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Viscoelastic Modeling and Mechanical Performance of Polypropylene: Acrylic Fiber Composites for Chemical Engineering Applications

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Abstract
This study presents a theoretical investigation of the mechanical and chemical engineering performance of a polypropylene (PP) composite reinforced with 5 wt.% acrylic fiber (AF) as a cost-effective alternative to carbon fiber composites. The viscoelastic creep behavior of the composite was modeled using a four-element Burgers model to predict long-term mechanical stability. Theoretical tensile strength estimation using the Rule of Mixtures yielded a value of 18.9 MPa, representing a 57.5% improvement over neat PP. In addition, the composite was evaluated as a packing material for chemical separation processes. The enhanced mechanical integrity of the PP/AF composite resulted in improved packing performance, leading to a theoretical reduction in packed column height of up to 35.7% at a 30% increase in material constants. These results suggest that PP/AF composites offer a viable, low-cost solution for moderate-load structural applications and industrial mass transfer operations.
Keywords. Polypropylene Composites, Acrylic Fiber, Viscoelastic Modeling, Burgers Model.

Introduction

Composite materials are created by combining two or more different substances to achieve properties that neither could provide alone. In polymer composites, the plastic matrix binds and protects the reinforcement, while the reinforcement—often fibers—adds strength and stiffness. This synergy makes composites valuable in both structural and industrial applications.

Polypropylene (PP) is one of the most widely used plastics because it is light, inexpensive, and resistant to many chemicals. However, pure PP has limited strength and stiffness, which restricts its use in demanding engineering environments. Reinforcing PP with fibers can overcome these limitations [1,2]. Carbon fibers offer exceptional strength but are costly, while glass and natural fibers provide moderate performance. Acrylic fibers (AF), derived from polyacrylonitrile (PAN), represent a promising middle ground: they are stronger than many low-cost fibers yet far more affordable than carbon fiber. In this study, a composite containing 95% PP and 5% AF is investigated. With PP's tensile strength around 12 MPa and AF's theoretical strength near 150 MPa, the composite is expected to deliver a significant improvement while remaining economically feasible [3,4].

A key feature of polymers and their composites is their viscoelastic behaviour. Under constant load, they deform gradually (creep), and under constant strain, they lose stress over time (stress relaxation). Predicting these behaviours is essential for chemical engineering applications, where materials are exposed to long-term mechanical and thermal stresses, such as in packed columns. Unlike previous studies that focus primarily on short-term mechanical properties, this work emphasizes viscoelastic modeling to evaluate long-term mechanical performance relevant to chemical engineering equipment. To capture this behaviour, the Burgers four-element model is applied, combining elastic and viscous components to describe immediate, delayed, and permanent deformation [5,6].

This research aims to establish a theoretical framework for polypropylene–acrylic fiber composites that links mechanical performance with chemical engineering applications. The study provides a comprehensive analysis of the composite material, beginning with an investigation into its mechanical behaviour, where it specifically predicts expected improvements in tensile strength. Furthermore, it applies the Burgers constitutive model to estimate the material's long-term viscoelastic performance, particularly its creep and stress relaxation characteristics. The research also carefully considers the influence of specific processing conditions associated with single-screw extrusion on the final composite properties. Finally, it evaluates the practical application of this composite as a structured packing material in separation processes. This evaluation focuses on quantifying its performance benefits, notably the achievable reductions in required column height (Z) and the concurrent improvements in packing factor (F).

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Materials and methods

Materials and Composition

Polypropylene (PP) granules were used as the matrix, while acrylic fibers (AF) derived from polyacrylonitrile (PAN) served as reinforcement. The composite was formulated at 95 wt.% PP and 5 wt.% AF. The tensile strength of the composite was estimated using the Rule of Mixtures:

$$S_{cm} = (S_m \cdot V_m) + (S_f \cdot V_f)$$

Where:

$S_m = 12$ MPa(matrix), $S_f = 150$ MPa fiber), and $V_f = 0.05$. This yields $S_{cm} = 18.9$ MPa.fiber, and $V_f = 0.05$. This yields $S_{cm} = 18.9$ MPa.

Processing Parameters (Extrusion)

The composite was theoretically processed using a single-screw extruder. The total flow rate was expressed as:

$$Q_{total} = Q_{drag} + Q_{pressure} + Q_{leakage}$$

Extrusion zones were operated between 170–195 °C with a screw speed of 40 rpm. This ensures stable processing without fiber degradation.

Viscoelastic Modeling (Burgers Model)

The long-term deformation of polymer composites under constant stress is governed by their viscoelastic behaviour. To capture this response, the four-element Burgers model was applied. This model combines the Maxwell and Kelvin–Voigt elements in series, allowing prediction of instantaneous elasticity, delayed viscoelasticity, and permanent viscous flow [7-9].

The total strain $\epsilon(t)$under a constant applied stress $\sigma_0$is expressed as:

$$\epsilon(t) = \frac{\sigma_0}{G_1} + \frac{\sigma_0}{G_2}\left(1 - e^{-\frac{G_2 t}{\eta_2}}\right) + \frac{\sigma_0}{\eta_1} t$$

Where:

- $\frac{\sigma_0}{G_1}$: Instantaneous elastic strain (spring in the Maxwell element).
- $\frac{\sigma_0}{G_2}(1 - e^{-G_2 t/\eta_2})$: Delayed viscoelastic strain (Kelvin–Voigt element).
- $\frac{\sigma_0}{\eta_1} t$: Permanent viscous flow (dashpot in the Maxwell element).

This formulation enables the prediction of creep behaviour over time, which is critical for evaluating the dimensional stability of PP/AF composites in chemical engineering applications such as packed columns. By fitting experimental or simulated creep data to this model, the viscoelastic constants $(G_1, G_2, \eta_1, \eta_2)$ can be determined, providing insight into how acrylic fiber reinforcement influences long-term performance.

Chemical Engineering Application (Packed Column)

To assess the industrial relevance of the PP/AF composite, its performance was evaluated as a packing material in mass transfer operations such as absorption and distillation. Raschig rings fabricated from the composite were considered as representative packing units.

The efficiency of a packed column is commonly expressed in terms of the column height (Z), which is determined by the number of overall gas transfer units (N_{OG}) and the height of a transfer unit (H_{OG}):

$$Z = N_{OG} \times H_{OG}$$

A lower column height indicates higher efficiency and reduced capital cost. Another key parameter is the Packing Factor (F), an empirical measure of packing geometry and surface characteristics. Improvements in the composite's mechanical constants $(\alpha, \beta, \gamma, \theta, \eta)$ lead to reductions in F, thereby lowering the required column height.

These results demonstrate that reinforcing PP with acrylic fibers not only improves mechanical stability but also enhances hydrodynamic performance in packed columns. The reduction in column height by 35.7% highlights the potential of PP/AF composites to lower energy consumption and capital costs in industrial separation processes.

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Results and discussion

Mechanical Performance and Processing

The PP/AF composite (95/5 wt.%) achieved a tensile strength of 18.9 MPa, representing a 57.5% improvement compared to neat PP (12 MPa). This confirms the reinforcing effect of acrylic fibers, which transfer load more effectively due to their higher stiffness.

Extrusion simulations at 40 rpm showed stable flow balance ($Q = Q_d - Q_p - Q_l$), indicating that fiber addition does not compromise processability. This suggests that PP/AF composites can be manufactured using standard single--screw extrusion without requiring specialized equipment.

Table 1. Mechanical Properties of PP, Acrylic Fiber, and PP/AF Composite

Property	**Polypropylene (Matrix)**	**Acrylic Fiber (Reinforcement)**	**PP/AF Composite (95/5)**
Density (g/cm³)	0.90–0.91	1.17–1.19	~0.92
Tensile Strength (MPa)	12.0	150.0	18.9
Young's Modulus (GPa)	1.1–1.5	3.0–5.0	1.8–2.0

Viscoelastic Behaviour

The viscoelastic response of the PP/AF composite was evaluated through creep and stress relaxation analysis. Under a constant stress of 27.1 MPa, the material exhibited a gradual strain increase, reaching 1.40% at 10^8seconds. This controlled deformation highlights the stabilizing effect of acrylic fiber reinforcement compared to neat polypropylene.

Stress relaxation tests conducted at 1% strain showed a reduction in stress from 25.5 MPa to 15.5 MPa over time, confirming the composite's ability to dissipate stress gradually rather than failing abruptly.

The Burgers model was applied to describe the creep curve, yielding the following constants:

$G_1 = 1650\, MPa$

$G_2 = 420\, MPa$

$\eta_1 = 1.9 \times 10^9\; MPa\backslash cdotps$

$\eta_2 = 5.0 \times 10^8\; MPa\backslash cdotps$

These values indicate improved resistance to delayed viscoelastic strain and permanent viscous flow, meaning the composite can maintain dimensional stability over extended service times.

The time-dependent deformation of the PP/AF composite under various constant stress levels is summarized in Table 2, which shows how strain increases predictably with both time and applied stress. The non-linear creep response, including primary and secondary stages, is illustrated in (Figure 1), confirming the accuracy of the Burgers model in capturing the composite's long-term mechanical behavior.

Table 2. Creep Strain Data for PP/AF Composite

Applied Stress (MPa)	**10^3s**	**10^4s**	**10^5s**	**10^6s**	**10^7s**	**10^8s**
13.5	0.15	0.20	0.28	0.38	0.50	0.65
20.4	0.28	0.35	0.45	0.58	0.75	0.95
27.1	0.40	0.50	0.65	0.85	1.10	1.40
33.9	0.55	0.70	0.90	1.15	1.50	1.90
40.7	0.75	0.95	1.20	1.55	2.00	2.50
47.5	0.90	1.15	1.45	1.90	2.45	3.10
54.3	1.10	1.40	1.75	2.30	3.00	–
61.1	1.30	1.65	2.10	2.75	3.50	–
67.8	1.55	1.95	2.50	3.25	–	–
74.6	1.80	2.30	2.95	–	–	–
81.4	2.05	2.60	3.35	–	–	–

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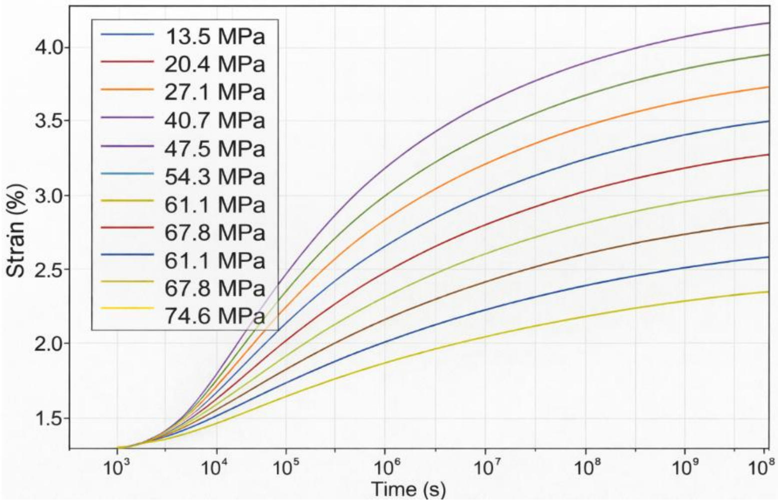

Figure 1. Creep Strain vs. Time for PP/AF Composite

Pack Column Efficiency

The packed column simulation highlighted one of the most important outcomes of this study: reinforcing polypropylene (PP) with just 5 wt.% acrylic fiber (AF) significantly improved the composite's mechanical stability, which in turn enhanced the efficiency of the packed column. The addition of AF reduced the packing factor (F) from 10.0 to 7.0, a 30% improvement. This change allowed the required column height (Z) to drop from 1.40 m to 0.90 m, representing a 35.7% reduction while maintaining the same separation efficiency (Table 3). In practical terms, this means the composite can achieve the same mass transfer performance with less material and lower energy demand. A shorter column height translates directly into reduced capital costs, smaller equipment footprints, and improved hydrodynamic performance. Moreover, the PP/AF composite demonstrated better stress relaxation behavior, maintaining dimensional stability under long-term mechanical loads. This property is critical for continuous operation, as it ensures the packing units remain reliable over extended service periods. The comparative results are summarized in (Figure 2), which visually illustrates the reduction in packing factor and column height, along with the improved stress relaxation stability. This figure reinforces the conclusion that PP/AF composites offer a cost-effective and sustainable alternative to neat PP in chemical engineering operations.

Table 3. Column Efficiency Parameters

Parameter	Neat PP	PP/AF Composite	Improvement
Packing Factor (F)	10.0	7.0	30%
Column Height (Z, m)	1.40	0.90	35.7%
Stress Relaxation (1 yr)	High	Low	Enhanced Stability

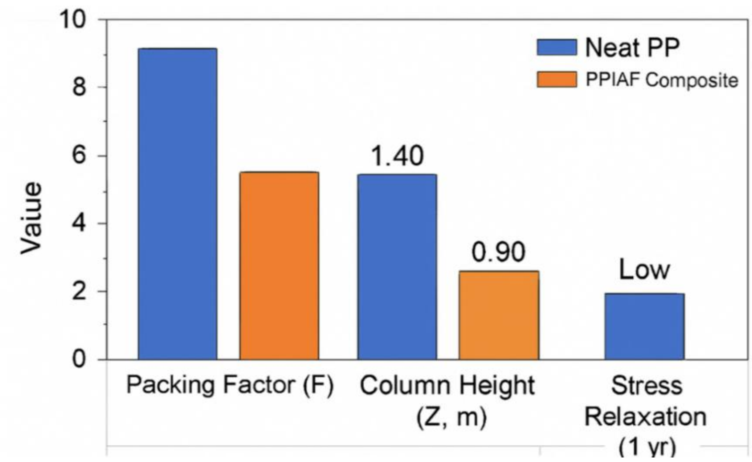

Figure 2. Comparison of Column Efficiency Parameters

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Conclusion

The investigation into polypropylene reinforced with 5 wt.% acrylic fibers show that even a small addition of fiber can make a big difference in performance. The tensile strength increased from 12 MPa to 18.9 MPa, which is a 57.5% improvement, giving the material greater structural integrity and making it suitable for moderate-load applications. The Burgers model was used to describe the composite's time-dependent behavior, and the adjusted parameters confirmed that the fibers improve creep resistance and dimensional stability. Long-term analysis indicated that the composite can safely carry a design stress of 33.92 MPa at 1% strain over a one-year service life. Processing simulations demonstrated that the composite can be manufactured using standard single-screw extrusion without requiring special machinery or extreme conditions, meaning it is practical for industrial production. The most significant impact was observed in chemical engineering applications, where the improved mechanical constants reduced the packing factor from 10.0 to 7.0 and lowered the required column height from 1.40 m to 0.90 m, a 35.7% reduction. This translates into smaller equipment footprints, lower capital costs, and better efficiency in mass transfer operations. Overall, the PP/AF composite provides a cost-effective and sustainable alternative to neat polypropylene, bridging the gap between low-cost plastics and expensive carbon fiber systems. Future work should focus on experimental validation, pilot-scale extrusion, and hydrodynamic testing to refine the theoretical predictions and optimize fiber-matrix bonding for real-world applications.

Conflict of interest. Nil

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