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Microstructural, Elemental, and Density Characterization of Bismuth-Clay-Reinforced Cement–Sand Composites for Radiation Shielding Applications

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Abstract

Cement-based composites reinforced with high atomic number additives are increasingly investigated as environmentally sustainable alternatives to conventional lead-based radiation shielding materials. This study evaluates the microstructural, elemental, and physical characteristics of cement–sand composites reinforced with bismuth clay, with emphasis on parameters governing photon attenuation. Composite samples containing 0 g, 10 g, and 20 g of bismuth clay were fabricated and characterized using density measurements, Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray Spectroscopy (EDS). Results revealed progressive microstructural densification, reduced porosity, and improved particle packing with increasing bismuth content. EDS confirmed successful incorporation and uniform dispersion of bismuth-rich phases within the cement matrix. Density increased systematically with both bismuth concentration and sample thickness. Given the dependence of photon attenuation on density and atomic number, the observed structural and compositional enhancements indicate strong potential for radiation shielding applications. The study establishes a foundational basis for further quantitative gamma-ray and X-ray attenuation investigations.

Keywords: radiation shielding, cement composite, bismuth clay, SEM, EDS, density, photon attenuation

Introduction

The growing use of ionizing radiation in medicine, nuclear energy, and industrial applications has intensified the demand for effective and environmentally safe radiation shielding materials. Traditionally, lead has been the material of choice due to its high atomic number and density, which enable strong attenuation of X-rays and gamma rays. However, lead presents significant environmental and health hazards due to toxicity and long-term exposure risks (Kharita et al., 2011; Akkurt et al., 2010).

Concrete remains one of the most widely used structural shielding materials because of its affordability, availability, and mechanical strength. Nevertheless, conventional concrete exhibits moderate shielding efficiency unless modified with high atomic number additives (Hassan et al., 2019). To enhance shielding performance, researchers have incorporated heavy minerals such as barite, magnetite, tungsten, and bismuth compounds into cement matrices (Al-Buriahi et al., 2020; El-Khatib & Abdelghany, 2021).

Bismuth is particularly attractive due to its high atomic number (Z = 83), high density, and lower toxicity relative to lead. Bismuth-containing materials demonstrate strong photon attenuation, especially in the low- and medium-energy regions where the photoelectric effect dominates (Sayyed et al., 2021).

Despite previous work on attenuation coefficients of bismuth-based concretes, limited studies have examined the underlying microstructural and compositional factors that influence density and shielding performance. Since photon attenuation depends strongly on density and elemental composition, understanding these structural parameters is critical.

This study therefore aims to investigate the microstructural evolution, elemental composition, and density enhancement of cement–sand composites reinforced with bismuth clay in order to evaluate their suitability for radiation shielding applications.

Literature Review

Previous investigations have established that radiation shielding effectiveness depends primarily on material density, atomic number, and thickness (Akkurt et al., 2010). The linear attenuation coefficient (μ) increases with density and atomic number, particularly at lower photon energies where the photoelectric effect is dominant.

Heavyweight concretes containing barite and magnetite have shown improved attenuation performance compared to ordinary concrete (Hassan et al., 2019). Similarly, incorporation of heavy metal oxides significantly enhances shielding properties (Al-Buriahi et al., 2020).

Bismuth-based materials have gained attention as eco-friendly alternatives to lead. Sayyed et al. (2021) demonstrated improved gamma attenuation performance in bismuth-containing composites. However, shielding performance is not solely determined by composition but also by microstructural characteristics such as porosity and particle distribution.

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) are widely used techniques for analyzing morphology and elemental

composition in cementitious materials (Goldstein et al., 2018). Reduced porosity and improved particle packing increase density and thus enhance radiation interaction probability. Although attenuation coefficients are widely reported, fewer studies have correlated microstructural densification with compositional enrichment in bismuth-clay systems. This gap motivates the present investigation.

Methodology

Materials and Sample Preparation

Ordinary Portland cement, clean river sand, and processed bismuth clay were used. Bismuth clay was ground, sieved, and oven-dried.

Three formulations were prepared:

- Control (0 g bismuth clay)
- 10 g bismuth clay
- 20 g bismuth clay

A cement-to-sand ratio of 1:3 and water-to-cement ratio of 0.5 were maintained. Samples were cast into molds of 1 cm, 2 cm, and 3 cm thickness, demolded after 24 hours, and water-cured for 28 days.

Microstructural and Elemental Analysis

SEM analysis was conducted at 15 kV accelerating voltage to evaluate morphology, porosity, and particle distribution. EDS was used to determine elemental composition and confirm incorporation of bismuth. SEM analytical procedures followed Goldstein et al. (2018).

Results

Density Measurement

Bulk density was determined using Archimedes' principle. Samples were weighed in air and in distilled water. Density was calculated for all compositions and thicknesses.

Microstructural Characteristics

The control sample exhibited visible capillary pores and loosely packed hydration products, indicating lower compactness.



Figure 1: The Scanning Electron Microscope image of 20 grams of cement + sand without addition of bismuth
Source: Author's experimental work (2026)

The 10 g composite showed reduced pore size and improved matrix uniformity, suggesting a micro-filler effect.

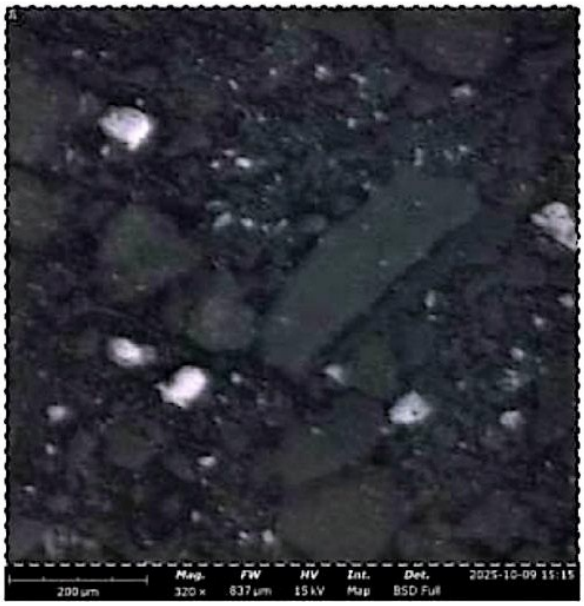


Figure 2: The Scanning Electron Microscope of 20 grams of cement + sand with 10grams of bismuth
Source: Author's experimental work (2026)

The 20 g composite demonstrated the highest compaction, minimal microcracks, and closely packed grains, indicating significant densification.

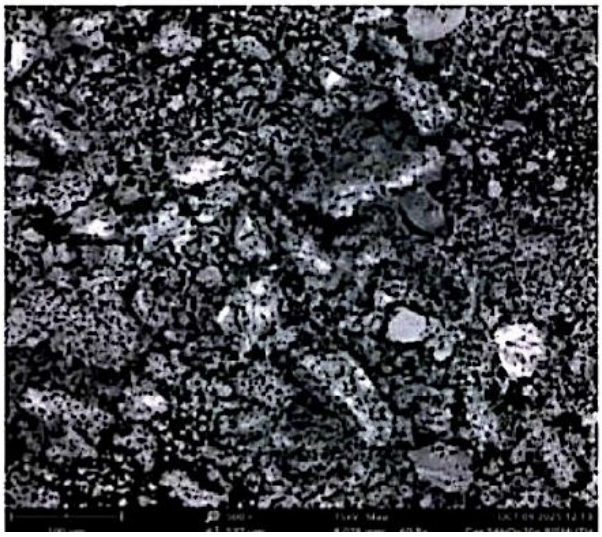


Figure 3: The Scanning Electron Microscope of 20 grams of cement + sand with 20grams of bismuth
Source: Author's experimental work (2026)

Elemental Composition

EDS spectra confirmed Ca, Si, O, and Al as primary cement hydration elements. Distinct bismuth peaks were observed in 10 g and 20 g samples, increasing with concentration.

Density Analysis

Density increased systematically with increasing bismuth content and increasing sample thickness. The 20 g composite exhibited the highest density values.

Discussion

The improvement in microstructure with increasing bismuth content indicates reduced porosity and enhanced particle packing. This densification contributes directly to improved photon attenuation.

Photon attenuation probability increases with atomic number approximately proportional to Z^4–Z^5 in the photoelectric region (Sayyed et al., 2021). Therefore, incorporation of bismuth significantly enhances shielding potential even at moderate concentrations.

The density increase observed experimentally aligns with theoretical radiation physics principles, where linear attenuation coefficient (μ) is proportional to material density.

Thus, the combination of heavy-element enrichment, microstructural refinement, and increased density collectively enhances expected radiation shielding performance.

Conclusion

Cement–sand composites reinforced with bismuth clay were successfully fabricated and characterized. Increasing bismuth content resulted in:

- Reduced porosity
- Improved particle packing
- Enhanced density
- Effective incorporation of heavy elements

Given the dependence of photon attenuation on density and atomic number, the developed composites demonstrate strong potential for radiation shielding applications.

This study provides a microstructural and compositional foundation for future quantitative gamma-ray and X-ray attenuation evaluation.

Recommendations

i. Conduct experimental gamma-ray and X-ray attenuation coefficient measurements.
ii. Determine Half Value Layer (HVL) and Tenth Value Layer (TVL).
iii. Perform mechanical strength testing to evaluate structural performance.
iv. Optimize bismuth clay percentage for maximum shielding efficiency.
v. Conduct cost-benefit and environmental impact assessment for large-scale application.

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