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Investigation of Thermal Conductivity and Gamma Radiation Shielding Properties of Cement Containing $BaSO_4$ and H_3BO_3

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ABSTRACT

In this study, the thermal conductivity and gamma radiation shielding properties of cement composites were investigated by incorporating barium sulfate ($BaSO_4$) and boric acid (H_3BO_3) into cement mixtures. Barium sulfate, due to its high atomic number and density, enhances gamma-ray shielding, while boric acid contributes to reducing thermal conductivity of the composites. Cement mortar samples were prepared with a constant 5 wt.% H_3BO_3 and varying $BaSO_4$ contents (5, 10, 15, and 20 wt.%). Thermal conductivity measurements revealed a significant reduction compared to reference samples without additives, decreasing from 1.728 W/mK in the control sample to 0.2345 W/mK in the sample with 20 wt.% $BaSO_4$. Gamma-ray sheilding properties were experimentally determined using a NaI detector in the energy range of 121–1528 keV, and results were found to be in good agreement with theoretical XCOM calculations. The incorporation of $BaSO_4$ effectively reduced the half-value layer (HVL), confirming its contribution to enhanced gamma shielding. Microstructural analyses (SEM-EDX) demonstrated homogeneous distribution of both $BaSO_4$ and H_3BO_3 within the cement matrix. These findings indicate that $BaSO_4$ and H_3BO_3 additives can improve both thermal insulation and gamma radiation shielding in cement-based materials, making them promising candidates for applications in radiation-prone environments.

Keywords: *Cement mortar, Thermal conducticity, Gamma radiation shielding*

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Introduction

Concrete is one of the most essential materials in civil engineering due to its mechanical strength, cost-effectiveness, and adaptability in construction applications. It is widely used in infrastructure ranging from buildings and bridges to nuclear facilities. However, the increasing demand for structures that can withstand or mitigate the effects of radiation exposure particularly in medical, nuclear, and industrial environments has driven researchers to explore ways to enhance the radiation shielding capacity of cement-based materials [1–4]. Traditional concrete offers only moderate protection against ionizing radiation, especially gamma radiation, due to its relatively low density and atomic number components. Consequently, enhancing the radiation shielding efficiency of concrete without compromising its mechanical integrity has become a critical goal. This has led to the inclusion of high atomic number materials into cement matrices, resulting in the development of specialized shielding concretes [5–8]. Among the various additives explored for this purpose, barium-containing compounds have shown considerable promise due to their ability to enhance gamma-ray shielding while maintaining compatibility with cementitious systems. $BaSO_4$ is a widely studied additive in radiation shielding concretes due to its high atomic number (Z=56) and density. These properties enable it to significantly improve gamma-ray shielding when incorporated into cementitious materials. Moreover, barium compounds have demonstrated chemical stability and compatibility within concrete matrices, making them favorable for long-term structural use in radiation-prone environments [9–13]. However, effective radiation shielding in nuclear applications often requires protection from gamma ray radiation.

Boric acid (H_3BO_3) is commonly known for its excellent neutron shielding capacity, primarily attributed to the high neutron capture cross-section of the boron-10 isotope. When introduced into concrete, boric acid enhances the neutron attenuation capability, which is particularly useful in nuclear reactors and spent fuel storage facilities. Its incorporation into cementitious systems can therefore contribute to dual-mode shielding against both gamma ray and neutron radiation [14, 15]. Several studies have explored the effects of various heavy metal oxides and neutron-absorbing additives on concrete's physical, mechanical, and radiation shielding performance. However, the combined influence of $BaSO_4$ and H_3BO_3 on radiation sheilding and structural properties remains underexplored.

In this study, a series of cement mortar mixtures were prepared with varying proportions of barium sulfate (5, 10, 15, 20 wt.%) and boric acid (5wt.%). The objective is to analyze the relationship between additive content and the radiation shielding behavior of the mixtures while maintaining acceptable structural integrity. In addition, the thermal conductivity and microstructure analysis results of the produced blended cement mixtures were also examined.

Materials and Methods

Materials

White Portland cement (WPC) was used in the mixture and BaSO4 (MW: 233.43 g/mol) with 96% purity and H3BO3 (MW: 61.83 g/mol) with 99.5% purity were used as additive materials. The sample production method is shown in Fig.1. Cement composite mixtures consist of standard sand, cement and water according to TS EN 196-1 standard [16].

Sample preparation

WPC, standard sand and water are used in the mixtures. Additives were determined by using previous studies. Boric acid was added replace of cement by keeping it constant at 5 wt.% and BaSO4 was added to the mixtures instead of sand at 5, 10, 15, 20 wt.% [17–20]. The cement-water ratio in the consistency mixture is 0.5. The mixing quantities are 1350 g sand, 450 g cement, and 225 g water, according to the standard. As seen in Fig. 1, the mixtures prepared with the determined ratios were molded into 4x4x4 cm and then left to dry. After drying step, microstructure of samples were analyzed with Scanning Electron Microscope (SEM-EDX), Thermal conductivity and gamma detector system were applied to samples.

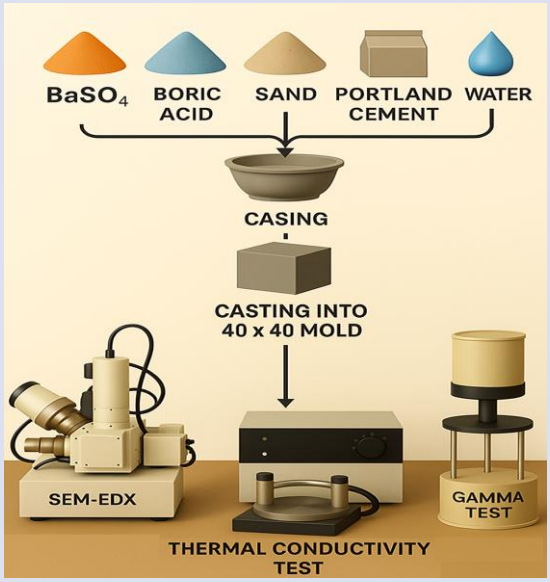

Figure. 1. Schematic diagram of sample preparation process

Results and Discussion

Thermal conductivity test

For the thermal conductivity coefficient measurement, measurements were made using the TPS (Transient Plane Source) probe (Fig. 2). The measurements, performed at room temperature with a probe diameter of Ø12.8 mm, were carried out at Ondokuz Mayıs University, Black Sea Advanced Technology Research and Application Center (KİTAM). The sample without additive is called the control sample. The boric acid additive is the same in all samples. The 5wt.% BaSO4 additive sample is coded as B5 according to the changing BaSO4 additive.

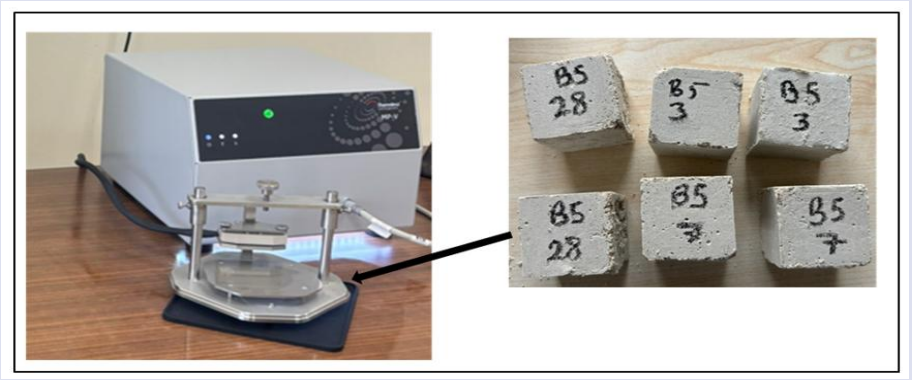

Figure. 2. Thermal Conductivity Test Unit

The thermal conductivity coefficient of the control sample was found to be 1.728 W/mK and the lowest thermal conductivity value (0.2345 W/mK) was obtained in the B20 sample (Table 1). According to this table, the thermal conductivity coefficient decreases with the addition of BaSO4 and H3BO3. This situation is due to the fact that the additives reduce the ability of the additives to conduct heat. BaSO4 is a substance with high density but low thermal conductivity. BaSO4 is added to the mixture as sand. BaSO4 aggregates, with their fine particle size, interrupt the heat flow paths in the matrix. This creates a micro-insulation effect that makes heat transfer difficult. With these additives, it is observed that the heat transfer process inside the structure slows down, that is, the heat spreads in a longer time, and the thermal insulation increases. This situation shows that the ability of the material to conduct heat exchange with its environment changes

according to the additive ratio [21, 22]. However, it is also observed that beyond a certain additive ratio, the reduction in thermal conductivity becomes more pronounced. This phenomenon can be attributed to the excessive incorporation of $BaSO_4$ particles, which not only disrupt the continuity of the heat conduction network but may also increase the porosity and interfacial thermal resistance within the matrix. Consequently, the ability of the material to exchange heat with its environment is significantly diminished as the additive ratio increases.

Table 1. Thermal conductivity test results

Sample	H_3BO_3(wt.%)	$BaSO_4$ (wt.%)	Thermal Conductivity Coefficient(W/mK)
Control	-	-	1.728
B5	5	5	0.4771
B10	5	10	0.5968
B15	5	15	0.252
B20	5	20	0.2345

Radiation Shielding Properties

Cement-based materials have emerged as promising candidates for radiation shielding applications due to their widespread use in construction and their ability to be engineered for enhanced protective properties. The increasing prevalence of electromagnetic interference (EMI) and ionizing radiation in modern environments has raised concerns about the safety of electronic devices and human health, driving research into the development of effective shielding materials that can be seamlessly integrated into building structures.

Gamma radiation shielding constitutes a critical requirement in a variety of industrial contexts, including but not limited to nuclear power stations, medical facilities and aerospace applications. Traditional radiation shielding materials such as lead and concrete have been extensively utilised due to their high density and effective attenuation of gamma rays. However, lead is a toxic and heavy metal, while conventional concrete, though cost-effective, may lack optimal mechanical and radiation shielding performance. In order to address these limitations, researchers have explored the incorporation of different powders into cementitious materials with a view to enhancing both structural integrity and gamma radiation shielding efficiency.

The parameters related to radiation shielding are linear attenuation coefficient μ and half value layer (HVL). Linear attenuation coefficient is given by

$$I = I_0 e^{-\mu x}$$

where I and I_0 are the attenuated and incident gamma ray intensities, respectively and x denotes thickness of the sample. HVL is the thickness of the material at which one half of the incident photons is attenuated via

$$HVL = \frac{0.693}{\mu}$$

In this work, we used an experimental setup shown in Fig. 3. The sample was placed between the 152Eu source and the detector. The measurements have been carried out in the range from 121 to 1528 keV. The measured photon attenuation coefficients μ and HVL are compared with the theoretical values obtained by using XCOM [23]. The technical features of the system is as follows: source-sample and sample–detector distances are both 25 cm.The sample thicknes is 4 cm. The acquisition time per line 3600 second. Energy calibration is done by using Co-60 and Eu-152 standard sources. Since the Eu-152 source is not so strong, real time and live time are approximately equal. Therefore there is no need for dead-time. Background subtraction is done and single thickness Beer–Lambert law for 4 cm sample thickness. The results are shown in Fig.4.

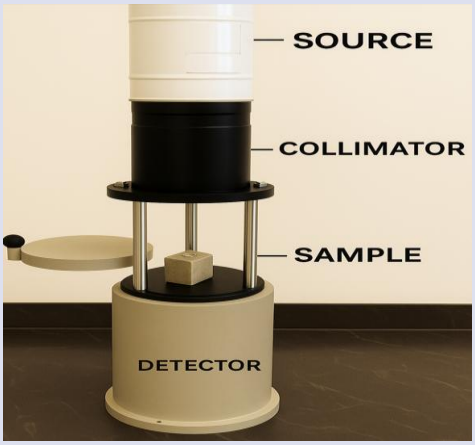

Figure 3. Schematic diagram of sample preparation process

It is clear from the Fig. 5 that linear attenuation coefficients for the samples are in good agreement in the range of 0.1-1 MeV energies with XCOM calculations. Looking in the Fig. 5, it can be observed that linear attenuation decreases as energy increases, consistent with the dominance of the photoelectric effect at low energies and Compton scattering at higher energies. $BaSO_4$ is a high-Z additive that significantly boosts attenuation, especially at low-to-intermediate energies. $BaSO_4$ effectively improves gamma radiation shielding, especially at low energies. For applications like medical imaging shielding (100–300 keV), even small $BaSO_4$ additions (e.g., 5–10%) would yield significant benefits.

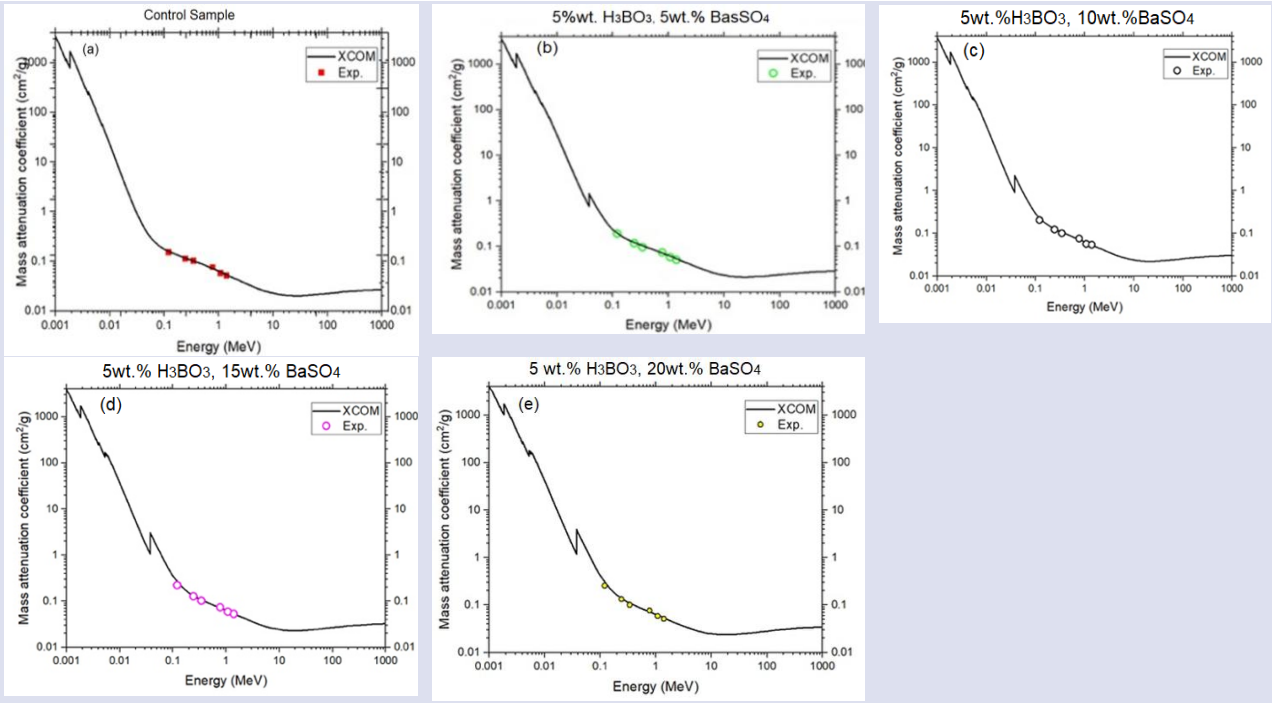

Figure 4. (a-e) Mass attenuation coefficient with respect to 5wt.% H3BO3 and different ratios of BaSO4

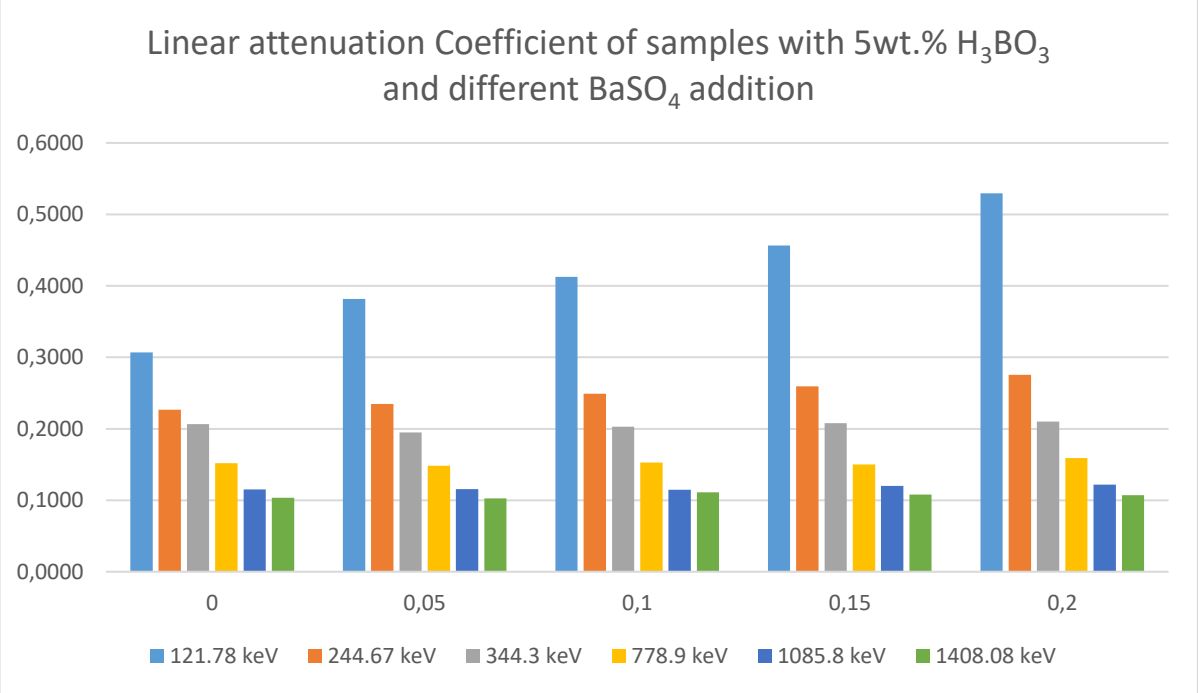

Figure 5. Linear attenuation coefficient of samples

HVL results are listed in Table 2. It is clear from the table that Adding $BaSO_4$ reduces HVL (improves shielding), especially at low energies (e.g., HVL drops from 2.26 cm to 1.31 cm at 121.78 keV as $BaSO_4$ increases from 0% to 20%). Lower HVL correlates with higher attenuation coefficients. $BaSO_4$ significantly enhances radiation shielding for ≤300 keV radiation, with diminishing returns above 1 MeV. Propagated uncertainty is about % 10.

To sum up, our results demonstrate that H3BO3 and $BaSO_4$ is a highly effective radiation shielding additive, particularly for low-to-intermediate energies. The mass attenuation coefficient provides a standardized metric to compare mixtures, confirming that $BaSO_4$ benefits scale with its concentration. The results of this work also support the use of H3BO3 and BaSO4 in radiation shielding applications.

Table 2. HVL of samples

BaSO4 Content (wt.%)	H3BO3 Content (wt.%)	HVL (cm) 121.78 keV	244.67 keV	344.3 keV	778.9 keV	1085.8 keV	1408.08 keV
-	-	2.26	3.06	3.36	4.56	6.03	6.70
5	5	1.82	2.95	3.56	4.67	6.00	6.75
10	5	1.68	2.78	3.41	4.53	6.03	6.24
15	5	1.52	2.67	3.33	4.61	5.78	6.43
20	5	1.31	2.52	3.30	4.36	5.68	6.47

Microstructural Analyzes

Samples were analyzed using a JEOL JSM-7001F Scanning Electron Microscope equipped with Energy Dispersive X-ray Spectroscopy (SEM-EDX) and analyzes were made at KİTAM. In EDX Spectrum Analysis (Fig 6c), Barium (Ba) (13.5%) and Boron (B) (7.3%) were detected. Barium (Ba) and Sulfur (S) signals are seen together, which confirms the presence of $BaSO_4$. Boron element usually appears in this ratio, indicating that H_3BO_3 has successfully integrated into the matrix. In elemental mapping analysis, Ba and S maps overlap (Fig 6g-h). It shows that $BaSO_4$ is homogeneously distributed in the matrix. The widespread distribution of boron (Fig. 6k) also means that H_3BO_3 contribution interacts with the matrix with homogeneous dispersion. Other elemental structures come from cement and sand

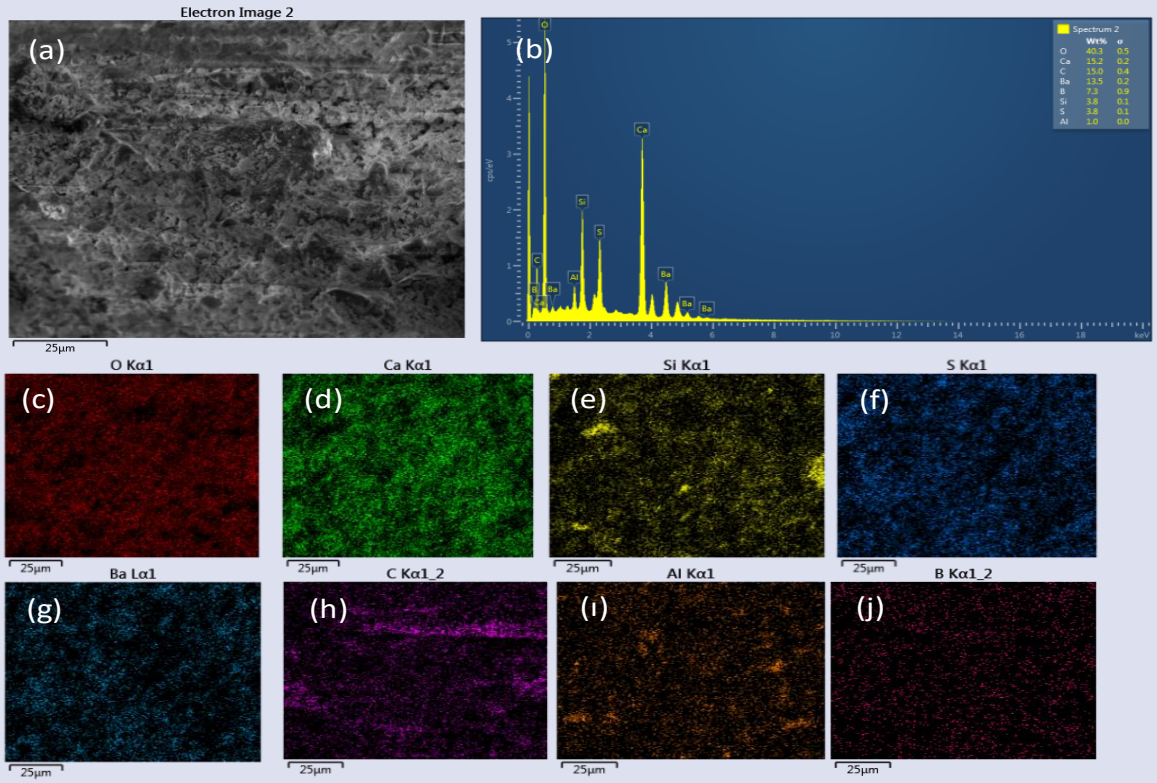

Figure 6. SEM-EDX analysis sample of B15

Conclusion

In this study, the thermal conductivity and gamma radiation shielding properties of cement composites were investigated by incorporating varying amounts of $BaSO_4$ and a constant amount of H_3BO_3. The experimental results demonstrated that the addition of these materials significantly improved the radiation sheilding capacity of the cement mixtures, particularly at low and intermediate photon energies. The linear attenuation coefficients obtained experimentally showed good agreement with XCOM theoretical values, and the half-value layer (HVL) results confirmed that increasing the $BaSO_4$ content led to enhanced radiation shielding efficiency, with HVL values decreasing from 2.26 cm (0 wt.% $BaSO_4$) to 1.31 cm (20 wt.% $BaSO_4$) at 121.78 keV.

Thermal conductivity measurements indicated that the incorporation of $BaSO_4$ and H_3BO_3 resulted in a substantial decrease in thermal conductivity, from 1.728 W/mK in the control sample to as low as 0.2345 W/mK in the sample with 20 wt.% $BaSO_4$. This suggests improved thermal insulation due to the low conductivity and microstructural disruption caused by the additives.

Furthermore, SEM-EDX and elemental mapping analyses confirmed the homogeneous distribution of $BaSO_4$ and H_3BO_3 within the cement matrix, indicating successful integration of the additives. These findings highlight the dual-function potential of $BaSO_4$ and H_3BO_3 in cement-based systems, offering improved gamma radiation protection and thermal insulation simultaneously. Therefore, such composite materials may be promising candidates for use in radiation-prone environments such as nuclear facilities, medical centers, and aerospace structures.

Conflicts of interest

The authors declare that there is no conflict of interest in this respect.

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