Sustainable and Cost-Effective Recycling of Thermoset Plastics via Cryogenic Grinding for Composite Manufacturing

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Abstract

Recycling thermoset plastics poses a significant challenge due to their highly cross-linked molecular structure, which prevents them from being remelted and reprocessed like thermoplastics. Thermoset plastics constitute approximately 18% of global plastic consumption and are widely used in the automotive, aerospace, electrical, and construction industries due to their superior mechanical properties, heat resistance, and durability. However, their inability to be reshaped or reused through conventional recycling methods results in large volumes of waste, contributing to environmental concerns. Existing recycling approaches primarily involve high-temperature degradation, which is energy-intensive and generates harmful emissions (Cho et al., 2024). Chemical methods, such as incorporating cleavable comonomers to break down cross-linked chains, have shown potential, yet their economic viability and scalability remain uncertain (Xu et al., 2021). Vitrimerization enables the recyclability of thermosets by utilizing dynamic chemical bonds and serves as a bridge between mechanical and chemical recycling methods (Yue et al., 2019). Microwave pyrolysis facilitates rapid polymer decomposition, recovering clean fibers while reducing energy input and improving efficiency (Deng et al., 2019). This study presents an alternative approach using cryogenic grinding to convert thermoset plastic waste into reusable composite material, aiming for a more environmentally sustainable and economically feasible solution.

The proposed process involves immersing waste thermoset plastic pieces in liquid nitrogen for 30 minutes to induce brittleness. Once sufficiently frozen, the brittle plastic is mechanically ground using a kitchen mixer-grinder to break it down into small granules. The resulting material is then sieved using a 1.00 mm sieve, ensuring that only finely ground particles pass through. These fine particles are subsequently blended with polypropylene to form a composite material. Melamine contains amine (-NH_2) and triazine (-C_3N_3) functional groups, making it a highly polar compound, whereas polypropylene is non-polar, resulting in weak composite formation when mixed with melamine granules. To incorporate functional groups, maleated polypropylene [(C3H6)n - (C4H2O3)m] is synthesized by grafting maleic anhydride (MA) onto the polypropylene (PP) backbone through a free-radical reaction using peroxide (Jubinville, 2022). The prepared mixture is then injection-molded into standardized sample blocks for testing and evaluation of mechanical properties.

A comprehensive set of mechanical, physical, and electrical tests was conducted to assess the performance and suitability of the developed composite material. The mechanical tests included tensile strength, flexural strength, impact resistance, shear strength, and compressive strength to determine the material's load-bearing and deformation characteristics. Additionally, water absorption, density, and void content were measured to evaluate the physical integrity of the composite, ensuring it meets industry standards for durability and structural stability. Electrical property tests were also performed to explore potential applications in the electronics and electrical industries.

Preliminary findings from these tests (Table 1) indicate that the developed composite material exhibits promising mechanical properties, comparable to conventional polypropylene-based composites. The incorporation of cryogenically ground thermoset plastic particles enhances certain properties, such as impact resistance and flexural strength, while maintaining acceptable levels of tensile and compressive strength. The results suggest that this cryogenic recycling method presents a feasible and cost-effective approach for repurposing thermoset waste, significantly reducing its environmental footprint.

Table 1: Mechanical properties of the Melamine and maleated polypropylene composite

	Virgin polypropylene	Melamine maleated polypropylene composite	Comments
Tensile strength (MPa)	31.55	28.82	The presence of melamine granules creates weak spots
Compressive strength (MPa)	22.12	28.59	The melamine granules act as fibre reinforcement
Young's Modulus (GPa)	1.18	1.28	The melamine granules act as fibre reinforcement
Density (g/cm^3)	0.91	0.91	No change
Flexural Strength (MPa)	34.92	41.23	The melamine granules act as fibre reinforcement
Water absorption (%)	<0.1%	>0.1 & <0.2%	More voids created

By offering a practical recycling strategy, this research contributes to the broader goals of sustainability, the circular economy, and waste reduction. The successful utilization of waste thermoset plastics in composite materials could pave the way for new industrial applications, reducing dependency on virgin plastics and mitigating the adverse environmental impact of plastic waste disposal. Future research will focus on optimizing particle size distribution, evaluating long-term durability, and exploring industrial-scale implementation to enhance the practical applicability of this method.

By offering a new practical recycling strategy, this research contributes to sustainability, the circular economy, and waste reduction by enabling the reuse of thermoset plastics in high-value composite materials. This approach not only mitigates environmental concerns but also reduces dependency on virgin plastics, aligning with global sustainability initiatives. The method holds promise for applications in industries such as automotive, aerospace, and construction, where durability and mechanical strength are critical. Additionally, it presents economic benefits by creating new market opportunities for recycled materials. Future research will focus on optimizing particle size distribution, assessing long-term durability, and exploring industrial-scale implementation to enhance its practical applicability.

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