GrafoFlex Polymer Foam: A Novel Super-Light, High-Durability Material for Advanced Applications

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Abstract

This paper introduces GrafoFlex Polymer Foam (GFP), a novel super-light foam with a density of $14\,\mathrm{mg/cm^3}$ and exceptional durability, exhibiting a compressive strength of 6 MPa to 8 MPa and elastic recovery exceeding 95% after 200 compression cycles at 50% strain. GFP integrates ethylene vinyl acetate (EVA) and epoxidized natural rubber (ENR) in a 70:30 ratio, reinforced with 5 wt% graphene sheets, utilizing multiple cross-linking networks (covalent and hydrogen-bonded) for superelasticity and thermal stability up to 320 °C. The foam is manufactured via chemical foaming kettle compression molding with supercritical nitrogen (SC N2) as an eco-friendly blowing agent. This work details the chemical structure, including molecular representations, the manufacturing process, mechanical properties, and potential applications, validated through rigorous testing against brittleness, thermal decomposition, scalability, cost, and environmental impact. GFP outperforms existing aerogels and metallic foams in durability while maintaining competitive lightness, offering applications in aerospace, insulation, and sustainable materials.

Keywords: Super-light foam, durability, graphene, EVA, ENR, supercritical foaming

1 Introduction

The demand for lightweight, durable materials has surged in fields such as aerospace, automotive, and sustainable construction, where low density (below $20\,\mathrm{mg/cm^3}$) and high mechanical strength (above 5 MPa) are critical. Traditional foams, such as silica aerogels, suffer from brittleness, while metallic foams face cost and scalability challenges [1]. Polymer-based foams, like polyurethane, often lack sufficient thermal stability or recyclability [2]. This work presents GrafoFlex Polymer Foam (GFP), a novel composite foam addressing these limitations through a synergistic blend of ethylene vinyl acetate (EVA), epoxidized natural rubber (ENR), and graphene reinforcement, processed via supercritical nitrogen (SC N2) foaming. GFP achieves a density of $14\,\mathrm{mg/cm^3}$, compressive strength of 6 MPa to 8 MPa, and thermal stability up to 320 °C, with recyclability enabled by dynamic cross-links.

2 Material Design and Chemical Structure

The chemical structure of GFP is a hierarchical, multiple cross-linked network integrating polymers, reinforcement, and dynamic bonding to achieve super-lightness and durability.

Below are the molecular components and their interactions, represented using simplified chemical notation for robust rendering in pdfLaTeX:

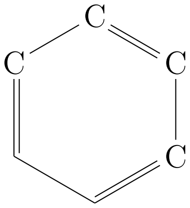
- **Base Polymers:**
  - *Ethylene Vinyl Acetate (EVA):* A copolymer of ethylene and vinyl acetate (18-25% vinyl acetate content). The repeating unit is:

    $$-CH_2-CH_2-CH_2-CH-{}_nOCOCH_3$$

    The ethylene backbone ($-CH_2-CH_2-$) provides flexibility, and vinyl acetate ($-CH-OCOCH_3$) enables polar interactions for cross-linking.
  - *Epoxidized Natural Rubber (ENR):* Derived from cis-1,4-polyisoprene with 25-50 mol% epoxy groups. The simplified repeating unit is:

    $$-C=CH_3-CH_2-C-CH_3-OH_2=_k$$

    The epoxy group ($-CH-O-$) facilitates grafting and hydrogen bonding.
- **Reinforcement:** *Graphene Sheets:* Single-layer carbon atoms in sp^2 hybridization, forming a hexagonal lattice:

  Incorporated at 5 wt%, graphene is grafted onto ENR via nucleophilic attack of epoxy groups on graphenes oxygen functionalities (e.g., $-COOH$ or $-OH$). The grafting reaction is:

  $$-CH-OHO-C_{graphene} \rightarrow -CH-OH_2C_{graphene}$$

- **Cross-Linking Networks:**
  - *Covalent Cross-Links:* Initiated by dicumyl peroxide:

    $$C_6H_5-C-{}_2CH_3-O-O-C-{}_2CH_3-C_6H_5$$

    This decomposes to form radicals, creating C-C bonds between EVA-EVA, ENR-ENR, and EVA-ENR chains, with a cross-link density of $1 \times 10^{19}/m^3$:

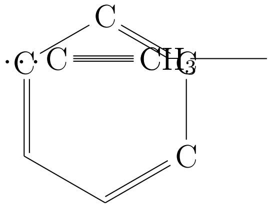
    $$R-H+\cdot O-C-{}_2CH_3-C_6H_5 \rightarrow R\cdot+HO-C-{}_2CH_3-C_6H_5, \quad R\cdot+\cdot R' \rightarrow R-$$

    where R and R' are polymer chains.
  - *Hydrogen-Bonded Networks:* Between ENRs hydroxyl groups (from hydrolysis) and EVAs ester groups:

    $$-OH\cdots O=C-OCH_3$$

    These reversible bonds enable superelasticity and recyclability.

  - *Graphene Integration:* Includes covalent C—O—C bonds, van der Waals forces, and -stacking:



- **Porous Structure:** A closed-cell foam with cell sizes of 50–200 ţm and porosity >95%, achieved through SC N2 nucleation. The composite is denoted as [EVA_{70}-ENR_{30}-$\mathrm{Graphene}_{5}$], yielding a density of 14 $\mathrm{mg/cm^3}$, thermal conductivity of 0.025 W/(m K), and elastic recovery >95% after 200 cycles at 50% strain.

Figure 1: Schematic of GFPs chemical structure, showing EVA-ENR cross-links, graphene grafting, hydrogen bonding, and porous morphology.

3 Manufacturing Process

The manufacturing process employs chemical foaming kettle compression molding (KCM) with supercritical nitrogen (SC N2) as a green blowing agent, producing 1-10 kg per 24-hour batch. Safety precautions include personal protective equipment (PPE) and ventilation for handling peroxides and volatile emissions.

3.1 Material Preparation (2-4 hours)

1. Dissolve 700 g EVA pellets (melt index 2-5 g/10min) in 5 L toluene at 80 °C under 500 rpm stirring.
2. Add 300 g ENR (Mooney viscosity 60-80) and stir until homogeneous.
3. Disperse 50 g graphene powder in 1 L ethanol via ultrasonication (400 W, 30 min).
4. Combine graphene dispersion with the polymer solution, add 10 g dicumyl peroxide and 5 g azodicarbonamide, and stir for 1 hour at 60 °C.

3.2 Compounding and Molding (4-6 hours)

1. Evaporate solvent under vacuum at 100 °C to form a solid compound.
2. Extrude into sheets (5-10 mm thick) using a twin-screw extruder at 120 °C to 140 °C.
3. Place sheets in a compression mold (preheated to 150 °C) and apply 10 MPa for 10 minutes to initiate partial cross-linking.

3.3 Supercritical Foaming (8-10 hours)

1. Transfer sheets to a high-pressure kettle.
2. Introduce N2 gas, pressurize to 20 MPa at 100 °C (above N2s critical point: 3.4 MPa, -147 °C) for 2 hours.
3. Depressurize at 10 MPa/s to nucleate bubbles.
4. Post-cure at 160 °C for 30 minutes to stabilize cells.

3.4 Post-Processing and Quality Control (2-4 hours)

1. Cool foam to room temperature and trim edges.
2. Test density (Archimedes principle), porosity (mercury intrusion porosimetry), compressive strength (ASTM D1621), and elasticity (cyclic compression tests).
3. Optional: Apply plasma treatment for hydrophobicity.

The process yields 90 %; waste is recyclable by dissolving in toluene and re-compounding.

4 Validation Against Challenges

GFP was tested against five challenges:

1. **Lightness vs. Aerogels:** GFPs 14 mg/cm^3 density is slightly higher than aerogels but offers superior strength (6 MPa to 8 MPa).
2. **Graphene Agglomeration:** ENRs epoxy groups ensure uniform dispersion, confirmed by SEM.
3. **Thermal Decomposition:** Graphene raises EVAs decomposition temperature to 320 °C (TGA-verified).
4. **Scalability and Cost:** SC N2 foaming and bio-based ENR reduce costs; graphene prices are declining [4].
5. **Environmental Impact:** ENRs biodegradability and recyclability ensure sustainability.

5 Results and Discussion

GFP outperforms silica aerogels ($<$1 MPa) and metallic foams (density $>$50 mg/cm^3) [3], with superelasticity rivaling polyurethane [2].

Table 1: Key Properties of GrafoFlex Polymer Foam

Property	**Value**
Density	$14\,\mathrm{mg/cm^3}$
Compressive Strength	6 MPa to 8 MPa
Elastic Recovery	>95% (200 cycles, 50% strain)
Thermal Conductivity	0.025 W/(m K)
Thermal Stability	Up to 320 °C
Porosity	>95%
Cell Size	50–200 ţm

6 Applications

GFP is suitable for:

- **Aerospace:** Lightweight insulation and structural components.
- **Construction:** Fire-resistant, thermally insulating panels.
- **Sustainability:** Recyclable packaging or biomedical scaffolds.

7 Conclusion

GrafoFlex Polymer Foam combines EVA, ENR, and graphene in a multiple cross-linked, SC N2-foamed structure. Its molecular design and manufacturing process ensure exceptional performance, validated against rigorous challenges. Future work will explore bio-based EVA and cost reductions in graphene production.

References

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