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Original article

Experimental Evaluation and EGSnrc Monte Carlo Modeling of Barium Sulfate Cement Composites for Sustainable Diagnostic X-Ray Shielding

Bsher Abour*[1], Rania Saad[2], Ibrahim Othman[1]

[1]*Faculty of Medical Technology, Aljufra University, Libya*
[2]*Aljefarah Medical Services, Ministry of Health, Libya*
Corresponding Email. bsher.abour@ju.edu.ly

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Abstract
The demand for non-toxic radiation shielding materials has intensified significantly due to severe environmental hazards, strict disposal regulations, and occupational health concerns associated with traditional lead-based protective barriers. Recent advances in composite material engineering have demonstrated that utilizing heavy mineral matrices enriched with barium sulfate ($BaSO_4$) can serve as a highly effective, chemically stable, and eco-friendly attenuator for ionizing radiation, particularly across diagnostic medical X-ray energy spectra. In this study, $BaSO_4$-cement composites were engineered and fabricated with a fixed filler concentration of 50% by weight and cast into multiple thickness profiles ranging from 0.2 cm to 1.0 cm. To evaluate their shielding efficacy, the fabricated composite blocks were exposed to typical clinical diagnostic radiation beams operating at low-energy (46 kV, 10 mAs) and high-energy (70 kV, 32 mAs) windows. To validate the physical measurements and establish a reliable framework for predictive barrier engineering, full-scale photon transport simulations were computationally executed utilizing the EGSnrc (Electron Gamma Shower) Monte Carlo software package. The experimental results revealed a sharp decrease in the transmitted radiation dose as a function of increasing sample thickness, showing exceptional alignment with the EGSnrc simulated attenuation profiles. Under the high-energy spectrum (70 kV), the 1.0 cm thick sample demonstrated the highest shielding performance, reducing the transmitted dose rate from a baseline of 442 μSv/h down to 26.1 μSv/h, which corresponds to an empirical attenuation efficiency exceeding 94%. Under low-energy conditions (46 kV), the same 1.0 cm configuration achieved near-complete beam absorption, letting through a negligible dose rate of only 0.99 μSv/h (99.58 % shielding efficiency). The computational EGSnrc models tracked these curves closely, yielding minimal relative deviations of +2.76 % and +3.13 % for the 1.0 cm sample at 70 kV and 46 kV, respectively. Higher relative deviations observed in the thinnest sample (0.2 cm at 46 kV, yielding +13.42 %) were elucidated via high-resolution fluoroscopic and X-ray diffraction (XRD) analyses, which revealed that microscopic structural inhomogeneities and casting voids in thin sections alter localized attenuation pathways compared to idealized, zero-porosity simulation media. Beyond technical shielding metrics, this study highlights the substantial economic and environmental advantages of utilizing locally available natural barite resources—such as those found in Libya—to fabricate sustainable structural shields for healthcare infrastructure. Collectively, these verified experimental and computational findings confirm the structural feasibility and predictive reliability of $BaSO_4$-cement composites as a high-performance, non-toxic, and economically sustainable alternative to conventional lead partitions in modern diagnostic radiology departments.

Introduction

Ionizing radiation is widely used in diagnostic imaging, interventional radiology, and radiotherapy; however, it poses severe biological risks, such as cellular damage, double-strand DNA breaks, and increased long-term cancer probability when exposure is not properly controlled [1,2]. Consequently, shielding remains a critical component of structural and occupational radiation protection strategies in healthcare facilities [3,4].

Traditionally, lead (Pb) has been the benchmark material for radiation protection due to its high atomic number (z = 82) and high mass density, which provide excellent photoelectric absorption and attenuation characteristics across wide energy spectra [5,6]. Despite its historic efficacy, lead presents significant disadvantages, including severe neurotoxicity, environmental hazards during mining and disposal, and mechanical instability such as creeping over long deployment periods [7,8]. These ecological and toxicological limitations have triggered strict international regulations, driving modern materials science toward sustainable, lead-free alternatives [9,10].

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Recent research has focused heavily on developing alternative concrete and polymer composites incorporating high-Z elements to mimic lead's attenuation performance without its toxicity [11,12]. Among these candidates, barium sulfate ($BaSO_4$) has emerged as an exceptionally promising candidate due to its chemical inertness, non-toxic nature, thermal stability, and moderate density [13,14]. Barium (Z = 56) possesses a critical K-absorption edge at 37.4 keV, making it uniquely effective at attenuating low-to-medium energy X-rays typically encountered in diagnostic clinical settings [15,16]. Studies have demonstrated that $BaSO_4$-based composites can effectively eliminate secondary scattered radiation and prime beam transmission within medical diagnostic thresholds [17,18]. Advanced material engineering designs, including nanoscale $BaSO_4$ doping, multilayer macrostructures, and crosslinked polymer-blend matrices, have further enhanced spatial filler homogeneity and photon-blocking capabilities [19,20]. Furthermore, integrating heavy minerals directly into Ordinary Portland cement offers exceptional physical structural benefits [21,22]. Cement-based shielding matrices provide high compressive strength, standard structural integrity, and architectural adaptability for casting walls and permanent room barriers in radiology departments [23,24]. However, despite these continuous developments, significant gaps remain regarding standardized, comprehensive comparisons between raw experimental measurements and computational transport calculations for $BaSO_4$-cement matrices under clinically controlled geometries [25,6]. Accurate thickness optimization and predictability of composite shielding behaviors require thorough algorithmic modeling to eliminate empirical measurement errors caused by localized micro-voids or sample non-uniformity [26,27]. To address these limitations, this study provides an integrated evaluation of $BaSO_4$-cement composites as a practical, eco-friendly alternative for structural diagnostic X-ray shielding. The empirical radiation transmission data obtained across typical diagnostic energy levels (46 kV and 70 kV) are evaluated and validated against advanced EGSnrc Monte Carlo code simulations, providing a highly reliable framework for predictive shield engineering [28,29].

Materials and Methods

Materials and Characterization

Commercial-grade Barium Sulfate ($BaSO_4$) fine powder with a high purity level (98.5 %) was selected as the main heavy aggregate filler due to its favorable atomic number (Z = 56) and strong attenuation cross-sections within diagnostic X-ray thresholds [1]. Ordinary Portland Cement (OPC, Type I, conforming to ASTM C150 standard specifications) served as the structural binding matrix. The elemental composition and particle distribution of both the binding matrix and the $BaSO_4$ filler play a critical role in minimizing internal scattering voids [7]. To ensure structural and shielding integrity, the physical properties of the component materials were characterized. The fine $BaSO_4$ powder exhibited a high specific density (approx 4.50 g/cm^3), whereas the dry Portland cement matrix possessed a base material density of approx 3.15 g/cm3. Distilled water was utilized during the initial hydration and mixing phases to prevent the introduction of unintended trace mineral impurities that could skew low-energy photon transport physics [25].

Composite Fabrication and Sample Preparation

The preparation of the $BaSO_4$-cement composite shields followed a precise multi-step mechanical blending process designed to guarantee particle homogeneity across the structural matrix. The dry components were systematically portioned to achieve a fixed filler concentration of 50 wt% $BaSO_4$ and 50 wt% OPC [8]. The dry constituents were mechanically blended in a high-shear rotary mixer for 15 minutes to guarantee absolute spatial distribution and eliminate the clustering of high-Z barium particles [8]. Following dry homogenization, distilled water was incorporated using a strictly monitored water-to-cement (w/c) mass ratio of 0.45 to optimize both structural workability and minimize internal microporosity during curing [15]. The resulting slurry was cast into precisely machined acrylic molds with lateral cross-sectional dimensions of (4.0 cm x 4.0 cm). The mixtures were cast into three targeted nominal thicknesses: 0.2 cm, 0.6 cm and 1.0 cm. To eliminate trapped air pockets and structural voids, which severely degrade shielding uniformity, the filled molds were consolidated on a laboratory vibrating table operating at 50 Hz for 3 minutes [5]. The molded composites were initially cured at ambient room temperature (25 °C ± 2 °C) under 90% relative humidity for 48 hours. After demolding, the blocks were completely submerged in a water curing tank for a standard 28-day hydration period to maximize compressive density and bind the elements into a stable crystalline structure [21]. Prior to experimental testing, the sample surfaces were carefully polished using fine-grit silicon carbide paper to establish flat parallel faces and remove localized skin-effects, resulting in a finalized bulk material density of rho = 2.41 g/cm^3.

Experimental Radiation Measurement Layout

The experimental evaluations were conducted within a dedicated diagnostic radiology environment utilizing a calibrated medical X-ray tube source (Toshiba IME 100-L system) to reproduce practical medical exposures [17]. Two distinct clinical operational profiles were established:

Low-Energy Window: 46 kVp tube voltage, 10 mAs tube current-time product.

High-Energy Window: 70 kVp tube voltage, 32 mAs tube current-time product.

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The experimental geometry utilized a narrow-beam collimation design to minimize the detection of broad-angle incoherent scattered photons from neighboring walls and objects [2]. Lead diaphragms with a central aperture diameter of 1.0 cm were aligned along the central beam axis. The target composite specimen was placed in an intermediate sample holder positioned exactly 100 cm downstream from the X-ray focal spot.

A high-sensitivity radiation monitor consisting of a calibrated Geiger-Müller counter assembly (RAM DA-2000 detector probe) was fixed coaxially 20 cm behind the rear exit face of the sample block to register the transmitted dose rate (micro Sv/h). Ambient environmental background radiation levels were systematically monitored before each individual test cycle and mathematically subtracted from the raw readouts to extract the pure net transmitted beam intensity [3]. Each thickness iteration underwent five independent exposure runs to minimize statistical variation and compute mean experimental attenuation metrics.

The total experimental shielding attenuation efficiency (AE %) for each sample was calculated using the following operational relation:

$AE (\%) = (1 - I/I_o) \times 100$

where I is the transmitted dose rate recorded with the composite shield in place, and Io represents the initial baseline unshielded dose rate recorded in an identical geometry under bare beam conditions (236 μSv/h at 46 kV; 442 μSv/h at 70 kV) [11].

EGSnrc Monte Carlo Computational Modeling

To validate the empirical measurements and verify the fundamental photon transport behaviors, full-scale computational simulations were executed using the EGSnrc (Electron Gamma Shower) Monte Carlo software engine, utilizing the specialized DOSXYZnrc core system architecture [26].

Material Definition via PEGS4

The precise physical parameters of the engineered 50 wt% $BaSO_4$ / 50 wt% cement composite were modeled using the PEGS4 pre-processor program. The composite bulk density parameter was explicitly restricted to the physical laboratory baseline value of 2.41 g/cm^3. The elemental mass fractions representing the complex mixture were broken down according to standard chemical breakdowns of Portland cement compounds combined with the barium sulfate aggregate fractions: Ba (0.294), S (0.069), O (0.372), Ca (0.198), Si (0.047), Al (0.012), and Fe (0.008) [26].

Source Profiles and Geometry Simulation

The transport layout was modeled within an automated 3D Cartesian voxel coordinate domain matching the physical test parameters. The input X-ray source configuration was established as a parallel-aligned disk beam directed along the positive z-axis. The initial photon energies were sampled from realistic continuous diagnostic spectrum profiles: a 46 kVp spectrum and a 70 kVp spectrum, generated via standard IPEM Report 78 computational spectral distribution algorithms to perfectly replicate the experimental filtration and bremsstrahlung output of the physical X-ray tube [16].

The target materials were designated as uniform, parallel slabs with solid continuous boundaries measuring (4.0 cm x 4.0 cm) cross-sections, using discrete simulated thicknesses of exactly 0.2 cm, 0.6 cm, and 1.0 cm. A downstream virtual voxel zone was designed behind the rear surface plane to act as a scoring detector. This virtual detector recorded the total accumulated photon energy fluence and air kerma, which was subsequently normalized to yield corresponding relative transmission dose metrics [28].

Physics Parameter Controls

To guarantee high tracking fidelity across low-energy diagnostic cross-sections, specialized transport physics variables were activated within the EGSnrc configuration file. Explicit Rayleigh scattering and atomic photo-effect bound electron cross-section models were turned on. Spin effects and photoelectron angular distributions were activated according to the standard default algorithms.

The globally enforced energy cut-off barriers for particle tracking were tightly constrained: the global photon cut-off energy (PCUT) was restricted to 0.001 MeV (1 keV), and the global electron transport cut-off (ECUT) was established at 0.521 MeV (521 keV total energy, representing a 1 keV kinetic threshold) to resolve localized secondary particle interactions [22]. Every independent geometric scenario ran a total allocation of 107 source histories, effectively keeping the computational statistical variance parameter for all scored tracking voxels well under a margin of ± 0.5%.

Results

High-Energy X-Ray Attenuation (70 kV) and Simulation Validation

The attenuation performance of the fabricated $BaSO_4$-cement composites under high-energy diagnostic exposure conditions (70 kV, 32 mAs) revealed a strong, predictable dependence on material thickness. The initial bare-beam baseline intensity, measured without any sample shielding positioned in the beam pathway, was recorded at

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approximately 442 µSv/h. This value served as the core experimental reference intensity (I_o) for computing the total relative shielding and attenuation metrics across the three selected profile thicknesses. When a thin composite sample measuring 0.2 cm was introduced into the beam path, the registered empirical transmitted dose rate dropped to approximately 163 µSv/h. This outcome demonstrates a physical reduction of 63.12% relative to the unshielded baseline beam. To validate this performance, the corresponding parallel setup modeled within the EGSnrc Monte Carlo system generated a predicted transmitted dose rate of 154.2 µSv/h, yielding a minor relative deviation of +5.71% between the experimental specimen and the idealized software model. This indicates that while thin composite boundaries offer partial protection, they remain insufficient for complete high-energy X-ray attenuation due to the elevated penetration capability of higher-energy photons.

Increasing the target sample thickness to 0.6 cm resulted in a substantial reduction in the empirical transmitted dose, lowering the reading to approximately 78.5 µSv/h. This structural shift corresponds to an experimental attenuation efficiency of 82.24%. This performance improvement stems from an enhanced interaction probability for traversing photons via both photoelectric absorption and Compton scattering events within the thicker, higher-density matrix. The EGSnrc computational code tracked this behavior closely, reporting a simulated transmission rate of 75.1 µSv/h for an identical thickness, which shrinks the relative variance between physical data and software tracking down to +4.53%.

The highest overall shielding performance was achieved by the maximum sample boundary of 1.0 cm. This thickness reduced the net transmitted dose rate experimentally to approximately 26.1 µSv/h, demonstrating a total attenuation efficiency of 94.10% (Table 1). The EGSnrc transport engine verified this outcome, calculating a transmitted dose profile of 25.4 µSv/h under identical configuration coordinates, which represents a relative deviation of only +2.76 %. This close alignment confirms that as bulk mass increases, the physical composite behavior increasingly matches the idealized theoretical projections of Monte Carlo code systems. The collective data establish a clear inverse relationship between sample thickness and transmitted dose.

Low-Energy X-Ray Attenuation (46 kV) and Simulation Validation

Under low-energy operational conditions (46 kV, 10 mAs), the engineered $BaSO_4$-cement composites demonstrated significantly greater photon-blocking capability than observed during the high-energy tests. The initial baseline intensity for the unshielded bare beam was recorded at an average value of approximately 236 µ Sv/h.

Even when operating at the lowest sample thickness parameter (0.2 cm), the physical composite sample achieved a major drop in transmission, reducing the dose rate to approximately 26.2 µSv/h. This corresponds to an immediate empirical attenuation efficiency of 88.90%. The corresponding EGSnrc code run estimated a simulated transmitted value of 23.1 µSv/h. The localized variance at this specific step was calculated at +13.42 %, which represents the highest relative deviation observed across the entire study. This deviation is primarily attributed to the high sensitivity of low-energy photon cross-sections to structural imperfections in thin physical specimens. Nevertheless, the data confirm that lower-energy photons are heavily attenuated by the material, driven by the dominance of photoelectric absorption processes at lower energy thresholds.

At a thickness of 0.6 cm, the empirical transmitted dose rate decreased further to approximately 8.3 µSv/h, translating into an attenuation efficiency of 96.48%. The EGSnrc software simulation calculated a corresponding transmitted value of 7.95 µSv/h, reducing the relative deviation to +4.40%. This improvement demonstrates how scaling the barrier thickness enhances total shielding efficiency across the low-energy diagnostic range.

The 1.0 cm sample achieved near-complete attenuation of the incoming radiation field, reducing the experimental transmitted dose rate to approximately 0.99 µSv/h. This achieves an exceptional total empirical attenuation efficiency of 99.58 %. The EGSnrc code strongly mirrored this near-total attenuation, reporting a simulated transmitted value of 0.96 µSv/h, which corresponds to a minimal relative deviation of +3.13 %. These findings confirm that a 1.0 cm thick $BaSO^4$-cement composite provides an effective radiation barrier for low-energy diagnostic radiology environments where similar energies are standard.

Comparative Transport Analysis: High vs. Low Energy Spectra

A direct comparative evaluation of the high-energy (70 kV) and low-energy (46 kV) datasets highlights significant performance differences determined by the incident photon spectrum. At every individual thickness step, the composite matrix consistently demonstrated higher attenuation efficiency when exposed to lower photon energies. This performance difference matches fundamental radiation interaction theory.

At 0.2 cm: The experimental transmitted radiation dropped sharply from 163 µSv/h at 70 kV to 26.2 µSv/h at 46 kV.

At 0.6 cm: The empirical transmitted dose decreased from78.5 µSv/h at 70 kV down to 8.3 µSv/h at 46 kV.

At 1.0 cm: The physical transmission fell from 26.1µSv/h at 70 kV to just 0.99 µSv/h under the 46 kV beam profile.

This energy-dependent behavior is illustrated in the comprehensive data summary presented in (Table 1).

Table 1. Comprehensive comparison of experimental metrics and EGSnrc Monte Carlo transport metrics.

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Thickness (cm)	Radiation Energy Spectrum (kV)	Experimental Transmitted Dose (µSv/h)	EGSnrc Simulated Transmitted Dose (µSv/h)	Relative Deviation (%)	Experimental Attenuation Efficiency (%)
0.2	70 kV (High)	163.00	154.20	+5.71%	63.12%
0.2	46 kV (Low)	26.20	23.10	+13.42 %	88.90%
0.6	70 kV (High)	78.50	75.10	+4.53%	82.24%
0.6	46 kV (Low)	8.30	7.95	+4.40%	96.48%
1.0	70 kV (High)	26.10	25.40	+2.76 %	94.10%
1.0	46 kV (Low)	0.99	0.96	+3.13 %	99.58 %

This performance profile occurs because the interaction cross-sections for photoelectric absorption scale proportionally with the atomic number as Z^4 or Z^5 and are inversely proportional to photon energy ($1/E^3$). Consequently, the high-Z barium atoms (Z=56) absorb low-energy photons much more effectively. Conversely, higher-energy photons are more likely to undergo Compton scattering, leading to greater penetration depth and a corresponding increase in the recorded transmitted dose.

Microstructural Uniformity and Its Impact on Transport Deviations

The structural and morphological assessments explained the slight differences between the experimental measurements and the idealized EGSnrc Monte Carlo simulations. X-ray diffraction (XRD) mapping confirmed the crystalline structure and phase composition of the composite, verifying that the $BaSO_4$ particles were successfully integrated into the hydration products of the cement matrix.

However, high-resolution fluoroscopic imaging revealed that sample thickness influenced the internal distribution of the heavy $BaSO_4$ particles. The thinnest sample (0.2 cm) showed visible internal inhomogeneities and localized material non-uniformity. These small variations or minor internal air pockets allowed higher photon transmission during physical testing than what was modeled in the fully homogeneous, zero-porosity EGSnrc material profile. This structural variance explains why the 0.2 cm sample produced the largest deviation from the simulation model (+13.42 % at 46 kV).

In contrast, the thicker 1.0 cm composite block demonstrated a highly uniform particle distribution and greater internal structural consistency. The larger volume of this sample allowed minor localized mixing variations to average out, resulting in a physical matrix that closely matched the idealized computational model. As a result, the deviation between experimental data and EGSnrc values dropped to a minimal +2.76 % at 70 kV and +3.13 % at 46 kV. This demonstrates that proper fabrication and uniform particle dispersion are essential for achieving consistent radiation attenuation.

Discussion

The strong correlation observed between the experimental measurements and the EGSnrc Monte Carlo simulations validates the physical mechanisms governing photon transport within the $BaSO_4$-cement matrix. The systematic reduction in transmitted dose rate as a function of increasing barrier thickness directly corresponds to the fundamental Beer-Lambert law of exponential attenuation. This agreement demonstrates that the experimental setup accurately captures primary beam attenuation characteristics while the computational model correctly represents the material cross-sections.

Microstructural Inhomogeneities and Simulation Deviations

A critical finding of this study is the variation in relative deviation between the empirical data and the idealized EGSnrc simulations across different sample thicknesses. The highest discrepancy occurred in the thinnest configuration (0.2 cm) under a 46 kV spectrum, yielding a relative deviation of +13.42 %. This behavior highlights the practical limits of assuming absolute structural homogeneity in computational transport models [28].

EGSnrc user codes model materials as perfectly uniform continuous media with a fixed bulk density and zero internal porosity. However, during laboratory fabrication, extremely thin cement layers (0.2 cm) are highly susceptible to microscopic air voids, surface bleeding, and localized particle agglomeration [6]. These localized defects establish thin pathways of lower effective density, which allow higher photon transmission during physical exposures. As sample thickness increases to 0.6 cm and 1.0 cm, the relative deviation drops sharply to under 4.5% and 3.2%, respectively. In thicker sample volumes, localized microstructural defects and random particle clustering average out across the bulk mass. This volumetric averaging creates a highly uniform composite matrix that closely matches the idealized material profiles defined in the simulation code [16].

Cross-Section Physics and Energy Dependence

The energy-dependent behavior—where the composite matrix demonstrates significantly higher attenuation efficiency at 46 kV compared to 70 kV—is confirmed by both experimental tracking and Monte Carlo data. At the lower energy threshold

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(46 kV), photon interactions within the composite are heavily dominated by the photoelectric effect. The interaction cross-section (σpe) for photoelectric absorption is highly sensitive to the atomic number (Z) of the target constituent elements and the incident photon energy (E), scaling approximately as $\sigma pe \propto Z^4 / E^3$ [5].

Barium (Z = 56) possesses a high atomic number relative to traditional concrete aggregates like silicon (Z = 14) or calcium (Z = 20), and features a critical K-absorption edge at 37.4 keV [8]. This K-edge position matches the primary energy distribution of a diagnostic 46 kVp continuous X-ray spectrum [22]. This overlap triggers a massive increase in photoelectric cross-sections, resulting in near-complete experimental attenuation (99.58 %) at a thickness of 1.0 cm.

Conversely, when the X-ray tube voltage scales up to 70 kV, a larger portion of the incident photon spectrum shifts past the K-edge threshold. In this higher diagnostic energy range, the probability of photoelectric interaction decreases, and Compton scattering begins to compete as an interaction mechanism [13]. Because Compton scattering cross-sections scale linearly with atomic number (Z) rather than to the fourth power, the total mass attenuation coefficient decreases [14]. This transition allows higher photon penetration through the composite barrier, increasing the recorded transmission rate. The EGSnrc code successfully models this physical transition. This validation demonstrates that while lead (Z=82) remains more effective per unit thickness, the lower atomic number of barium (Z=56) can be compensated for by increasing total component thickness, making these composites viable structural barriers [23].

Material Sustainability and Clinical Optimization

From an engineering perspective, validating the radiation transport behavior of $BaSO_4$-cement composites with EGSnrc provides a reliable standard for clinical radiation protection design [26]. Traditional lead panels present severe occupational and environmental hazards, including toxic dust generation during installation, structural creep over long periods, and strict disposal protocols [7]. The non-toxic nature of barium sulfate eliminates these health risks, making it an eco-friendly option for medical facilities [8,9].

Furthermore, using natural barite resources provides significant economic benefits, particularly in regions with large natural deposits, such as Libya. Incorporating raw barite aggregates directly into localized structural cement formulations enables cost-effective construction of permanent radiation shielding walls [25]. This approach reduces reliance on expensive imported lead sheets while meeting modern safety and environmental standards [24].

Limitations and Future Frameworks

While this study demonstrates the efficacy of $BaSO_4$-cement composites, certain structural limitations remain. The evaluations were restricted to diagnostic energy ranges (46 kV and 70 kV) and a single fixed aggregate concentration (50 wt%). Further investigations are required to assess performance across higher-energy healthcare fields, such as computed tomography (120–140 kVp) and orthovoltage radiotherapy.

Additionally, future work should focus on long-term mechanical testing, micro-hardness stability, and curing shrinkage over prolonged radiation exposures to confirm structural durability [13]. Exploring multi-component hybrid composite matrices—such as combinations of nano-scale $BaSO_4$, bismuth oxide (Bi_2O_3), or tungsten particles—could also yield further shielding improvements [17]. This study provides a foundational framework for utilizing validated Monte Carlo models to engineer optimized, lead-free structural shielding.

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 measurements showed that radiation attenuation increased consistently with composite thickness, with the 1.0 cm specimen achieving the highest shielding efficiency under both 46 kV and 70 kV X-ray beams. The results further confirmed that the shielding performance was more effective at lower photon energies, where photoelectric absorption is the dominant interaction mechanism. A strong agreement between the experimental measurements and the EGSnrc Monte Carlo simulations was observed, with only small deviations attributed primarily to microstructural inhomogeneities and minor casting voids in the fabricated samples. This close correlation demonstrates that the EGSnrc code is a reliable tool for predicting the radiation shielding performance of $BaSO_4$-based cement composites and can be effectively used for the design and optimization of lead-free shielding materials.

Beyond its shielding performance, the developed composite offers important environmental and economic advantages because $BaSO_4$ is non-toxic, chemically stable, and can be obtained from locally available barite resources. These characteristics make the material a practical candidate for structural shielding applications in diagnostic radiolopgy facilities. Although this study was limited to a single $BaSO_4$ concentration (50 wt%) and diagnostic X-ray energies (46 and 70 kV), the findings provide a solid foundation for future investigations involving different filler concentrations, higher-energy imaging systems, hybrid composite formulations, and long-term mechanical durability. Overall, the proposed $BaSO_4$–cement composite represents a sustainable and effective alternative to lead for diagnostic radiation shielding.

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Despite these highly promising outcomes, the study acknowledges certain boundary limitations, including the restricted range of diagnostic photon energies, the single fixed material composition (50 wt%), and the lack of long-term mechanical degradation testing. Therefore, further systematic research is strongly recommended to expand this computational and experimental framework. Future investigations should explore:

1. A wider range of optimized $BaSO_4$ aggregate concentrations to identify the ideal balance between density and structural matrix integrity.
2. Multi-component hybrid composite systems incorporating additional non-toxic high-Z elements, such as bismuth oxide (Bi_2O_3) or tungsten particles, to form synergistic attenuation networks.
3. Long-term mechanical durability, compressive strength validation, micro-hardness stability, and environmental resistance against aging or crack propagation under continuous radiation fields.
4. Large-scale testing and performance validation under real-world clinical operating conditions, including high-scatter broad-beam geometries and advanced continuous computed tomography (CT) spectrum boundaries.

Advancements in composite material engineering, particularly through nanostructuring and advanced multi-component fabrication techniques, are expected to further enhance the attenuation capabilities of non-toxic shielding systems in the near future. In conclusion, the engineered $BaSO_4$-cement composites evaluated in this study represent a technically effective, economically feasible, and environmentally sustainable alternative to traditional lead shielding in diagnostic radiology. Continued scientific optimization and computational validation using the EGSnrc platform will facilitate the large-scale integration of these materials into next-generation radiation protection systems, aligning modern healthcare infrastructure with rigorous safety and ecological sustainability standards.

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