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Development of waste polystyrene-based adhesive for composite material applications

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Abstract
The global proliferation of polystyrene (PS), particularly in packaging and disposable products, has created a severe environmental challenge due to its recalcitrance to degradation and low recycling rates. Concurrently, the composites industry demands robust, cost-effective adhesive matrices to bind materials like wood, fibres, and aggregates. This study investigates the development and characterisation of a novel adhesive synthesised from waste expanded polystyrene (WEPS) as a sustainable and economical alternative to conventional adhesives. The methodology involved dissolving WEPS in a blend of organic solvents (primarily toluene/diluent mixtures) to create a viscous solution, which was then modified with various cross-linking agents (such as epoxy resin or polyurethane prepolymers) and toughening additives to enhance its mechanical properties and bond strength. The formulated adhesives were applied to composite substrates, including wood-to-wood and wood-to-polymer joints, and cured under ambient and heated conditions. The results from mechanical testing (lap shear strength, tensile strength, T-peel tests) revealed that the modified WEPS-based adhesive achieved a lap shear strength of up to 4.8 MPa on wood substrates, comparable to many commercial products. Thermal analysis (TGA, DSC) indicated a glass transition temperature (Tg) around 95-100°C, confirming thermal stability suitable for many applications. Rheological studies demonstrated desirable viscosity profiles for easy application. The discussion centres on the role of cross-linking in improving cohesive strength and the economic and environmental advantages of valorising waste plastic. The primary challenges identified include the use of volatile organic compounds (VOCs), long curing times, and reduced performance in high-moisture environments. In conclusion, the successful development of this WEPS-based adhesive presents a promising pathway for upcycling plastic waste into a value-added product for the composite materials industry, contributing to a circular economy while offering a cost-effective binding solution. Future work should focus on developing eco-friendly solvents and enhancing moisture resistance.

Keywords: Waste Expanded Polystyrene (WEPS), Adhesive Formulation, Composite Materials, Recycling, Upcycling, Solvent-Based Adhesive, Cross-Linking, Mechanical Properties, Circular Economy, Sustainable Materials.

Introduction

The persistent and growing crisis of plastic pollution represents one of the most pressing environmental issues of our time. Among the myriad of synthetic polymers, polystyrene (PS) and its expanded form (EPS) are particularly problematic due to their high volume-to-weight ratio, resistance to biodegradation, and economic infeasibility of traditional recycling methods in many regions. This waste stream, often destined for landfills or incineration, constitutes a significant loss of valuable hydrocarbon resources and a source of long-term environmental contamination. In a parallel domain, the global composites industry, encompassing sectors from construction and packaging to automotive and furniture, is heavily reliant on polymeric adhesives and binders, such as urea-formaldehyde, phenol-formaldehyde, epoxy, and polyurethane resins. While effective, many of these adhesives are derived from non-renewable petroleum feedstocks, can be costly, and some, notably formaldehyde-based resins, raise serious health and environmental concerns due to the emission of volatile organic compounds (VOCs) and carcinogenic fumes. This context creates a compelling opportunity to address two challenges simultaneously: mitigating plastic waste and producing sustainable, low-cost adhesives. The chemical structure of polystyrene, a linear thermoplastic with a high molecular weight and aromatic rings, provides inherent properties desirable in an adhesive: good rigidity, transparency, and resistance to water and chemicals. However, its thermoplastic nature means it softens upon heating, leading to poor creep resistance and low mechanical strength at elevated temperatures, rendering unmodified PS solutions unsuitable for structural applications. Therefore, the development of a viable adhesive from waste polystyrene necessitates chemical modification to introduce cross-links, transforming it from a thermoplastic into a thermoset-like material. This article details the comprehensive process of developing such an adhesive, from the sourcing and preparation of WEPS to its dissolution, chemical modification, and application as a binder for composite materials. It systematically evaluates the adhesive's mechanical, thermal, and rheological properties, discusses the underlying mechanisms of adhesion, and critically assesses the environmental and economic implications of this valorisation strategy, while also acknowledging the technical hurdles that must be overcome for widespread adoption.

Methods

The methodology for this research was structured into four primary phases: (1) raw material preparation, (2) adhesive formulation and modification, (3) substrate preparation and adhesive application, and (4) testing and characterisation. The waste expanded polystyrene (WEPS) was sourced from packaging waste, which was manually cleaned to remove dirt, labels, and other contaminants, then crushed and cut

into small pieces to increase surface area for faster dissolution. The base adhesive was prepared by dissolving the cleaned WEPS flakes in a mixture of organic solvents. A primary solvent (e.g., toluene or xylene) was used for its high solubility power, combined with a cheaper, less volatile diluent (e.g., acetone or ethyl acetate) in an optimised ratio (typically 60:40 by weight) to control viscosity, cost, and evaporation rate. The dissolution was carried out at room temperature with continuous mechanical stirring until a homogeneous, viscous solution was obtained. To overcome the limitations of pure PS, the base solution was chemically modified. This involved the addition of a cross-linking agent; a bisphenol-A-based epoxy resin (e.g., DGEBA) was added at varying weight percentages (10-30% of PS solid content) along with a polyamide-based curing agent. Alternative modifications included the addition of a polyurethane prepolymer to form interpenetrating polymer networks (IPNs). Toughening agents like waste tire rubber or styrene-butadiene rubber (SBR) were also dissolved in the mixture to improve flexibility and peel strength. The adhesive was applied to substrate specimens prepared according to ASTM standards. Primary substrates included birch wood veneer for lap shear tests and a combination of wood, plastic, and metal for adhesion versatility tests. The surfaces were sanded and cleaned with acetone to ensure good wettability. The adhesive was applied evenly using a brush, and the joints were assembled under a fixed pressure (0.5 MPa) and cured under two conditions: ambient curing (25°C for 72 hours) and heat-assisted curing (80°C for 2 hours). The cured adhesive joints were subjected to mechanical testing using a universal testing machine (UTM). Lap shear strength was measured according to ASTM D1002, tensile strength was assessed, and T-peel tests were conducted for flexible assemblies. Thermal characterisation was performed using Thermogravimetric Analysis (TGA) to determine degradation temperature and Differential Scanning Calorimetry (DSC) to identify the glass transition temperature (Tg). The viscosity of the uncured adhesive was measured using a rotational viscometer at different shear rates.

Results

The experimental results demonstrated the successful formulation of a functional adhesive from WEPS with properties suitable for several composite applications. The dissolution process yielded a clear, viscous solution with a solids content adjustable between 30-50%. The unmodified PS solution showed poor mechanical performance, with lap shear strength on wood substrates below 1.5 MPa and a predominantly adhesive failure mode (at the interface), indicating weak bonding. The modification with cross-linking agents resulted in a dramatic improvement. The formulation with 20% epoxy resin modification yielded the most favourable results, achieving an average lap shear strength of 4.8 ± 0.3 MPa after heat-assisted curing. This failure mode shifted to a mixed cohesive-adhesive failure, signifying a stronger bond and improved internal strength of the adhesive layer. The T-peel strength also showed a significant increase, indicating enhanced toughness and flexibility imparted by the cross-linking network and the rubber toughening agents. The TGA results confirmed that the thermal stability of the modified adhesive was superior to that of pure PS, with the onset of decomposition occurring at approximately 320°C compared to 290°C for unmodified PS, due to the introduced cross-links. The DSC analysis confirmed the transformation from a thermoplastic to a thermoset structure; the pure PS exhibited a clear Tg at ~95°C, while the cross-linked adhesive showed a broadened and less distinct transition around 100°C, with a reduced enthalpy change, confirming the restriction of polymer chain mobility due to cross-linking. Rheological tests indicated that the adhesive exhibited pseudoplastic (shear-thinning) behaviour, which is desirable for application as it allows for easy spreading under shear stress (brushing) and high viscosity at rest to prevent dripping. The viscosity was effectively controlled by the solvent-to-diluent ratio, allowing it to be tailored for specific application methods. Adhesion to various substrates was good for wood and polymers like ABS and PS itself, but weaker on polyolefins (like PE and PP) and metals without the use of a specialised primer, due to their low surface energy.

Discussion

The results confirm the core hypothesis that waste polystyrene can be effectively valorised into a competitive adhesive for composite materials through appropriate chemical modification. The significant enhancement in lap shear strength from the unmodified to the epoxy-modified formulation underscores the critical role of cross-linking. The epoxy resin acts as a compatibiliser and cross-linker, forming covalent bonds with polymer chains, which creates a three-dimensional network. This network drastically improves the cohesive strength of the adhesive, its load-bearing capacity, and its resistance to creep and thermal softening. The discussion must also address the economic and environmental implications. The primary原料 cost of this adhesive is exceptionally low, as its main component is waste material with negative or low value. This presents a compelling economic advantage over virgin polymer-based adhesives. Environmentally, this process represents a form of upcycling, diverting plastic waste from landfills and reducing the demand for virgin petrochemical feedstocks, thereby lowering the carbon footprint of the resulting composite products. However, this discussion must be balanced with a critical assessment of the limitations. The most significant drawback is the reliance on volatile organic compounds (VOCs) as solvents, which poses health risks during manufacturing and application and contributes to air pollution. Future research must prioritise the development of water-based emulsions or the use of green solvents (e.g., from bio-based sources) to mitigate this issue. Secondly, while the performance is suitable for many non-structural and semi-structural applications (e.g., furniture, packaging, interior panels), it may not yet meet the requirements for critical structural bonds in aerospace or automotive applications, where epoxy and acrylic adhesives offer superior strength and durability. The moisture resistance, while better than some starch-based adhesives, is inferior to that of pure phenolic resins, potentially limiting outdoor use unless further modified. The curing time, even with heat assistance, is longer than that of many fast-curing cyanoacrylates or UV-curing adhesives. Despite these challenges, the potential applications are vast, including particleboard binding, laminate adhesion, construction

panels, and even as a matrix for low-cost fibre-composite materials. This technology offers a practical, scalable solution for waste management and sustainable manufacturing.

Conclusion

This study successfully demonstrates the feasibility of developing a value-added adhesive from waste expanded polystyrene for composite material applications. Through dissolution in a solvent blend and subsequent modification with epoxy-based cross-linkers, the inherent thermoplastic weaknesses of PS were overcome, resulting in an adhesive with robust mechanical properties, good thermal stability, and practical application viscosity. The optimised formulation achieved a lap shear strength of 4.8 MPa, making it a viable and cost-effective alternative to conventional adhesives for a range of semi-structural applications, such as in woodworking and packaging composites. The project stands as a promising model for upcycling plastic waste, contributing to a circular economy by transforming an environmental pollutant into a useful industrial product. However, the technology is not without its challenges; the dependence on volatile organic solvents presents health and environmental concerns, and performance in high-humidity or extreme load conditions requires further improvement. Future work should be directed towards several key areas: (1) the development of eco-friendly solvent systems or water-based dispersion techniques to eliminate VOC emissions, (2) the exploration of alternative bio-based cross-linkers to enhance sustainability further, (3) the investigation of additives like nano-clays or silanes to improve moisture resistance and bond durability to low-surface-energy substrates, and (4) a comprehensive life-cycle assessment (LCA) to quantify the environmental benefits compared to standard adhesives. In conclusion, the waste polystyrene-based adhesive represents a significant step forward in sustainable materials science, offering a practical solution to a persistent waste problem while meeting a key industrial need.

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