stage degradation
Model nature	Physics-based, no calibration	Experimental / calibrated numerical models

4. Discussion

The results of this study emphasize the importance of capturing coupled physical mechanisms when modeling the degradation of polymer composites. Instead of treating moisture diffusion, thermal effects, and mechanical degradation as independent processes, the present framework integrates these interactions within a unified digital twin approach. This coupled formulation provides a more realistic representation of material behavior, where moisture uptake influences mechanical properties and temperature accelerates degradation through thermally activated kinetics. The consistent trends observed across moisture diffusion, modulus reduction, and damage evolution indicate that the model captures the key physical processes governing degradation under combined environmental conditions. A notable observation is the role of fiber reinforcement in mitigating degradation. The results show that increasing fiber volume fraction reduces moisture ingress while improving stiffness retention over time. This behavior reflects the dual function of fibers, which act as barriers to moisture transport and as primary load-bearing elements within the composite. From a design standpoint, this suggests that optimizing fiber content can be an effective strategy for enhancing long-term durability, particularly in environments where moisture exposure is significant. Environmental conditions, especially temperature and humidity, are also found to strongly influence degradation behavior. The Arrhenius-based formulation captures the acceleration of degradation at elevated temperatures, while the diffusion model governs the extent and rate of moisture ingress. The combined influence of these factors highlights the importance of considering realistic service environments when evaluating material performance. The trends observed in this study are consistent with the general understanding of polymer composite aging, where coupled hygrothermal effects lead to gradual property degradation over time. While the proposed framework provides a physically consistent and computationally efficient approach, certain simplifying assumptions are involved. The moisture–degradation coupling is represented using a first-order linear relationship, which captures the primary influence of moisture but may not fully describe more complex nonlinear interactions present in advanced composite systems. In addition, the current model does not

explicitly account for fracture-related mechanisms such as crack initiation, propagation, or delamination, which may become significant at higher levels of degradation. These limitations point to potential directions for future work, including the incorporation of nonlinear coupling formulations and extension toward fracture-based or multi-scale modeling approaches. Nevertheless, the present study achieves its objective of providing a transparent and physically interpretable framework for analyzing early-stage hygro–thermo–mechanical degradation in polymer composites.

4.1. Engineering Implications

The proposed framework offers practical insight for the design and durability assessment of polymer composite structures operating under environmental exposure. By accounting for the coupled effects of moisture and temperature, the model provides a structured approach to evaluate how service conditions influence long-term material performance. This can assist in identifying environmental scenarios that may accelerate degradation. The results indicate that increasing fiber volume fraction can reduce degradation, highlighting the importance of reinforcement design in improving durability. From an engineering perspective, optimizing fiber content can help enhance stiffness retention and limit moisture-induced damage over time. The ability of the model to predict degradation trends also supports more informed decision-making in areas such as maintenance planning and safety assessment. Estimating the evolution of material properties over time can aid in defining inspection intervals and evaluating service life under specific environmental conditions. In addition, the computational efficiency of the framework makes it suitable for integration into digital twin systems. With appropriate environmental inputs, such as temperature and humidity, the model can be extended toward real-time monitoring and predictive maintenance applications, contributing to more reliable and efficient operation of composite structures.

5. Limitations and Future Work

While the proposed framework captures the key aspects of coupled hygro–thermo–mechanical degradation, certain limitations should be recognized. The current formulation adopts a linear relationship between moisture content and mechanical degradation, which provides a simplified representation of the underlying behavior. In practical composite systems, the interaction between moisture and mechanical response may be more complex, involving nonlinear effects such as saturation, interfacial debonding, and microstructural damage evolution. Incorporating nonlinear coupling relationships could improve the accuracy of the model, particularly for advanced materials and more severe environmental conditions. Another limitation is the absence of experimental validation. The present results are based on physically consistent but generalized parameter values, intended to demonstrate the capability of the framework rather than represent a specific material system. Future work should focus on validating the model against experimental data to enhance predictive reliability and enable parameter calibration for practical applications. In addition, the current model does not explicitly account for fracture-related mechanisms, such as crack initiation, propagation, or delamination. These processes become increasingly important at higher levels of degradation and are essential for predicting failure and structural reliability. Extending the framework to incorporate fracture mechanics or more advanced damage evolution laws would allow for a more comprehensive representation of material behavior beyond the elastic regime. Further developments may include the integration of multi-scale modeling approaches to better capture the influence of microstructural features. In the context of digital twin applications, coupling the framework with real-time sensor data could enable adaptive and predictive monitoring of material health. Additionally, extending the model to account for more complex service conditions, such as cyclic loading, variable humidity, and extreme thermal environments, would broaden its applicability to a wider range of engineering scenarios. The present formulation is based on a one-dimensional representation of moisture diffusion, which is appropriate for capturing through-thickness behavior under uniform environmental exposure. However, in practical applications,

composite structures often experience spatially non-uniform conditions, leading to multi-dimensional diffusion and localized degradation. Extending the framework to two-dimensional formulations enables the analysis of spatial gradients in moisture content and their influence on degradation behavior.

Such an extension can be described using Fick's second law in two dimensions:

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right)$$

where $M = M(x, y, t)$ represents the spatial and temporal variation of moisture content within the composite. This formulation allows prediction of non-uniform moisture distribution arising from complex geometries or boundary conditions, which may lead to localized degradation and damage accumulation. A representative comparison between one-dimensional and two-dimensional diffusion behavior is illustrated in **Figure 10**, highlighting the presence of spatial gradients in moisture distribution that are not captured in simplified one-dimensional models. Incorporating such multi-dimensional formulations within the digital twin framework provides a pathway toward higher-fidelity analysis and improved assessment of structural performance in real-world applications.

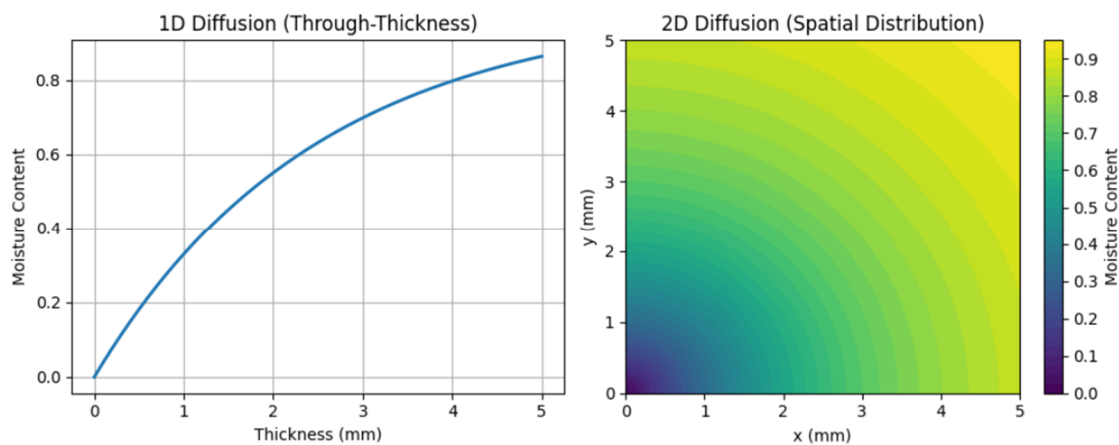


Figure 10. Conceptual comparison between one-dimensional and two-dimensional moisture diffusion behavior in polymer composites. The one-dimensional profile represents through-thickness moisture variation, while the two-dimensional contour provides a schematic visualization of spatial moisture gradients under non-uniform conditions. The illustration highlights the potential for non-uniform diffusion fields, which may contribute to localized degradation in composite structures under realistic service environments.

6. Conclusions

This study presents a physics-based digital twin framework for modeling the hygro-thermo-mechanical degradation of fiber-reinforced polymer composites under environmental exposure. By integrating moisture diffusion, thermally activated degradation kinetics, and mechanical property evolution within a unified formulation, the framework provides a consistent and physically interpretable approach for evaluating time-dependent material behavior. The results demonstrate that the coupled effects of moisture and temperature can be effectively captured using a simplified yet robust model. Key degradation features, including moisture saturation, gradual stiffness reduction, and stable damage evolution, are reproduced in a manner consistent with expected behavior under moderate service conditions. These trends highlight the capability of the framework to represent the dominant mechanisms governing early-stage degradation. The analysis further emphasizes the role of fiber reinforcement in enhancing durability. Increasing fiber volume fraction reduces moisture ingress and improves stiffness retention, underscoring the importance of microstructural design in controlling long-term performance. A key strength of the proposed framework lies in its transparency and scalability. Unlike empirical or data-driven approaches, the

model is grounded in fundamental physical principles, enabling application across different material systems and environmental conditions without extensive recalibration. In this context, the framework serves as a qualitative benchmarking and predictive tool, particularly in the absence of system-specific experimental calibration. Overall, the proposed approach offers a computationally efficient and physically grounded methodology for analyzing degradation mechanisms and supporting engineering decisions related to material selection, design optimization, and durability assessment. Future work will focus on incorporating nonlinear degradation behavior, uncertainty quantification, and experimental validation to further enhance predictive capability and practical applicability.

Algorithm 1: Physics-Based Digital Twin Framework for Hygro-Thermo-Mechanical Degradation

Input:

Initial modulus E_0 , matrix diffusion coefficient D_m , thickness L , fiber volume fraction V_f , temperature T , relative humidity RH , Arrhenius parameters A, E_a , moisture sensitivity coefficient α , time domain $t \in [0, t_{\max}]$

Step 1: Pre-processing

Compute effective diffusion coefficient:

$$D_{\text{eff}} = D_m(1 - V_f)^2 \quad (\text{A1})$$

Compute temperature-dependent degradation rate:

$$\beta = A \exp\left(-\frac{E_a}{RT}\right) \quad (\text{A2})$$

Step 2: Time-stepping Procedure (1D Model)

For each time step t_i :

(a) Moisture Diffusion Update

$$M(t_i) = \left[1 - \exp\left(-\frac{\sqrt{D_{\text{eff}} t_i}}{L}\right)\right] \times RH \quad (\text{A3})$$

(b) Mechanical Degradation Update

$$E(t_i) = E_0 \exp(-\beta t_i)(1 - \alpha M(t_i)) \quad (\text{A4})$$

(c) Residual Stiffness Constraint

$$E(t_i) = \max(E(t_i), 0.2E_0) \quad (\text{A5})$$

(d) Damage Evaluation

$$D(t_i) = 1 - \frac{E(t_i)}{E_0} \quad (\text{A6})$$

Step 3: Output

Return time evolution of:

- Moisture content $M(t)$
- Elastic modulus $E(t)$
- Damage variable $D(t)$

Step 4: Post-processing

Normalized modulus:

$$\frac{E(t)}{E_0} \quad (\text{A7})$$

Lifetime estimation based on critical damage threshold D_{crit}

Extension: Multi-Dimensional Diffusion (2D Formulation)

The framework can be extended to spatially resolved analysis as follows:

$$\frac{\partial M(x, y, t)}{\partial t} = D_{\text{eff}} \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right) \quad (\text{A8})$$

Discretized Moisture Update (Conceptual Form)

For each spatial node (i, j) and time step t_k :

$$M_{i,j}^{k+1} = M_{i,j}^k + D_{\text{eff}} \Delta t \left(\frac{M_{i+1,j}^k - 2M_{i,j}^k + M_{i-1,j}^k}{\Delta x^2} + \frac{M_{i,j+1}^k - 2M_{i,j}^k + M_{i,j-1}^k}{\Delta y^2} \right) \quad (\text{A9})$$

Coupled Degradation in 2D

$$E(x, y, t) = E_0 \exp(-\beta t) (1 - \alpha M(x, y, t)) \quad (\text{A10})$$

$$D(x, y, t) = 1 - \frac{E(x, y, t)}{E_0} \quad (\text{A11})$$

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Availability of Data and Materials: No experimental datasets were generated in this study. The results are based on numerical simulations performed using a physics-based computational framework developed by the author. All relevant modelling details and results are included within the manuscript. Additional information can be provided upon reasonable request.

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