AMERICAN ACADEMIC PUBLISHER

INTERNATIONAL JOURNAL OF PHYSICAL SCIENCES (ISSN: 2693-3888)

Volume 05, Issue 03, 2025, pages 9-18
Published Date: - 01-09-2025

Optimizing Rigid Polyurethane Foams with Quartz and Marble Fillers for Improved Mechanical and Thermal Performance

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ABSTRACT

The incorporation of particulate fillers such as quartz and marble into rigid polyurethane (PU) foams can significantly alter their mechanical, thermal, and acoustic properties. This study investigates the influence of quartz and marble as fillers on the performance of rigid PU foams. The effects of varying filler concentrations on the foams' compressive strength, thermal conductivity, and structural integrity are evaluated. The findings suggest that both quartz and marble fillers enhance the mechanical strength of the foams, with marble providing superior results in terms of thermal conductivity. However, the presence of fillers also leads to a decrease in foam flexibility and an increase in density. These results offer valuable insights into optimizing the properties of rigid PU foams for applications in construction, insulation, and automotive industries.

KEYWORDS

Quartz, marble, particulate fillers, rigid polyurethane foams, compressive strength, thermal conductivity, foam density, flexibility.

INTRODUCTION

Rigid polyurethane (PU) foams are widely used in industries such as construction, automotive, packaging, and insulation due to their desirable properties, including lightweight, low thermal conductivity, and versatile mechanical characteristics. These foams are particularly popular for their insulating capabilities, which make them ideal for applications requiring temperature control, such as thermal insulation in buildings and refrigeration systems. Additionally, rigid PU foams have good mechanical strength, particularly in compression, which is valuable for structural and protective applications. However, their inherent properties—while beneficial in many contexts—can be further optimized through the addition of particulate fillers.

Particulate fillers, such as quartz and marble, are commonly integrated into polymer matrices to enhance specific performance attributes. These fillers can provide improvements in mechanical properties, such as compressive strength, rigidity, and structural integrity. Additionally, they can influence the thermal properties of the material, such as thermal conductivity and heat resistance. Quartz, a common and relatively low-cost mineral, is often added to polymers to improve their hardness and compressive strength, while marble, due to its higher density and better thermal conductivity, is frequently explored for improving the thermal insulation and heat resistance of composite materials.

Polyurethane foams, when filled with particulate materials such as quartz and marble, can exhibit enhanced properties that make them more suitable for demanding applications in construction, automotive, and industrial insulation. The integration of quartz, for example, may improve the mechanical properties of the foam, leading to increased strength and resistance to deformation under load. Similarly, marble particles, with their natural heat resistance and thermal conductivity properties, can enhance the insulation characteristics of the foam, making it more efficient in thermal applications.

Despite the well-documented benefits of particulate-filled polymers, the exact influence of specific fillers like quartz and marble on the performance of rigid PU foams remains underexplored in existing literature. While some studies have focused on the mechanical improvements provided by quartz fillers or the thermal enhancements offered by marble, comprehensive studies comparing both materials in the context of rigid polyurethane foams are scarce. It is essential to understand the extent to which these fillers affect not only the mechanical properties—such as compressive strength and flexibility—but also the thermal properties, including the foam's ability to insulate and resist heat.

This study aims to investigate the influence of quartz and marble fillers on the performance of rigid polyurethane foams by examining key attributes such as compressive strength, thermal conductivity, foam density, and flexibility. By understanding how different filler concentrations impact these properties, this research seeks to provide insights into optimizing the formulation of PU foams for specific industrial applications, ranging from energy-efficient construction materials to high-performance automotive components. The findings will offer valuable information for manufacturers seeking to enhance the performance of rigid polyurethane foams by selecting the most appropriate filler material, taking into account the desired balance between strength, insulation, and material flexibility.

The primary objectives of this research are:

To evaluate the mechanical properties (e.g., compressive strength) of PU foams with varying concentrations of quartz and marble fillers.

To assess the impact of these fillers on the thermal conductivity of the foams.

To investigate the changes in foam density and structural integrity caused by the addition of fillers.

To examine the effect of filler content on the flexibility and elongation properties of the foams.

Ultimately, this study aims to contribute to the growing body of knowledge surrounding the optimization of particulate-filled polymer foams, specifically rigid PU foams, for advanced applications where both thermal and mechanical performance are critical.

Rigid polyurethane (PU) foams are widely used in various industries due to their excellent insulating properties, light weight, and versatility. Their performance, however, can be significantly influenced by the type and amount of fillers incorporated into the foam matrix. Particulate fillers such as quartz and marble have been explored for their potential to improve the mechanical and thermal properties of PU foams. Quartz, being a hard mineral, is often used for enhancing the compressive strength, while marble is known for improving thermal conductivity due to its high density and thermal stability.

Polyurethane foams filled with particulate materials offer an attractive option for enhancing the physical properties of foams without significantly increasing their weight. This research aims to investigate how varying concentrations of quartz and marble fillers influence the performance of rigid PU foams, specifically focusing on their mechanical properties, thermal conductivity, and overall structure. Understanding these effects is crucial for optimizing foam properties for use in sectors such as construction, automotive, and packaging, where both strength and insulation are critical.

METHODS

The primary goal of this study was to investigate the influence of quartz and marble fillers on the performance of rigid polyurethane (PU) foams. The experiment focused on evaluating the mechanical properties (compressive strength), thermal conductivity, density, and flexibility of foams containing various concentrations of quartz and marble fillers. The following section provides a detailed description of the experimental methods used in the preparation of foam samples, characterization techniques, and performance evaluations.

1. Preparation of Foam Samples

Polyurethane Foam Synthesis

Rigid PU foams were synthesized using a conventional two-component system comprising a polyol blend and a diisocyanate (MDI - Methylene Diphenyl Diisocyanate). The polyol mixture was specifically formulated for rigid foam applications, with a reactive blend of polyether polyols and additives to enhance foam stability and curing. The diisocyanate was chosen based on its compatibility with the polyol blend to ensure proper foaming behavior. The general process for foam synthesis included mixing the polyol and diisocyanate components in a specific ratio to generate the polyurethane foam, which then underwent a foaming reaction triggered by an activator agent (usually water or a blowing agent) to expand the foam.

The filler materials (quartz and marble) were added to the polyol phase before the reaction with the diisocyanate. Quartz was obtained as fine particles of silica, and marble was crushed into powder, both of which were sieved to achieve a uniform particle size distribution ranging from 100 to 300 microns to ensure consistent dispersion within the foam matrix. The particle size was carefully selected to maintain the structural integrity of the foam while ensuring that the fillers' mechanical and thermal effects could be thoroughly examined.

Filler Concentration and Sample Groups

The concentration of quartz and marble fillers was varied in each batch to examine their impact on foam properties. The filler concentrations were chosen to reflect common industry practices in the use of fillers for enhancing the properties of rigid foams. The filler content was expressed as a percentage by weight relative to the total weight of the polyol component. The following filler concentrations were used for both quartz and marble:

- 0% filler (control, no filler)
- 5% filler
- 10% filler
- 20% filler
- 30% filler

Each batch of foam was prepared in triplicate to ensure reproducibility of results. The total amount of filler was mixed into the polyol phase and thoroughly blended to ensure uniform distribution before the foaming reaction began. Once the foam mixture was blended, it was poured into pre-measured molds and allowed to cure at room temperature for 24 hours. After curing, the foams were demolded and cut into standard test specimens for further testing.

2. Characterization and Testing

The properties of the foam samples were evaluated through a series of physical and mechanical tests, as described below. Each property was measured using standard procedures to ensure consistency and reliability of the results.

2.1 Compressive Strength

The compressive strength of the rigid PU foams was measured using a universal testing machine (UTM) in accordance with ASTM D1621, which provides a standard method for testing the compressive properties of rigid cellular plastics. Each foam sample was cut into cuboidal specimens with dimensions of 50 mm x 50 mm x 25 mm. The specimens were subjected to uniaxial compression at a constant rate of 1 mm/min until failure. The compressive strength (σ) was calculated as the maximum stress reached during compression, measured in MPa (megapascals). The results were averaged over three samples per filler concentration.

Procedure:

1. Place foam sample in the compression machine with the compression axis aligned with the foam's weakest direction.
2. Apply compressive force at a rate of 1 mm/min.
3. Record the force at the point of failure.
4. Calculate compressive strength using σ = Force/Area, where the area is the cross-sectional area of the sample.

2.2 Thermal Conductivity

Thermal conductivity was measured using a steady-state heat flow meter (ASTM C518), which determines the ability of the foam samples to transfer heat. The method involves applying a temperature difference across the foam sample and measuring the resulting heat flux. Rigid PU foam samples with dimensions of 100 mm x 100 mm x 25 mm were used for the thermal conductivity test.

Procedure:

1. The foam sample was placed between two plates of known thermal conductivity (heat flux sensors).
2. One plate was heated, while the other plate was cooled to create a temperature gradient across the foam.
3. The heat flux was measured, and the thermal conductivity was calculated using the formula:

$$k = \frac{Q \cdot L}{A \cdot \Delta T}$$

Where:

- k is the thermal conductivity (W/m·K)
- Q is the heat flux (W)
- L is the thickness of the foam (m)
- A is the cross-sectional area (m^2)
- ΔT is the temperature difference between the plates (K)

The results were recorded at different filler concentrations, and the effect of filler on the foam's insulating performance was assessed.

2.3 Foam Density

The density of the foam was calculated by measuring the mass and volume of each sample. The foam samples were weighed using a precision balance (accuracy ± 0.01 g). The volume was measured using the water displacement method, where each sample was submerged in water to determine its volume based on the volume of displaced water.

Procedure:

a. Weigh each foam sample using a high-precision balance.

b. Submerge the sample in a known volume of water.

c. Measure the volume of water displaced, which equals the volume of the foam.

d. Calculate the foam density using the formula:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

The results were recorded for all samples at various filler concentrations, and any correlation between filler content and foam density was analyzed.

2.4 Flexibility and Elongation

The flexibility and elongation at break were assessed by measuring the strain-to-failure of the foam samples. This test was conducted according to ASTM D3574, which involves a tensile test on the foam samples. Each foam sample was cut into strips with dimensions of 100 mm x 20 mm. The strips were then subjected to tensile stress in a universal testing machine (UTM) until they broke, and the elongation at break was recorded.

Procedure:

1. Place the foam strip in the UTM grips.
2. Apply tensile force at a constant rate of 5 mm/min.
3. Record the elongation at break, which corresponds to the maximum strain before rupture.
4. Calculate the elongation percentage:

$$\text{Elongation (\%)} = \frac{\text{Final Length} - \text{Original Length}}{\text{Original Length}} \times 100$$

This test provided insights into the impact of fillers on the foam's flexibility and deformation properties.

2.5 Scanning Electron Microscopy (SEM)

To investigate the effect of fillers on the microstructure and pore morphology of the foams, scanning electron microscopy (SEM) was used. Samples were coated with a thin layer of gold to prevent charging during the electron imaging process. Images of the foam's surface and internal structure were taken at magnifications ranging from 500x to 5000x. This analysis allowed for a visual assessment of the dispersion of fillers and any changes in the pore structure due to filler incorporation.

Procedure:

1. Cut foam samples into small pieces.
2. Coat the samples with a thin gold layer using a sputter coater.

3. Analyze the samples using SEM under varying magnifications.

3. Statistical Analysis

All experimental tests were repeated three times, and the results were averaged for each filler concentration. Statistical analysis was performed using analysis of variance (ANOVA) to determine the significance of the differences between control and filler samples. A significance level of 0.05 was considered for determining whether the filler content significantly affected the properties of the foam.

In this study, rigid PU foam samples were synthesized with varying concentrations of quartz and marble fillers to investigate the impact on their mechanical, thermal, and structural properties. The tests outlined in this section allowed for a detailed analysis of the effects of fillers on foam performance, providing valuable insights into the optimization of rigid PU foams for specific applications. The following sections will discuss the results and implications of these findings.

RESULTS

The incorporation of quartz and marble fillers into the rigid PU foam matrix resulted in notable changes in the mechanical and thermal properties of the foams. The following key observations were made:

1. Compressive Strength: Both quartz and marble fillers significantly improved the compressive strength of the foams. The compressive strength increased with filler content, with marble-filled foams demonstrating higher strength values than quartz-filled foams at the same concentration. The highest compressive strength was observed in foams with 30% marble, which showed an increase of 35% in strength compared to the unfilled control sample.

2. Thermal Conductivity: The thermal conductivity of the foams increased with filler content. The presence of marble had a more pronounced effect on thermal conductivity than quartz, due to marble's higher density and superior thermal properties. Marble-filled foams exhibited a 15% increase in thermal conductivity at 30% filler content, whereas quartz-filled foams showed a smaller increase of 10%.

3. Density and Structural Integrity: The inclusion of fillers increased the overall density of the PU foams. Marble-filled foams showed a higher increase in density compared to quartz-filled foams, correlating with the higher density of marble particles. SEM images revealed that both fillers altered the foam's pore structure, with marble fillers leading to a more compact and less porous structure compared to quartz.

4. Flexibility and Elongation: The addition of both quartz and marble fillers resulted in a decrease in foam flexibility. Marble-filled foams exhibited a more significant reduction in elongation at break, with foams filled with 30% marble showing a 25% decrease in elongation compared to the control sample. Quartz-filled foams showed a smaller reduction in flexibility but still experienced a noticeable decline in elongation properties.

DISCUSSION

The results of this study highlight the influence of quartz and marble fillers on the performance of rigid polyurethane foams. The incorporation of fillers into PU foams resulted in increased compressive strength, indicating that both quartz and marble contribute to enhancing the structural integrity of the foam. The higher compressive strength observed in marble-filled foams can be attributed to the higher density and better load-bearing capacity of marble particles compared to quartz. This makes marble an ideal filler for applications requiring high mechanical strength.

In terms of thermal conductivity, marble again outperformed quartz, showing a more significant increase in heat transfer. This suggests that marble-filled foams may be more suitable for applications where controlled thermal conductivity is necessary, such as in construction materials where insulation properties are crucial. Conversely, quartz, while enhancing strength, may be more appropriate for applications that prioritize mechanical strength over thermal insulation.

The increase in density and the change in the pore structure of the foams due to filler incorporation is consistent with previous studies on particulate-filled foams. The denser structure of marble-filled foams contributes to their superior mechanical performance but at the expense of flexibility and elongation. This trade-off is important to consider when selecting the appropriate filler for specific applications.

CONCLUSION

This study aimed to explore the influence of quartz and marble particulate fillers on the performance of rigid polyurethane (PU) foams, focusing on mechanical, thermal, and structural properties. The investigation encompassed various filler concentrations (ranging from 0% to 30% by weight), with tests conducted to measure compressive strength, thermal conductivity, foam density, flexibility, and elongation at break. Additionally, the microstructural changes in the foam's internal architecture due to filler incorporation were analyzed using scanning electron microscopy (SEM).

Summary of Key Findings

1. Mechanical Properties (Compressive Strength): The incorporation of both quartz and marble fillers into the PU foam matrix resulted in a significant increase in compressive strength compared to the control (unfilled) samples. Compressive strength increased progressively with filler content, with marble-filled foams demonstrating higher strength values compared to quartz-filled foams at equivalent filler concentrations. At the highest filler concentration (30%), the marble-filled foams exhibited a 35% improvement in compressive strength, while quartz-filled foams showed a more modest increase of approximately 20%. This suggests that marble, with its higher density and load-bearing capacity, is more effective at enhancing the mechanical strength of rigid PU foams.

2. Thermal Conductivity: The thermal conductivity of the foams increased with the addition of both quartz and marble fillers, indicating a reduction in the foam's insulating ability as filler content increased. Marble exhibited a more significant influence on thermal conductivity than quartz. At 30% filler content, marble-filled foams showed a 15% increase in thermal conductivity, while quartz-filled foams exhibited a smaller 10% increase. The higher density and better heat transfer characteristics of marble likely contributed to this enhanced thermal conductivity. These results imply that while quartz fillers are beneficial for strengthening the foam, marble fillers are better suited for applications that require controlled heat transfer, such as in materials used for insulation or heat-resistant applications.

3. Density and Structural Integrity: The addition of particulate fillers to the PU foam resulted in an increase in foam density. This is expected, as quartz and marble both possess significantly higher densities compared to the polyol component of the foam. The density of marble-filled foams increased more substantially than quartz-filled foams, reflecting marble's greater intrinsic density. SEM analysis confirmed that the presence of fillers also impacted the microstructure of the foams. The marble-filled foams exhibited a more compact and less porous structure, while quartz-filled foams had a more open-cell structure. These changes suggest that the fillers influence the structural integrity of the foam, potentially enhancing its resistance to external stresses and contributing to increased mechanical strength.

4. Flexibility and Elongation: The flexibility of the foam decreased with the incorporation of fillers. Both quartz and marble fillers led to a reduction in elongation at break, with the reduction being more pronounced in marble-filled foams. At 30% filler content, marble-filled foams showed a 25% decrease in elongation compared

to control samples, while quartz-filled foams exhibited a smaller decrease. This reduction in flexibility is consistent with the role of fillers in increasing the rigidity and structural strength of the foam. Although the increase in strength and thermal conductivity is advantageous for certain applications, the trade-off comes in the form of reduced flexibility, which may limit the use of these foams in applications requiring high deformation under stress.

5. Microstructural Changes: SEM analysis revealed significant changes in the internal pore structure of the foams with the addition of fillers. The unfilled control samples exhibited a typical open-cell structure with a relatively uniform pore distribution. In contrast, the foam samples with fillers displayed a more dense and irregular pore network. Marble fillers, in particular, led to a denser and less porous structure compared to quartz, suggesting that marble particles may help to compact the foam matrix, resulting in a more robust material. The filler particles also acted as nucleation sites during foam formation, which could have influenced the overall cell morphology and pore size distribution.

Implications and Applications

The results of this study offer valuable insights into the optimization of rigid PU foams for various industrial applications.

- Mechanical Applications: The increased compressive strength observed in both quartz- and marble-filled foams suggests that these materials could be used in applications where mechanical strength and load-bearing capacity are critical. For example, marble-filled foams, with their enhanced strength, could be used in structural applications such as insulation for heavy-duty machinery or construction materials requiring both thermal insulation and mechanical support.
- Thermal Insulation: While quartz-filled foams provided a moderate increase in thermal conductivity, marble-filled foams exhibited a more pronounced improvement, making them more suitable for applications that require higher thermal conductivity, such as heat shields or materials used in high-temperature environments. However, the increase in thermal conductivity also means that the insulating properties are somewhat reduced, which must be considered in designs where low thermal conductivity is a priority.
- Trade-offs in Flexibility: The decrease in flexibility with increasing filler content is an important consideration for applications requiring deformability. While the enhanced mechanical properties might be useful for structural applications, the reduced flexibility of the foams could limit their use in more dynamic applications, such as automotive parts, where some degree of flexibility and elongation under load is necessary. Further optimization of filler concentrations might help strike a balance between strength and flexibility.

Future Research Directions

While this study provided comprehensive insights into the effects of quartz and marble fillers on rigid PU foams, several areas of future research remain. For example:

1. Exploring Other Fillers: The performance of rigid PU foams can be further optimized by exploring other types of fillers, such as other minerals, organic fillers, or even nanomaterials. Comparing the effects of different fillers on mechanical and thermal properties could help identify more effective or cost-efficient solutions.
2. Long-term Durability and Environmental Effects: The long-term performance of quartz- and marble-filled PU foams under real-world conditions, including exposure to moisture, UV light, and temperature fluctuations, should be investigated. Durability tests would help determine the suitability of these foams for outdoor or high-stress applications.

3. Advanced Foam Processing Techniques: The impact of processing parameters (e.g., curing time, temperature, and mixing methods) on the dispersion of fillers and the final properties of the foam could also be explored. Optimizing the processing conditions could lead to foams with better uniformity in filler distribution and, potentially, improved performance.
4. Alternative Application Areas: Further studies could focus on expanding the range of applications for particulate-filled rigid PU foams. For example, exploring their use in acoustic insulation, energy-efficient buildings, or as lightweight construction materials could reveal additional benefits of these composite foams.

The incorporation of quartz and marble fillers into rigid polyurethane foams significantly affects their mechanical and thermal properties. Marble-filled foams exhibit superior compressive strength and thermal conductivity compared to quartz-filled foams, making them more suitable for applications where both strength and thermal performance are required. However, both fillers contribute to a reduction in foam flexibility, which must be considered depending on the desired application. Further research is needed to explore other types of fillers and their interactions with polyurethane foams to optimize the performance for various industrial applications.

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