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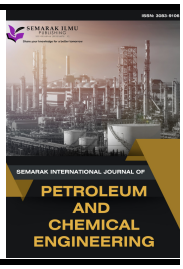

Enhancing Compression Performance and Morphology of Flexible Polyurethane Foam via Al_2O_3 Nanoparticle Reinforcement

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ABSTRACT

Flexible polyurethane foam is widely used for cushioning and structural applications. However, it always faces limitations in mechanical strength and cell stability. The incorporation of inorganic nanoparticles such as aluminum oxide (Al_2O_3) offers a good alternative to overcome these drawbacks by enhancing foam morphology and mechanical resilience. The present work aims to explore the influence of Al_2O_3 nanoparticle reinforcement on the compression behavior and cellular morphology of synthesized flexible PU foam. The novelty of this work is to show that low Al_2O_3 loadings can refine the cellular architecture and improve the compressive response by achieving a balance of flexibility and strength that is not typically attainable with conventional fillers. PU foams were synthesized via a one-shot method with 0, 0.2, and 0.4 g Al_2O_3 nanoparticles incorporated as fillers. Scanning Electron Microscopy (SEM) revealed progressive cell refinement with increasing nanoparticle content, where pore size decreased from 1.65–1.81 mm in the neat PU, 1.45–1.46 mm with 0.2 g Al_2O_3 and 824 µm at 0.4 g filler loading. Compression testing confirmed that this morphological refinement improved strength, as Al_2O_3 acted as nucleating agents, by limiting bubble growth allowing more uniform cellular structure. Therefore, the foam with 0.4 g Al_2O_3 delivered the best balance of mechanical strength and flexibility. In general, this study demonstrates that controlled incorporation of Al_2O_3 nanoparticles is an efficient strategy to control the microstructure and mechanical properties of flexible PU foams.

1. Introduction

Flexible polyurethane (PU) foam is a versatile polymeric material extensively utilized in automotive seating, furniture, packaging, and vibration-damping applications [1] due to its low density, comfort, and ease of processing [2]. Despite these advantages, conventional PU foams often exhibit limited mechanical strength, poor load-bearing capacity, and non-uniform cell morphology [3], which restrict their broader structural use [4]. These limitations primarily arise from the intrinsic trade-off between flexibility and mechanical integrity within the polymer network. Therefore,

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enhancing the compression performance and cellular stability of flexible PU foam without compromising its elasticity remains a critical challenge in polymer engineering [5].

Recent research has shown that the incorporation of inorganic nanoparticles can significantly improve the physical and mechanical characteristics of polymeric foams [6]. Nanoparticles, owing to their high surface area and interfacial reactivity, can act as heterogeneous nucleation sites during foam formation, influencing bubble growth [7], coalescence [8], and stabilization [9]. Among various fillers such as silica (SiO_2), titanium dioxide (TiO_2), and zinc oxide (ZnO), aluminum oxide (Al_2O_3) nanoparticles stand out due to their high modulus, thermal stability, and surface polarity [10], which promote strong interfacial interactions with the PU matrix [11]. Previous studies have demonstrated that Al_2O_3 addition enhances tensile, thermal, and abrasion resistance in rigid PU systems [12], but its influence on flexible PU foams, particularly at low filler concentrations, remains underexplored.

The reinforcement mechanism of nanoparticles in flexible PU foams is closely associated with their control over cellular architecture. Properly dispersed nanoparticles can refine cell structure [13], increase wall thickness [14], and suppress bubble coalescence [15], resulting in improved compression performance and dimensional stability [16]. However, achieving a homogeneous distribution of nanoparticles within the reactive PU matrix remains challenging due to their tendency to agglomerate [17], which can reduce interfacial adhesion [18] and deteriorate foam uniformity [19]. Hence, a systematic understanding of how nanoparticle loading influences foam morphology and mechanical behavior is essential to optimize their reinforcing potential [20].

This study investigates the effect of Al_2O_3 nanoparticle reinforcement on the cellular morphology and compression performance of flexible PU foams synthesized via a one-shot process. The novelty of this work lies in demonstrating that even low Al_2O_3 loadings (0.2–0.4 g) can substantially refine the cell structure and enhance compressive response, achieving a balanced combination of strength and flexibility rarely attainable with conventional fillers. Scanning Electron Microscopy (SEM) and compression analysis were conducted to establish a quantitative link between microstructural evolution and mechanical enhancement. The findings provide new insights into the design of lightweight, energy-absorbing PU foams suitable for next-generation automotive, cushioning, and structural applications.

2. Methodology

Methylene diphenyl diisocyanate (MDI), polyethylene glycol 400 (PEG400), dimethylpolysiloxane, triethylenediamine, and distilled water were used as the main reagents. Aluminum oxide (Al_2O_3) nanoparticles were incorporated as a reinforcing filler. All chemicals were used as received without further purification.

2.1 Synthesis of Flexible Polyurethane Foam

Flexible polyurethane (PU) foams were synthesized via a one-shot method with an isocyanate-to-polyol ratio of 1:1 [21]. The process involved two components, which are component A and component B. Component A comprises PEG400, triethylenediamine (as catalyst), dimethylpolysiloxane (as surfactant), distilled water (as blowing agent), and Al_2O_3 nanoparticles. Component B was MDI, serving as the isocyanate source.

2.2 Incorporation of Al_2O_3 Nanoparticles into Polyurethane (PU) Foam

Aluminum oxide (Al_2O_3) nanoparticles were incorporated into the polyol mixture at varying loadings of 0 g, 0.2 g, and 0.4 g to produce nanocomposite foams with different filler concentrations. The nanoparticles were dispersed thoroughly within the polyol prior to the addition of isocyanate to ensure homogeneous distribution and minimize agglomeration, which is essential for consistent cell morphology and mechanical performance.

Table 1
Compositions of Al_2O_3 nanoparticles for each PU foam sample

Sample type	A	B	C
PEG400 (wt%)	48.23	48.23	48.23
MDI (wt%)	48.23	48.23	48.23
Al_2O_3 (g)	0	0.2	0.4

2.3 Curing Process

Following mixing and foaming, the synthesized nanocomposite foams were allowed to cure at ambient temperature for 12 hours. This curing duration ensured complete polymerization and stabilization of the foam structure before analysis.

2.4 Characterization and Analysis
2.4.1 Scanning Electron Microscopy (SEM)

The microcellular morphology of the foams was examined using Scanning Electron Microscopy (SEM). Cellular structure plays a critical role in determining foam properties such as compression strength and comfort. Smaller and uniformly distributed pores typically yield excellent mechanical and cushioning performance [22]. In this analysis, approximately 1 mm thickness of thin slices was cut perpendicular to the foam rise direction. The sample was then subsequently frozen in liquid nitrogen to produce clean and freeze-fractured surfaces. This sample was then gold-coated before SEM observation to enhance surface conductivity and image clarity.

2.4.2 Compression Testing

The compressive behavior of the foams was evaluated using an Instron universal testing machine equipped with a 100 kN load cell, following ASTM D695 standards. During testing, a compressive load was applied to the specimens at a constant crosshead speed of 10 mm/min under room temperature conditions [23]. Both the applied force and corresponding displacement were recorded simultaneously to obtain the stress–strain response. Three specimens from each formulation were tested to ensure data reproducibility. After unloading, the thickness recovery of the foams was measured at 30 minute intervals to assess their elastic recovery characteristics.

3. Result

3.1 Scanning Electron Microscopy (SEM)

The morphological properties of the synthesized foams were characterized by SEM at 30× magnification. In this study, the cellular morphology of polyurethane (PU) foams containing 0 g, 0.2 g, and 0.4 g of aluminum oxide (Al_2O_3) nanoparticles was investigated, as presented in **Figure 1**. The unfilled PU foam (sample A) exhibited a distinctly larger cell structure, with pore sizes ranging from 1.65 to 1.81 mm. The absence of Al_2O_3 nanoparticles in the formulation allowed for unrestricted gas expansion, resulting in the formation of larger and more open cells. The incorporation of fillers is known to influence cellular architecture by acting as heterogeneous nucleation sites [24], which restricts gas bubble growth and promotes finer cell structures [25].

Upon addition of 0.2 g Al_2O_3 (sample B), the foam exhibited smaller and more uniformly distributed cells, with pore diameters in the range of 1.45–1.46 mm. The decrease in cell size corresponded with reduced porosity, supporting the findings of [26] who reported that filler particles act as nucleating agents to control foam expansion by lowering surface tension and enhancing the number of nucleation sites.

A further increase in Al_2O_3 loading to 0.4 g (sample C) resulted in the smallest and most compact cellular morphology, with pore sizes between 824 and 826 µm. The higher nanoparticle content effectively limited gas bubble coalescence, yielding a denser and more homogeneous structure [27]. These observations indicate that the inclusion of Al_2O_3 nanoparticles, particularly at 0.4 g, significantly refines the cell structure and reduces porosity, which may contribute to improved mechanical flexibility and softness of the PU foam matrix [28].

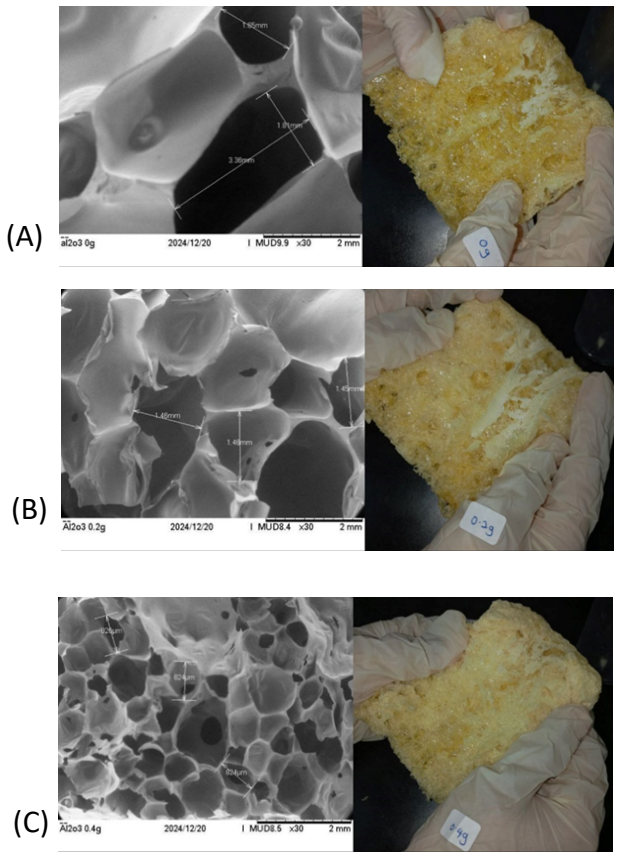

Fig. 1. Cell structure of polyurethane foam with 0g, 0.2g, and 0.4g Al_2O_3

3.2 Compression Testing

The compression behavior of polyurethane (PU) foams containing different loadings of Al_2O_3 nanoparticles was evaluated at a crosshead speed of 2 mm·min^{-1}, as presented in **Table 2**. The results demonstrate the significant influence of Al_2O_3 incorporation on the mechanical performance of PU foams synthesized from diphenylmethane-4,4′-diisocyanate (MDI) and polyethylene glycol 400 (PEG400).

Table 2
Compression test result

Sample	Diameter (mm)	Height before compress (mm)	Height after compress (mm)	Differences height (mm)
A	73.88	47.53	44.80	2.73
B	73.78	46.24	45.32	0.92
C	75.77	47.70	46.38	1.02

The unfilled PU foam exhibited a compressed thickness of 44.80 mm. Upon the addition of 0.2 g Al_2O_3, the compressed thickness increased to 45.32 mm, indicating that even a small amount of nanoparticle filler enhanced the resistance of the foam to deformation under load. Further increasing the filler content to 0.4 g resulted in a compressed thickness of 46.68 mm, reflecting a proportional improvement in compression resistance with higher filler concentration.

This progressive increase in compressed thickness suggests that Al_2O_3 nanoparticles effectively reinforced the PU matrix, improving the structural stability [29] of the foam during compression [30]. The enhanced load-bearing capacity with increasing filler content highlights the role of Al_2O_3 as a functional reinforcement that restricts cell wall collapse and facilitates uniform stress distribution. Overall, these results confirm the potential of Al_2O_3 nanoparticle incorporation to improve the resilience and durability of flexible PU foams for applications requiring superior mechanical integrity.

These mechanical improvements are in strong agreement with the morphological observations obtained from scanning electron microscopy (SEM). As previously shown in Figure 1, the addition of Al_2O_3 nanoparticles resulted in smaller, more uniform cell structures, with pore sizes decreasing from approximately 1.65–1.81 mm in the unfilled PU to 824–826 μm at 0.4 g filler loading. The refined cellular architecture likely enhanced load distribution throughout the foam, reducing localized stress concentration and improving the overall compressive performance.

The synergistic relationship between the finer cell morphology and increased compression resistance highlights the reinforcing role of Al_2O_3 nanoparticles in the PU matrix. The nanoparticles act as nucleation centres during foam formation, resulting in a denser and more homogeneous structure that prevents excessive gas expansion and cell wall collapse. Consequently, the combination of microstructural refinement and filler–matrix interaction contributes to the enhanced mechanical resilience and durability observed in the PU foam with higher Al_2O_3 content.

4. Conclusions

The incorporation of Al_2O_3 nanoparticles into polyurethane (PU) foams significantly enhanced both their morphological and mechanical characteristics. SEM analyses revealed that increasing Al_2O_3 content from 0 to 0.4 g effectively reduced the average cell size and produced a more uniform cellular architecture. This microstructural refinement was directly correlated with improved compressive performance, as evidenced by the increased compressed thickness with higher filler loadings. The results demonstrate that Al_2O_3 nanoparticles act as efficient heterogeneous nucleating agents,

promoting controlled cell formation and enhancing the foam's ability to dissipate mechanical stress. The denser and more homogeneous structure achieved at higher filler concentrations restricted gas expansion during foaming, resulting in greater load-bearing capacity and improved dimensional stability under compression.

In a nutshell, this study confirms the potential of Al_2O_3 nanoparticles as functional reinforcements for tailoring the morphology and mechanical resilience of flexible PU foams. The strong structure–property relationship established here provides a foundation for designing next-generation PU-based materials with enhanced durability, flexibility, and energy absorption performance suitable for applications in cushioning, packaging, and structural damping systems.

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