Polyurethane Applications: A Review

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Abstract

This paper presents a thorough review of the current technology and applications of polyurethane (PU), spanning a broad spectrum from clothing to industrial and infrastructural domains. PU, renowned for its versatility and favorable material properties, has emerged as a key player in various industries due to its exceptional thermal and acoustic characteristics. With a focus on exploring its multifaceted applications, this review delves into the utilization of PU in diverse sectors such as fashion, manufacturing, and construction. Specifically, it highlights the remarkable thermal insulation properties of PU, which make it indispensable in energy-efficient clothing and building materials. Furthermore, the acoustic properties of PU contribute to its extensive use in soundproofing and noise reduction applications. By synthesizing the latest advancements and potential avenues for innovation, this paper underscores the significant role of PU in shaping modern technologies and underscores its vast potential for future developments across numerous sectors.

Keywords: Polyurethane applications, Infrastructure, Automotive industry

Introduction

Chemistry of Polyurethane

Polyurethanes are formed by the reaction of di/polyisocyanates and diols or polyols, creating repeating urethane linkage in the presence of chain extenders and other additives. The fundamental components of polyurethane are a polyol and an isocyanate, which are crucial in determining the final properties of the product. Varying either the polyol or the isocyanate can significantly alter the properties of the polyurethane, making the structure-property relationship of these components essential for understanding and designing polyurethane products. In the formed polyurethane, the polyol and isocyanate create distinct domains or regions, which impart properties such as softness, flexibility, or hardness to the final product. These soft and hard segments. Polyols typically have longer chain lengths, which result in greater mobility and thus provide flexibility to the polyurethane; diols with longer chain lengths offer even more flexibility. Isocyanates are generally very short-chain molecules, which leads to higher crystallization and results in compact, densely packed segments that are very hard and non-flexible. This combination of hard and soft segments gives polyurethane its characteristic versatility, making it highly effective for a wide range of applications.[2]

Polyols

Polyols are substances that contain more than one functional hydroxyl group. They may also include ester, ether, amide, acrylic, metal, metalloid, and other functional groups. Polyols are broadly classified into polyether polyols and polyester polyols. Polyether polyols are produced from the reaction between an epoxide and an active hydrogen-containing compound. They are created by adding ethylene oxide or propylene oxide to a polyhydroxy precursor molecule in the presence of catalysts. Common precursor molecules include glycerol, ethylene glycol, propylene glycol, and trimethylolpropane (TMP). Polyethers can also be synthesized through ring-opening reactions or polymerization of epoxy monomers. A wide variety of branched and crosslinked polymers can be prepared by altering the functionalities of the parent molecules, which are the hydroxyl-terminated compounds or the isocyanates, to suit the needs of the reaction or application. Some of the simplest polyols are glycols, similarly, ethylene glycol, 1,4-butanediol (BDO), and 1,6-hexanediol are also polyols. Technically, low molecular weight polyols result in the formation of hard and rigid polyurethane due to the higher concentration of urethane linkages. The shorter chains react more vigorously with the isocyanate (NCO) groups, producing a higher molecular weight polymer or pre-polymer.[2]

Isocyanates

Isocyanates are essential building blocks for polyurethane synthesis. These compounds are di- or polyfunctional, containing two or more isocyanate (NCO) groups per molecule. They can be aliphatic, cycloaliphatic, or aromatic in nature. Isocyanates are incorporated into the polyurethane backbone through their reaction with hydroxyl-containing compounds, such as various polyols, due to their high reactivity. However, this reactivity is slow at room temperature and is influenced by several other factors. Catalysts are generally used to increase the reaction rate by polarizing either the isocyanate or hydroxyl compound through polar interactions. The isocyanate group features a cumulated double bond sequence (R–N=C=O), where the reactivity is governed by the positively charged carbon atom, which is susceptible to attack by nucleophiles like oxygen and nitrogen, and electrophiles. Aromatic isocyanates, such as TDI (toluene diisocyanate) and MDI (diphenylmethane diisocyanate), are usually more reactive than their aliphatic counterparts like IPDI (isophorone diisocyanate) and HDI (hexamethylene diisocyanate). This difference in reactivity is primarily due to the resonance stabilization of the aromatic rings, which affects the carbon atom on the NCO group. In aromatic isocyanates, the nature of the substituent also influences reactivity; electron-attracting substituents in the ortho or para positions increase reactivity, while electron-donating substituents decrease it. In diisocyanates, the presence of an electron-attracting second isocyanate group increases the reactivity of the first isocyanate. Additionally, para-substituted aromatic diisocyanates are more reactive than their ortho analogs, mainly due to the steric hindrance caused by the second NCO functionality. The reactivities of the two NCO groups in isocyanates also vary based on their positions.[3]

Table 1 Various components of Polyurethane formulation.

Component	**Effects**
Isocyanate	Responsible for the PU reactivity and curing properties
Polyol	Contributes flexible long segments, produce elastic polymers
Catalysts	speeds up the reaction at lower temperatures
Plasticizers	Reduces material hardness
Pigments	Aesthetics to the material (color)

Cross linkers/ Chain extenders	For structural modification of PU, providing mechanical support to enhance tensile strength and hardness
Blowing agents and surfactants	To aid to the production of PU foams and control the foam cell structure
Fillers	To improve stiffness and tensile strength and reduce cost
Flame Retardants	To reduce material flammability

Polyurethane in Infrastructure

PU (polyurethane) finds numerous applications within infrastructural industries. The most common PU products utilized across various applications include rigid and flexible foams, coatings, castable elastomers, fibers and fabrics, adhesives, sealants, thermoplastics, millable gums, as well as hybrids and composites. These applications encompass a wide range of uses, such as foams employed in both structural and non-structural capacities, various protective coatings including clear glossy exterior paints renowned for their chemical resistance and weather stability, adhesives and sealants, absorbents, fuel binders, flame retardants, biomedical applications, automotive sector, grouting technologies, metal extraction processes, treatment of industrial wastewater, crashworthiness enhancements, among others.

PU (polyurethane) is typically a polymer known for its relatively high strength and consistent, scalable material properties, making it suitable for a wide range of applications. In the construction and infrastructural sectors, PU sees extensive use due to these characteristics. A significant application in building construction involves PU foams, particularly in insulated panels utilized for wall and roof insulation, as well as in filling gaps around doors and windows. The advantages of employing PU foams for insulation purposes include enhanced energy efficiency, mechanical and thermal performance, and environmental benefits. PU adhesives represent another significant market for PU materials. These adhesives find widespread use in various applications such as flooring, roofing, wallboard installation, as well as door and window installations. They are favored for their exceptional bond strength, fast curing time, and resistance to weather conditions.

Sandwich panels featuring a PU foam core have been employed for over 60 years, offering efficient and versatile structural solutions applicable across various scenarios. These panels find use in diverse applications, including roof and floor panels, cladding for building walls, and pedestrian bridge decks. Their widespread adoption can be attributed to their exceptional properties, including low density, excellent insulation characteristics, high strength, and a favorable stiffness-to-weight ratio.

Manufacturing Process Innovations

In addition to alternative chemistries, innovative manufacturing processes play a crucial role in enhancing the sustainability of polyurethane production. Water-based polyurethane formulations eliminate the need for organic solvents, reducing volatile organic compound (VOC) emissions and minimizing environmental impact. Moreover, advancements in polymerization techniques, such as enzymatic polymerization and microwave-assisted synthesis, offer energy-efficient and environmentally friendly alternatives to conventional methods, further contributing to the sustainability of polyurethane manufacturing.

Collaboration and Innovation Across Industries

Achieving sustainable growth in the polyurethane industry requires collaboration and innovation across multiple sectors, including academia, industry, government, and non-governmental organizations (NGOs). Collaborative research initiatives can foster the development of new technologies, materials, and processes that address sustainability challenges while promoting economic growth and competitiveness. Moreover, industry-wide initiatives and voluntary sustainability standards can drive adoption of sustainable practices and encourage continuous improvement in environmental performance.

Drawbacks of Polyurethane Products

Viscosity

Polyurethanes often have high viscosity, which can complicate their processing and application.

Oxidative Stability

PU can have poor oxidative stability, which affects its durability and performance over time when exposed to oxygen.

Modulus/Strength

The mechanical properties such as modulus and strength can be lower compared to other materials, limiting its use in certain structural applications.

Thermal Instability

Polyurethanes may not perform well at high temperatures, leading to degradation and loss of mechanical properties.

Flammability

Polyurethane is generally flammable and can catch fire easily, posing safety concerns, especially in applications requiring fire resistance.

Hydrolytic Stability

PUs may exhibit poor stability in the presence of water, leading to hydrolysis and degradation of properties.

Cost

The production and raw material costs for high-performance PUs can be high, making them less economically feasible for some applications.

Low Flexibility

Certain types of PUs, particularly those with high cross-linking densities, can have low flexibility, limiting their use in applications requiring elasticity.

Solvent Resistance

While some PUs are resistant to solvents, others can be susceptible to solvent attack, which can affect their structural integrity and performance in environments where solvents are present These drawbacks need to be considered when selecting polyurethane for specific applications, and ongoing research aims to mitigate these limitations through various modifications and enhancements.

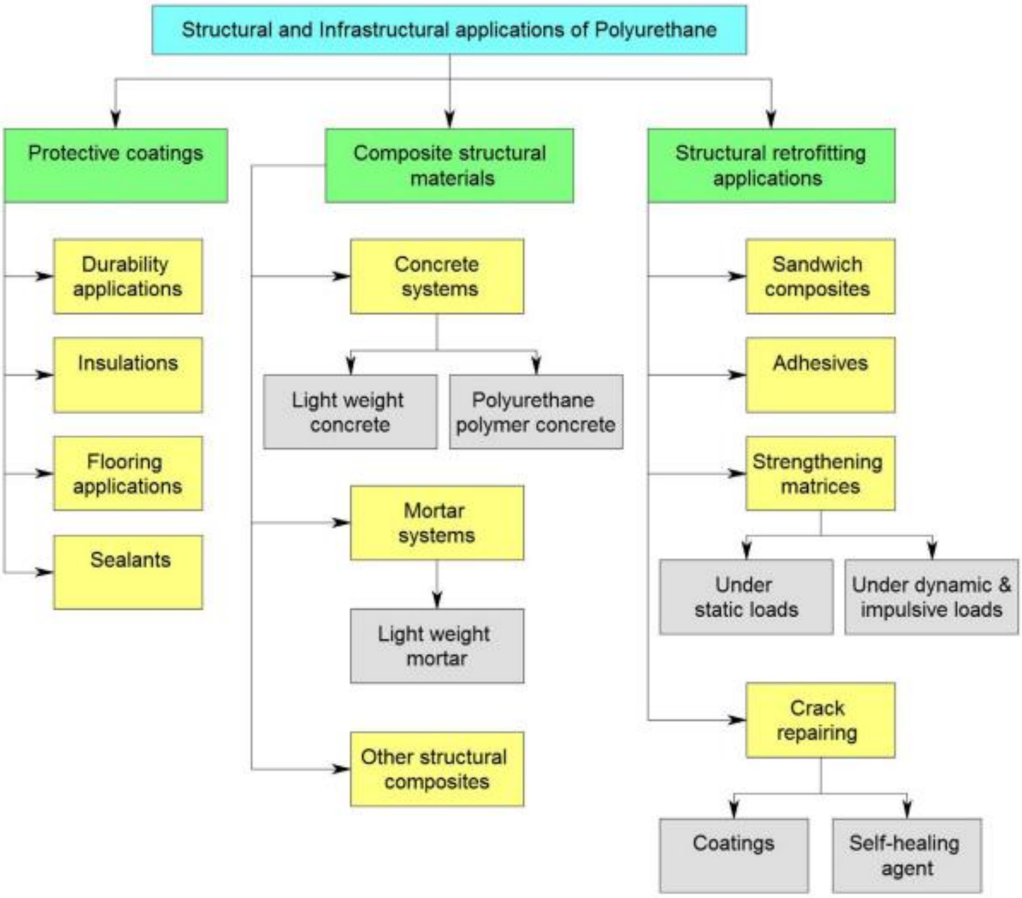
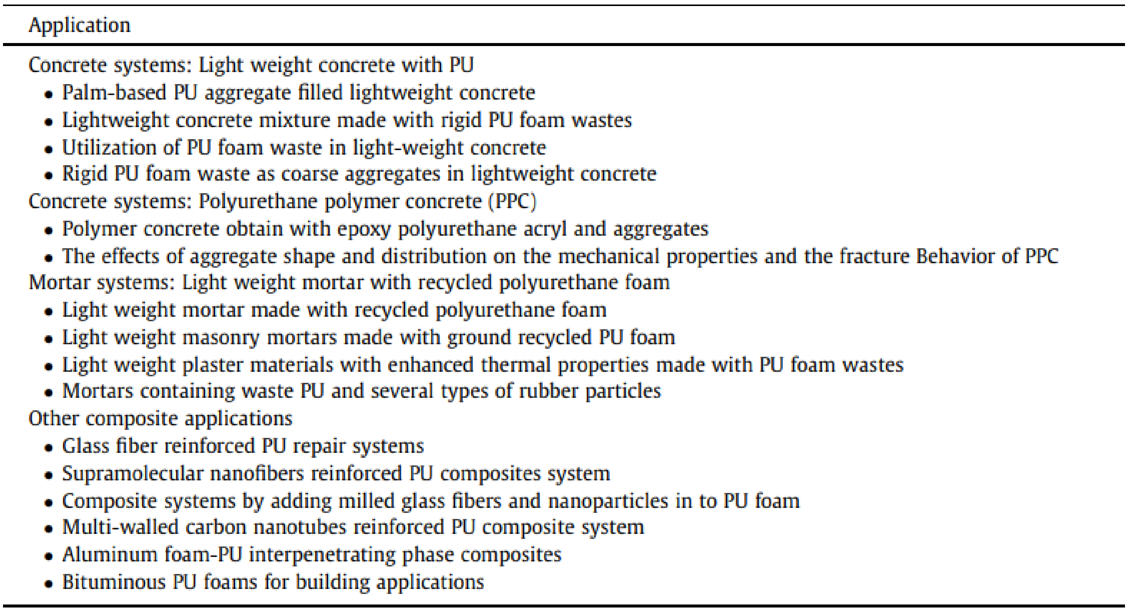


Figure 1. Areas of Application of polyurethane

Table 1. Summary of Researches utilizing PU in composite applications



Application
Concrete systems: Light weight concrete with PU
• Palm-based PU aggregate filled lightweight concrete
• Lightweight concrete mixture made with rigid PU foam wastes
• Utilization of PU foam waste in light-weight concrete
• Rigid PU foam waste as coarse aggregates in lightweight concrete
Concrete systems: Polyurethane polymer concrete (PPC)
• Polymer concrete obtain with epoxy polyurethane acryl and aggregates
• The effects of aggregate shape and distribution on the mechanical properties and the fracture Behavior of PPC
Mortar systems: Light weight mortar with recycled polyurethane foam
• Light weight mortar made with recycled polyurethane foam
• Light weight masonry mortars made with ground recycled PU foam
• Light weight plaster materials with enhanced thermal properties made with PU foam wastes
• Mortars containing waste PU and several types of rubber particles
Other composite applications
• Glass fiber reinforced PU repair systems
• Supramolecular nanofibers reinforced PU composites system
• Composite systems by adding milled glass fibers and nanoparticles in to PU foam
• Multi-walled carbon nanotubes reinforced PU composite system
• Aluminum foam-PU interpenetrating phase composites
• Bituminous PU foams for building applications

Literature Review

Somarathna (2018). Polyurethane (PU) stands as a prominent member of the plastic polymer category, boasting a wide array of applications in both structural and nonstructural realms. Over the past few decades, employing PU and its various forms has emerged as a prevalent and efficient approach for the repair, reinforcement, rehabilitation, and safeguarding of civil engineering infrastructure. A diverse range of PU products has been harnessed for such purposes, including castable elastomers, rigid and flexible foams, coatings, fibers and fabrics, adhesives, sealants, thermoplastics, and millable gums. The appeal of PU lies in its versatile nature, offering an attractive morphology and a broad spectrum of desirable mechanical properties, which can be tailored to meet specific application needs by manipulating its microstructure. Moreover, PU can be synthesized with ease using minimal techniques and exhibits excellent bonding characteristics with various substrates, making it applicable across a wide range of surfaces. Its self-supporting feature obviates the need for additional adhesives. This review provides a comprehensive overview of the current state-of-the-art literature concerning PU and its integration into structural and infrastructural applications, covering engineering properties, protective coatings, composite applications, as well as the reinforcement and retrofitting of structural elements using PU and its derivatives.[1]

Abhijit Das (2020). Polyurethane stands out as a material renowned for its remarkable versatility. The relationship between diisocyanates and polyols in its structure-property dynamic offers manufacturers a broad spectrum of options for customization. This versatility allows polyurethane to span the gamut of properties, from yielding soft-touch coatings to rigid materials of substantial hardness, catering to diverse construction needs. Its mechanical, chemical, and biological attributes, coupled with its ease of customization, have sparked significant interest not only within the scientific community but also among various industries. The potential for enhancing polyurethane further lies in the manipulation of raw materials and the incorporation of diverse additives and nanomaterials. By skillfully modifying these components, polyurethane can be tailored to suit virtually any application. This study sheds light on the fundamental chemistry underlying polyurethane's building blocks, along with recent advancements in its applications across a spectrum of fields including medical science, automotive, coatings, adhesives, sealants, paints, textiles, marine industry, wood composites, and apparel.[2]

John O. (2016). Polyurethanes (PUs) represent a versatile class of materials with considerable potential across diverse applications, largely owing to their structure-property relationships. Their unique mechanical, physical, biological, and chemical characteristics have garnered significant research interest, prompting efforts to tailor PUs for specific applications. Improving the properties and performance of PU-based materials can be achieved through adjustments in production processes, raw materials, or by employing advanced characterization techniques. It's evident that by appropriately modifying raw materials and production techniques, PUs can be tailored to suit a wide range of applications. This study aims to elucidate the chemistry, types, and synthesis of various PUs while comprehensively discussing significant research endeavors related to their synthesis, characterization techniques, and findings. Additionally, recent advancements in novel PU types and their synthesis for diverse applications are highlighted. Furthermore, emphasis is placed on the environmental aspects of PUs, particularly their recyclability and recoverability, underscoring their potential eco-friendliness.[3]

Joseph J. (2019). Polyurethanes (PUs), resulting from the reaction between diisocyanates and polyols (or equivalents) in the presence of a catalyst, find extensive use across various industries. In recent times, there has been considerable interest in their biomedical applications, largely due to their biocompatibility, biodegradability, and ability to be tailored into diverse chemical and physical forms. These applications encompass a broad spectrum, including antibacterial surfaces and catheters, drug delivery vehicles, stents, surgical dressings/pressure-sensitive adhesives, tissue engineering scaffolds and electrospinning, nerve generation, cardiac patches, and PU coatings for breast implants. After providing a brief overview of PUs, this review examines selected articles, primarily from 2014 to 2017, that underscore the manifold biomedical applications offered by PU materials and coatings.[4]

Ayesha Kausar (2017). Polyurethane foam, characterized by its cellular structure, serves as a polymeric material offering diverse functionalities. By reinforcing it with nanofillers, multifunctional polyurethane foams have been developed, exhibiting improved specific properties alongside reduced density. This article primarily explores key aspects of various foam processing techniques. A range of nanofillers including graphite, graphene, graphene oxide, carbon black, carbon nanotubes, nanoclays, and inorganic nanoparticles have been incorporated into polyurethane foam. Special attention is given to different categories of composite foams, including polymer/carbon nanofiller and polymer/inorganic nanofiller composites. The applications of polyurethane composite foams are examined with specific relevance to aerospace and automotive industries, radar absorption and electromagnetic interference shielding, oil absorbents, sensors, fireproof materials, shape memory applications, and biomedical materials.[5]

Murat Ates (2022). This review article explores the diverse industrial applications of polyurethane (PU) foam materials. PU foams have emerged as substitutes for metals and plastics across various engineering domains, offering a blend of the hardness and durability of metals alongside the flexibility of rubber. They can be synthesized using a variety of isocyanates, polyols, chain extenders, and crosslinkers, catering to specific applications such as bio-based composite foam, flexible hard/soft PU foam, and polymer foam. Altering the hard and soft segments of PUs through different factors yields various products like urethanes, biurets, allophanates, and isocyanurates. The review primarily delves into the fundamental chemistry underlying PU building blocks and recent advancements in their industrial applications. These applications span a wide range, including insulation materials, sound insulators, refrigerator and freezer insulators, furniture, footwear, automotive components, coatings, adhesives, and beyond.[6]

Bing-Xu Cheng (2022). The microphase separation of polyurethane arises from the thermodynamic incompatibility between its hard and soft segments, profoundly influencing its microstructure and performance. In recent years, numerous studies have explored this phenomenon, yet there remains a gap in summarizing the recent advances in characterization methods and applications. To address this gap, this paper meticulously compares and analyzes characterization techniques such as Fourier transform infrared spectroscopy (FT-IR), Differential scanning calorimetry (DSC), Dynamic thermomechanical analysis (DMA), Atomic force microscopy (AFM), Transmission electron microscopy (TEM), and Small-angle X-ray scattering (SAXS) concerning microphase separation. Furthermore, the paper delves into the applications of microphase-separated polyurethane in areas like shape memory, water resistance, and gas separation, providing detailed insights.[7]

Conclusion

In conclusion, the redesign of the life cycle of polyurethane presents an opportunity to enhance sustainability and promote responsible resource management in the polymer industry. By exploring alternative chemistries, adopting innovative manufacturing processes, and fostering collaboration across industries, stakeholders can address the sustainability challenges associated with polyurethane production and pave the way for a more sustainable future. Embracing innovation and sustainability as guiding principles will not only benefit the environment but also contribute to long-term economic prosperity and social well-being.

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