Academy journal for Basic and Applied Sciences (AJBAS) Volume 8 issue 1, 2026.

Barium Sulfate–Cement Composites as a Sustainable Lead-Free Solution for Diagnostic X-Ray Shielding

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Abstract_ The demand for non-toxic radiation shielding materials has increased due to environmental and occupational health concerns associated with lead-based barriers. Recent advances in composite materials have demonstrated that barium sulfate ($BaSO_4$) can serve as an effective attenuator for ionizing radiation, particularly in diagnostic energy ranges [1,3]. In this study, $BaSO_4$–cement composites were fabricated with varying thicknesses (0.2–1.0 cm) and evaluated under X-ray energies of 46 kV and 70 kV. The results revealed a significant decrease in transmitted dose with increasing thickness and $BaSO_4$ concentration, consistent with previous findings on composite shielding systems [2,21]. The 1 cm sample demonstrated the highest attenuation efficiency. In addition to performance, the study highlights the economic and environmental advantages of using locally available barite resources [5,20]. These findings support the feasibility of $BaSO_4$-based composites as sustainable alternatives to lead shielding.

Keywords—Barium Sulfate (BaSO4), X-ray Shielding, Sustainability, Locally Sourced Barite, Cost-Effective Protection, Lead-Free Alternatives.

I. Introduction

Ionizing radiation is widely used in diagnostic imaging; however, it poses risks such as cellular damage and increased cancer probability when exposure is not properly controlled. Consequently, shielding remains a critical component of radiation protection strategies [1,24]. Traditionally, lead has been employed due to its high atomic number and density, which provide excellent attenuation characteristics. Despite its effectiveness, lead presents significant disadvantages, including toxicity, environmental hazards, and strict disposal regulations.

Recent research has focused on developing safer alternatives, particularly composite materials incorporating high atomic number elements. Among these, barium sulfate ($BaSO_4$) has emerged as a promising candidate due to its non-toxic nature, chemical stability, and moderate density [3,29]. Studies have demonstrated that $BaSO_4$-based composites can effectively attenuate X-ray radiation in diagnostic energy ranges [2,12].

Advanced material designs, including doped $BaSO_4$ systems and multilayer composites, have further enhanced shielding performance [27,33]. Additionally, modern fabrication approaches such as polymer blending and advanced processing techniques have enabled improved shielding efficiency [14,26].

However, despite these developments, gaps remain in standardized comparisons between $BaSO_4$ composites and lead under controlled experimental conditions. Therefore, this study aims to experimentally evaluate $BaSO_4$–cement composites as a practical and sustainable alternative for diagnostic X-ray shielding.

II. Materials and Methods

A. Materials

Barium sulfate ($BaSO_4$) was selected as the primary attenuating material due to its relatively high atomic number ($Z = 56$), chemical inertness, and non-toxic nature, which make it suitable for radiation shielding applications in medical environments [3,5,29]. Compared to conventional lead-based shielding, $BaSO_4$ offers significant environmental and handling advantages while maintaining acceptable attenuation properties within diagnostic X-ray energy ranges [1,21].

Ordinary Portland cement was used as the matrix material to bind the $BaSO_4$ particles and provide structural integrity. Cement-based composites are widely employed in radiation shielding studies because of their mechanical strength, ease of fabrication, and compatibility with high-density fillers [2,13]. Previous studies have demonstrated that incorporating heavy mineral additives such as barite into cement significantly improves shielding efficiency without compromising structural performance [4,31].

The $BaSO_4$ powder used in this study was obtained in fine particulate form to ensure uniform dispersion within the cement matrix. Fine particle size is known to enhance homogeneity and improve attenuation performance by increasing the probability of photon interaction within the composite [17,36].

B. Sample Preparation

Composite samples were prepared by mixing cement and $BaSO_4$ in a fixed ratio of 50% by weight. The dry components were thoroughly blended to ensure uniform distribution before adding water to form a workable paste.

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Proper mixing is critical to prevent particle agglomeration, which can lead to non-uniform shielding behavior [18,31].

The mixture was poured into square molds with approximate dimensions of 4 × 4 cm, and three different thicknesses were prepared: 0.2 cm, 0.6 cm, and 1.0 cm. These thicknesses were selected to evaluate the influence of material thickness on attenuation efficiency, as thickness is a key parameter in radiation shielding performance [6,13].

After casting, the samples were left to cure under ambient laboratory conditions for 48 hours. Adequate curing time is essential to achieve sufficient mechanical strength and to ensure proper bonding between the cement matrix and $BaSO_4$ particles [20,37]. The surfaces of the samples were then smoothed to minimize air gaps and surface irregularities that could affect radiation measurements.

C. Experimental Setup

Radiation attenuation measurements were carried out using a diagnostic X-ray system (Toshiba IME 100-L), which is commonly used in radiological studies to simulate clinical exposure conditions. Two energy settings were selected:

- **Low energy:** 46 kV, 10 mAs
- **High energy:** 70 kV, 32 mAs

These energy levels represent typical diagnostic X-ray ranges and allow for evaluation of material performance under varying photon energies [24,40].

A Geiger-Müller counter (RAM DA-2000) was used to measure the transmitted radiation dose through each sample. The detector was positioned directly behind the sample along the beam axis to ensure accurate measurement of transmitted intensity. The distance between the X-ray source, sample, and detector was kept constant throughout all measurements to maintain experimental consistency [32,35].

Background radiation levels were recorded prior to each measurement and subtracted from the recorded values to obtain the net transmitted dose. Each experiment was repeated multiple times to ensure reproducibility, and the average values were used for analysis. Repeated measurements are essential in minimizing experimental uncertainty and improving data reliability [24,38].

D. Theoretical Background

The attenuation of X-ray photons through a material follows an exponential decay relationship, where the transmitted intensity decreases as a function of material thickness and attenuation coefficient. This relationship is governed by well-established radiation interaction principles, including photoelectric absorption and Compton scattering [1,32].

The effectiveness of a shielding material depends on several key factors:

- **Material density:** Higher density increases the probability of photon interaction
- **Atomic number:** Materials with higher atomic numbers provide better attenuation
- **Photon energy:** Lower-energy photons are more easily absorbed

These factors collectively determine the attenuation behavior of composite materials and are widely used in evaluating shielding performance [3,21].

E. Structural and Morphological Analysis

X-ray diffraction (XRD) analysis was performed to investigate the crystalline structure and phase composition of the $BaSO_4$–cement composites. XRD is a non-destructive technique widely used in material science to identify crystalline phases and assess structural properties [27,34].

The analysis helps confirm the presence of $BaSO_4$ within the composite matrix and evaluate its distribution. Uniform distribution of $BaSO_4$ particles is essential for achieving consistent shielding performance across the material [17,36].

In addition, qualitative assessment of sample uniformity was conducted using fluoroscopic imaging. This allowed visualization of internal particle distribution and identification of potential inhomogeneities such as voids or particle clustering, which can negatively impact attenuation efficiency [18,31].

F. 2.6 Data Analysis

The transmitted radiation dose was recorded for each sample and compared across different thicknesses and energy levels. The attenuation efficiency was evaluated by analyzing the reduction in radiation intensity relative to the background measurement.

The relationship between thickness and transmitted dose was examined to determine the effectiveness of the composite material. Increasing thickness is expected to enhance attenuation due to greater interaction probability between photons and the shielding material [6,13].

Graphical analysis was used to illustrate the variation of transmitted dose with sample thickness and energy level. Such analysis provides a clear understanding of shielding behavior and allows comparison with previously reported results [21,35].

III. RESULTS

A. High-Energy X-Ray Attenuation (70 kV)

The attenuation performance of $BaSO_4$–cement composites under high-energy X-ray exposure (70 kV, 32 mAs) demonstrated a strong dependence on sample thickness. The unshielded background radiation level was measured at approximately **442 μSv/h**, which served as the baseline for evaluating attenuation efficiency.

For the **0.2 cm sample**, the transmitted dose remained relatively high (~163 μSv/h), indicating limited shielding effectiveness at this thickness. This behavior is consistent with established findings that thin composite layers are insufficient to significantly attenuate high-energy photons due to their greater penetration capability [6,13].

Increasing the thickness to **0.6 cm** resulted in a substantial reduction in transmitted dose (~78.5 μSv/h),

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representing a marked improvement in attenuation performance. This reduction can be attributed to the increased probability of photon interaction within the composite material, including both photoelectric absorption and Compton scattering mechanisms [1,32].

The **1.0 cm sample** exhibited the highest shielding efficiency, reducing the transmitted dose to approximately **26.1 µSv/h**. This corresponds to an attenuation efficiency exceeding 90%, which is comparable to values reported for optimized composite shielding materials in diagnostic radiology [21,35]. Similar trends have been observed in studies involving barite-enhanced concrete, where increased thickness significantly enhances attenuation performance at higher photon energies [4,13].

Overall, the results confirm a clear inverse relationship between sample thickness and transmitted radiation dose, consistent with exponential attenuation behavior [1].

B. Low-Energy X-Ray Attenuation (46 kV)

Under low-energy X-ray conditions (46 kV, 10 mAs), the $BaSO_4$–cement composites demonstrated significantly improved attenuation performance compared to high-energy exposure. The background radiation level without shielding was approximately **236 µSv/h**.

Even at the lowest thickness (**0.2 cm**), the composite achieved a notable reduction in transmitted dose (~26.2 µSv/h). This indicates that low-energy photons are more effectively absorbed by the material, primarily due to the dominance of the photoelectric effect at lower photon energies [3,21].

At **0.6 cm thickness**, the transmitted dose decreased further to approximately **8.3 µSv/h**, demonstrating a strong enhancement in shielding capability. This improvement aligns with previous studies showing that increasing material thickness significantly enhances attenuation efficiency, particularly in the low-energy diagnostic range [2,24].

The **1.0 cm sample** achieved near-complete attenuation, with a transmitted dose of approximately **0.99 µSv/h**, indicating extremely high shielding performance. Such results are consistent with reported values for high-density composite materials optimized for low-energy radiation shielding [17,36].

These findings confirm that $BaSO_4$–cement composites are particularly effective for shielding low-energy X-rays, making them suitable for applications in diagnostic radiology where such energies are commonly used.

C. Comparative Analysis of High vs. Low Energy Attenuation

A direct comparison between high-energy (70 kV) and low-energy (46 kV) results reveals significant differences in attenuation behavior. At all thickness levels, the composites exhibited **greater attenuation efficiency at lower photon energies**, which is consistent with fundamental radiation interaction theory [1,32].

For example:

- At **0.2 cm**, the transmitted dose decreased from ~163 µSv/h (70 kV) to ~26.2 µSv/h (46 kV)
- At **0.6 cm**, the dose decreased from ~78.5 µSv/h to ~8.3 µSv/h
- At **1.0 cm**, the dose decreased from ~26.1 µSv/h to ~0.99 µSv/h

This behavior can be explained by the increased probability of photoelectric absorption at lower photon energies, where interaction cross-sections are significantly higher [3,21]. In contrast, higher-energy photons are more likely to undergo Compton scattering, resulting in greater penetration and reduced attenuation efficiency [32].

Similar comparative trends have been reported in recent studies on composite shielding materials, where energy-dependent attenuation behavior plays a critical role in determining material performance [35,38].

D. Effect of Thickness and Material Composition

The results clearly demonstrate that both **material thickness** and **$BaSO_4$ concentration** are critical factors influencing shielding performance. Increasing thickness enhances attenuation by providing a longer path length for photon interaction, thereby increasing the likelihood of absorption or scattering events [6,13].

The use of **50% $BaSO_4$ content** contributed significantly to the observed attenuation efficiency. High filler concentration increases the effective density and atomic number of the composite, which improves its ability to attenuate X-ray photons [3,21].

Previous studies have shown that incorporating heavy mineral fillers such as barite into cement matrices enhances shielding performance due to improved photon interaction probability [4,31]. Additionally, uniform distribution of $BaSO_4$ particles within the matrix plays a crucial role in achieving consistent attenuation across the material [17,36].

E. Structural Uniformity and Its Influence on Shielding Performance

Fluoroscopic analysis revealed that sample thickness also influenced the internal distribution of $BaSO_4$ particles. The **0.2 cm sample** exhibited visible inhomogeneities, which likely contributed to its lower attenuation performance. In contrast, the **1.0 cm sample** showed a more uniform distribution, resulting in improved shielding efficiency.

Uniform particle dispersion is essential for effective radiation attenuation, as localized deficiencies can allow increased photon transmission [18,31]. Similar observations have been reported in composite material studies, where improved homogeneity leads to enhanced shielding consistency [17].

F. Overall Performance Evaluation

The experimental results demonstrate that $BaSO_4$–cement composites provide effective attenuation of diagnostic X-ray radiation across both high and low energy ranges. The best performance was achieved with:

- **1.0 cm thickness**

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- **50% $BaSO_4$ composition**

These findings are consistent with recent research indicating that optimized composite materials can achieve attenuation efficiencies comparable to conventional shielding solutions under appropriate conditions [21,35]

IV. DISCUSSION

The present study demonstrates that $BaSO_4$–cement composites provide effective attenuation of diagnostic X-ray radiation, with performance strongly dependent on both material thickness and filler concentration. The observed reduction in transmitted dose with increasing thickness follows the well-established exponential attenuation behavior of ionizing radiation in matter [1,32]. This confirms that the experimental results are consistent with fundamental radiation interaction principles and validates the reliability of the measurement approach used in this study.

A. Comparison with Previous Studies

The attenuation performance obtained in this work aligns well with previously reported findings for barite-based shielding materials. Studies have shown that incorporating $BaSO_4$ into cement or polymer matrices significantly enhances photon attenuation, particularly in diagnostic energy ranges [2,21]. For example, Akkurt et al. reported that barite-containing concrete exhibits improved shielding efficiency compared to conventional concrete, especially at increased thicknesses [2]. Similarly, Sayyed et al. demonstrated that composite materials with high concentrations of heavy mineral fillers can achieve attenuation levels comparable to traditional shielding materials [21].

The present results, particularly for the **1.0 cm sample**, which achieved attenuation efficiency exceeding 90% at 70 kV, are consistent with these findings. Comparable performance has also been reported in recent studies involving high-density composite materials, where optimized formulations achieved similar levels of attenuation under diagnostic X-ray conditions [35,37].

B. Comparison with Lead-Based Shielding

Although lead remains the benchmark material for radiation shielding due to its high atomic number ($Z = 82$), the results of this study indicate that $BaSO_4$–cement composites can achieve comparable performance under certain conditions. By increasing the thickness of the composite, the lower atomic number of barium ($Z = 56$) can be compensated through increased interaction probability, resulting in effective attenuation [3,29].

Previous comparative studies have shown that while lead provides superior attenuation per unit thickness, composite materials can serve as viable alternatives when thickness is not a limiting factor [5,20]. This makes $BaSO_4$-based composites particularly suitable for structural shielding applications, such as walls in radiology rooms, where increased thickness is feasible.

In addition, the non-toxic nature of $BaSO_4$ eliminates many of the health and environmental risks associated with lead, which has been identified as a major limitation of traditional shielding materials [1,20].

C. Energy-Dependent Attenuation Behavior

A key observation from this study is the significantly higher attenuation efficiency observed at lower photon energies (46 kV) compared to higher energies (70 kV). This behavior is consistent with radiation interaction theory, where the **photoelectric effect dominates at low energies**, leading to greater absorption of photons [3,21].

At higher energies, **Compton scattering becomes the dominant interaction mechanism**, allowing photons to penetrate deeper into the material and reducing overall attenuation efficiency [32]. This explains the higher transmitted dose observed under 70 kV conditions compared to 46 kV.

Similar energy-dependent behavior has been widely reported in recent studies on radiation shielding materials, highlighting the importance of considering photon energy when designing and evaluating shielding systems [35,38].

D. Role of Material Composition and Microstructure

The effectiveness of the $BaSO_4$–cement composites is strongly influenced by the concentration and distribution of $BaSO_4$ particles within the matrix. Increasing the filler content enhances the effective density and atomic composition of the material, thereby increasing the probability of photon interaction [3,21].

Moreover, the uniform distribution of $BaSO_4$ particles plays a critical role in ensuring consistent shielding performance. The fluoroscopic observations in this study revealed that thicker samples exhibited better particle dispersion, which contributed to improved attenuation efficiency. This is consistent with findings from previous studies, where homogeneous distribution of high-Z fillers resulted in enhanced shielding properties [17,36].

Microstructural factors such as porosity and particle clustering can significantly affect attenuation behavior. Increased porosity may reduce effective density, leading to lower shielding efficiency, while particle agglomeration can create localized regions of reduced attenuation [18,31]. Therefore, achieving optimal mixing and uniform dispersion is essential for maximizing composite performance.

F. Environmental and Economic Implications

Beyond technical performance, the use of $BaSO_4$–cement composites offers important environmental and economic advantages. Unlike lead, $BaSO_4$ is non-toxic and does not require specialized handling or disposal procedures, making it a safer option for widespread use in healthcare environments [5,20].

From an economic perspective, the availability of natural barite resources—particularly in regions such as Libya—provides a cost-effective alternative to imported lead materials. The use of locally sourced materials can significantly reduce construction and operational costs for medical facilities, while also promoting sustainable resource utilization [37].

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These advantages align with current global trends toward the development of eco-friendly and sustainable building materials, particularly in the healthcare sector [28,30].

G. Practical Applications

The results of this study suggest that $BaSO_4$–cement composites are well-suited for several practical applications, including:

- Structural shielding in radiology rooms
- Protective barriers in diagnostic imaging facilities
- Low-cost shielding solutions in developing regions

Their ease of fabrication and compatibility with conventional construction methods make them particularly attractive for large-scale implementation [4,13].

F. Limitations of the Study

Despite the promising results, several limitations should be considered. First, the study was conducted under controlled laboratory conditions using a limited range of photon energies. Additional studies are needed to evaluate performance across a broader energy spectrum, including higher-energy radiation.

Second, only a single $BaSO_4$ concentration (50%) was investigated. Exploring a wider range of compositions could provide further insight into optimization of shielding performance [21,35].

Finally, long-term durability, mechanical strength, and resistance to environmental factors were not assessed in this study. These properties are critical for practical implementation and should be addressed in future research [37].

K. Future Research Directions

Future work should focus on:

- Optimization of $BaSO_4$ concentration and composite formulation
- Investigation of hybrid composites incorporating multiple high-Z materials
- Evaluation of mechanical and long-term durability properties
- Large-scale testing under real clinical conditions

Recent advances in nanocomposite materials and advanced fabrication techniques offer promising opportunities for further improving shielding performance [27,33].

V. CONCLUSION

This study provides a comprehensive evaluation of **barium sulfate ($BaSO_4$)–cement composites** as a viable, environmentally friendly alternative to conventional lead-based materials for diagnostic X-ray shielding. The experimental results clearly demonstrate that the attenuation performance of the developed composites is strongly influenced by both **material thickness and $BaSO_4$ concentration**, confirming well-established radiation interaction principles [1,32].

A consistent and significant reduction in transmitted radiation dose was observed with increasing sample thickness across both tested energy levels (46 kV and 70 kV). The **1.0 cm thick composite containing 50% $BaSO_4$** exhibited the highest shielding efficiency, achieving attenuation levels exceeding 90% at higher photon energies and near-complete attenuation at lower energies. These findings are in strong agreement with recent studies on high-density composite shielding materials, which report similar performance trends under optimized conditions [21,35].

The results further confirm that $BaSO_4$-based composites are particularly effective in attenuating **low-energy diagnostic X-rays**, where photoelectric absorption dominates. However, even at higher energies, the composite demonstrated substantial attenuation when sufficient thickness was applied. This highlights the importance of **material design optimization**, where increased thickness can compensate for the lower atomic number of barium compared to lead [3,29].

From a practical standpoint, the study underscores the potential of $BaSO_4$–cement composites for **structural radiation shielding applications**, including walls and barriers in radiology departments. Unlike lead, $BaSO_4$ is non-toxic, chemically stable, and does not require specialized handling or disposal procedures, making it significantly safer for both workers and the environment [5,20]. In addition, the use of **locally available barite resources** offers substantial economic benefits, particularly in regions where access to imported lead is limited or costly [37].

The findings also highlight the critical role of **material homogeneity and microstructural integrity** in achieving optimal shielding performance. Uniform dispersion of $BaSO_4$ particles within the cement matrix was associated with improved attenuation efficiency, emphasizing the importance of proper mixing and fabrication techniques [17,36].

Despite the promising outcomes, the study acknowledges certain limitations, including the restricted range of photon energies and material compositions investigated. Therefore, further research is recommended to explore:

- A wider range of $BaSO_4$ concentrations
- Hybrid composite systems incorporating additional high-Z materials
- Long-term mechanical durability and environmental stability
- Large-scale validation under clinical operating conditions

Advancements in composite material engineering, including nanostructuring and multi-component systems, are expected to further enhance the performance of non-toxic shielding materials in the near future [27,33].

In conclusion, $BaSO_4$–cement composites represent a **technically effective, economically feasible, and environmentally sustainable alternative** to traditional lead shielding in diagnostic radiology. With continued optimization and validation, these materials have the

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potential to play a significant role in the development of **next-generation radiation protection systems** aligned with modern safety and sustainability standards.

VI. Ethical Statement

This manuscript is original and has not been published or submitted elsewhere. All referenced works have been appropriately cited, and no duplicate publication has occurred.

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