



Effect of moisture content on gamma ray and neutron attenuation properties of barite fillers

Nem içeriğinin barit dolguların gama ışını ve nötron soğurma özelliklerine etkisi

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Abstract

Today, demands for energy sources and new technologies that will contribute to the challenge of global warming have contributed to the research and activities carried out in the field of nuclear energy. Increasing and diversifying nuclear activities lead to an increase in the studies to be carried out for the elimination of radioactive emissions during their operation. This study aims to investigate the gamma ray and neutron shielding capabilities of barite backfill materials at different moisture contents (1-5%, by weight) compacted with a Proctor test apparatus. After a standard compaction procedure, the gamma ray and neutron attenuation properties of these compacted filler materials were simulated with NGCal software using the density and elemental fractions. The results indicate that the optimum moisture content (OMC) lies between 3% and 4%, achieving maximum density at 2.917 g/cm³. While gamma-ray attenuation exhibited minimal sensitivity to moisture variation, neutron attenuation improved significantly with increased moisture content due to hydrogen's role in neutron moderation. The findings suggest that moisture control is essential in optimizing radiation shielding efficiency, balancing gamma-ray attenuation stability with enhanced neutron absorption. These insights contribute to the development of more effective radiation shielding materials for nuclear energy applications.

Keywords: Moisture, Filler, Barite, Gamma-ray and neutron shielding capability

1 Introduction

A critical challenge in implementing nuclear technology across industries such as business, healthcare, and scientific research is the construction of radiation-shielded structures. These structures are essential in several critical sectors, particularly in nuclear power plants, research reactors, and radioactive waste storage repositories, where strict shielding requirements are necessary to protect personnel and the environment from ionizing radiation. In the healthcare industry, radiology units, computed tomography rooms, and radiation oncology centers also rely heavily on effective shielding materials to ensure patient and staff safety during diagnostic imaging and therapeutic procedures.

Öz

Günümüzde küresel ısınma sorununa katkı sağlayacak enerji kaynaklarına ve yeni teknolojilere olan talepler, nükleer enerji alanında yapılan araştırma ve faaliyetlere katkı sağlamıştır. Artan ve çeşitlenen nükleer faaliyetler, işletilmeleri sırasında radyoaktif emisyonların giderilmesi için yapılacak çalışmaların da artmasına neden olmaktadır. Bu çalışmanın amacı, Proctor test cihazı ile sıkıştırılan farklı nem içeriklerindeki (ağırlıkça %1-5) barit dolgu malzemelerinin gama ışını ve nötron zırlama yeteneklerini araştırmaktır. Standart bir sıkıştırma işleminden sonra, bu sıkıştırılmış dolgu malzemelerinin gama ışını ve nötron zayıflatma özellikleri, yoğunluk ve element fraksiyonları kullanılarak NGCal yazılımı ile simüle edilmiştir. Sonuçlar, optimum nem içeriğinin %3 ile %4 arasında olduğunu ve 2.917 g/cm³'te maksimum yoğunluğa ulaştığını göstermektedir. Gama ışını zayıflaması nem değişimine karşı minimum hassasiyet gösterirken, nötron zayıflaması, hidrojenin nötron moderasyonundaki rolü nedeniyle artan nem içeriğiyle önemli ölçüde iyileşmiştir. Bulgular, nem kontrolünün radyasyon kalkanı verimliliğini optimize etmek için gerekli olduğunu ve gama ışını zayıflatma kararlılığını gelişmiş nötron emilimi ile dengelediğini göstermektedir. Bu bilgiler, nükleer enerji uygulamaları için daha etkili radyasyon kalkanı malzemelerinin geliştirilmesine katkıda bulunmaktadır.

Anahtar kelimeler: Nem, Dolgu, Barit, Gama ışını ve nötron zırlama kabiliyeti

Additionally, industrial radiography, nuclear medicine facilities, and particle accelerator laboratories all demand reliable and cost-efficient shielding solutions, underscoring the importance of developing practical, high-performance materials such as barite fillers. Concrete, composed of cement, sand, coarse aggregates, and water, has evolved over centuries and is widely used not only for protection against environmental elements but also for its effectiveness in shielding against high-penetration radiation. For decades, concrete has been a preferred material for radiation shielding [1]. The primary factor influencing its ability to block gamma rays is its density, making heavyweight concrete an effective protective barrier [2-4]. However, for neutron

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shielding, only material density may play a misleading role due to the unique scattering process involved. Instead, neutron attenuation depends on the chemical composition of the shielding material [5]. Steel-walled concrete containers employed for the storage of spent nuclear fuel and radioactive waste are fortified with substantial fillers to improve shielding against gamma rays and neutrons [6].

Considering radioactive waste, concrete products offer limited engineering use under long-term storage conditions. The sustainability and cost-effectiveness of producing such materials can be enhanced by minimizing the utilization of stabilizing (binding) agents such as cement and fly ash [7]. Radioactive waste repositories are fortified with backfills and geological barriers intended for deep geological storage [8]. Specific clay-based infill materials are utilized as protective layers atop these repositories [9]. Considering the low structural (load-bearing) specifications, these filler materials prioritize exceptional shielding characteristics over mechanical strength.

A study in the literature has indicated that optimum moisture content and degree of compression maximize radiation absorption performance [10]. Augmenting the density of shielding materials through the reduction of porosity and the integration of denser constituents markedly improves their efficacy in attenuating gamma rays [11, 12]. Furthermore, increased density enhances the physical, mechanical, and durability characteristics of the shields. Attaining maximal density via optimal water content—a compaction process presents a viable approach in this context [13, 14]. Compared to other high-performance radiation shielding agents such as boron carbide, silicon carbide, or graphite-carbon composites, barite stands out not only for its effective gamma-ray attenuation due to its high barium content ($\text{BaO} \approx 65.8\%$) but also for its economic viability. While boron carbide and silicon carbide offer strong neutron absorption, their high cost and production complexity limit their practical use in large-scale or cost-sensitive infrastructure. Graphite-based composites, although useful in certain radiation contexts, may suffer from performance degradation under high temperatures or oxidative environments. Barite, on the other hand, is naturally abundant, chemically stable, and significantly more affordable, which makes it especially attractive for widespread use in radiation shielding applications, particularly in civil engineering and nuclear facility design [3]. Enhancing shielding efficiency can be achieved by integrating high-density materials with high atomic number elements, in conjunction with compaction, which is regarded as one of the most successful methods [15]. While this high density is achieved, the increased water content provides the presence of H, which is a quite effective to slow down neutrons by elastic scattering [16]. Therefore, the Proctor application can be considered as a standard method to ensure both optimum moisture content and maximum dry density of infill materials.

The aim of this study is to contribute to the existing knowledge in the literature by investigating the gamma ray and neutron absorption capacities of barite filler materials at different moisture contents and compaction conditions. In

particular, this study presents an original contribution by examining the combined effects of moisture variation and compaction on both gamma-ray and neutron shielding performance of barite-based fillers—a subject not extensively explored in prior literature. Unlike conventional shielding research focusing on hardened concrete or stabilized binders, this work focuses on compacted loose-fill materials, making it directly applicable to backfill or barrier designs in nuclear infrastructure. Furthermore, the integration of NGCal software for theoretical modeling of shielding behavior adds a unique computational layer to the experimental moisture-density characterization. These aspects collectively differentiate the study and provide a novel reference point for the design of lightweight, cost-effective, and adaptable radiation shielding systems. The analysis for shielding properties have been conducted using NGCal, an online software, which enables theoretical simulations of the shielding properties against thermal and fast neutrons, as well as photons (X-rays and gamma rays).

2 Methodology

2.1 Materials

A barite source obtained from a quarry in Isparta (Türkiye) was used as the main component of the filling materials. The barite source is a sand material (please see its grading curve in Figure 1) which is suitable for heavy concrete production. The barite used in this study was not combined with a natural soil matrix such as clay or sand, but was instead employed as a standalone, compacted mineral filler with a controlled particle size distribution.

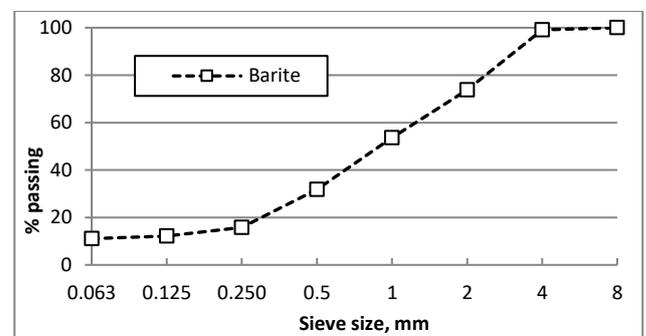


Figure 1. Particle size distribution of barite

It is important to emphasize that barite was used in this study as the sole filler material, not as an additive to a separate soil matrix. Therefore, no mixing ratio or blending method was involved. The attenuation results presented throughout the study reflect the performance of compacted barite alone under varying moisture contents. This allows a direct assessment of barite's shielding capacity without matrix-related interference, which was a deliberate methodological choice.

The selected grain size range of 0–5 mm was based on its compatibility with standard Proctor compaction procedures and reflects practical gradations used in fill applications. This size range was chosen to ensure both compaction efficiency and realistic particle packing, consistent with previous barite-based shielding research [3,4]. The specific

gravity (Gs) of the barite material was measured as 4.2. Traditional geotechnical classification systems (e.g., Unified Soil Classification System — SC, CL, SP) were not applied, since the objective was to isolate the shielding behavior of barite itself, independent of matrix effects. It should be emphasized that the tested material consisted exclusively of processed barite aggregate (0–5 mm), which is considered a coarse-grained mineral filler, not a fine-grained soil such as silt or clay. Therefore, the effects of inherent hydrogen content from natural clays or plastic fines on neutron attenuation were not part of the current study’s scope. The moisture-dependent neutron shielding observed in this research was primarily due to the added water, rather than any intrinsic hydrogen-bearing minerals.

It is acknowledged that in natural or composite soil systems, this distinction—between fine- and coarse-grained matrices—plays a critical role in neutron moderation, compaction behavior, and permeability characteristics [15,16]. Future studies may investigate blended systems that combine barite with silts or clays to leverage both hydrogen content and density for optimized performance. However, the current experimental design aimed to eliminate variability from matrix type by focusing on a standardized filler gradation, thus ensuring that shielding trends could be directly attributed to moisture variation and barite content alone. Consequently, tests such as Atterberg limits and hydrometer analysis were not conducted, as the material does not exhibit plastic behavior or clay/silt fraction dominance.

However, future studies may include extended geotechnical characterizations, including specific gravity (Gs), porosity (n), void ratio (e), dry unit weight (γ_d), and hydraulic conductivity (k), particularly if barite is to be used in composite backfill blends. The focus in this research was to examine radiation shielding properties under standardized compaction rather than mechanical or permeability behavior. This decision aligns with similar shielding studies focusing on filler materials rather than load-bearing soils [4,10]. The chemical composition of barite and water (by mass, %) used in the study is specified in Table 1.

Table 1. The chemical composition of barite and water (by mass, %).

Composition (%)	Barite	Water
SiO ₂	14.80	-
Fe ₂ O ₃	0.53	-
Al ₂ O ₃	4.67	-
CaO	1.06	-
MgO	0.42	-
K ₂ O	0.85	-
SO ₃	8.51	-
P ₂ O ₅	0.07	-
BaO	65.8	-
H ₂ O	-	100
Total	100	100

2.2 Method

The preparation and testing of the stabilized filler series involved multiple detailed steps to ensure consistency and

accuracy in the analysis. First, barite aggregate was carefully sieved to achieve a particle size range of 0–5 mm, ensuring uniformity for subsequent mixing and testing procedures. The sieved barite was then used to create barite-filled soil samples, which were subjected to Proctor compaction tests. These tests aimed to determine the optimal compaction characteristics of the mixtures, specifically focusing on the effect of varying water content. For the Proctor tests, samples were prepared with water contents of 1%, 2%, 3%, 4%, and 5%, allowing for a comprehensive evaluation of the moisture effect on compaction. The tests were conducted using a standard mold with a volume of 944 cm³ and a height of 30.5 cm. Each sample was compacted by applying 25 drops using a standard Proctor hammer. This procedure ensured consistent energy input across all samples, allowing for reliable comparisons between different water content levels.

The gamma ray linear attenuation coefficient (LAC) “ μ ” and thermal neutron linear attenuation factor (LAF) of the fillers were theoretically computed using NGCal software (<http://ngcal.com/>) developed by Gökçe et al. [17]. The software enables users to precisely ascertain several shielding characteristics of radiation shields, including the mass attenuation coefficient (MAC), LAC/LAF, mean free path (MFP), half-value layer (HVL), and tenth-value layer (TVL). The simulations provided insights into the attenuation properties of the samples, making it possible to assess their suitability for applications requiring enhanced radiation shielding. These combined methods ensured a robust evaluation of the physical and radiological properties of the barite-based filler series.

3 Results and discussions

3.1 Proctor test

The results of the Proctor test are presented in Figure 2. This test was performed using 25 blows, a mold volume of 944 cm³, and a drop height of 30.5 cm.

The Proctor test results for barite aggregate (0-5 mm) illustrate the relationship between moisture content and density. It is important to note that the density values reported here correspond to wet bulk density, which includes the mass of water in the compacted sample. This choice was made intentionally, as radiation shielding performance is influenced by the total mass per unit volume—particularly due to hydrogen content introduced through water. However, the authors acknowledge that in geotechnical engineering, compaction behavior is typically evaluated using dry density versus moisture content curves to assess soil mechanics behavior. For this study’s scope—focused on shielding efficiency—wet density was more directly aligned with shielding metrics. Nevertheless, future studies may include both dry and wet densities to facilitate cross-disciplinary interpretation. The density starts at 2.838 g/cm³ with 1% moisture content and increases steadily, reaching a peak of 2.917 g/cm³ at 3% and 4% moisture content. Beyond this point, the density decreases slightly to 2.903 g/cm³ at 5%. The optimum moisture content (OMC), where the aggregate achieves its maximum density, lies between 3% and 4%. This observation aligns with field practice, where a moisture range around the optimum—typically OMC \pm 1% or even

OMC + 2%—is often acceptable due to natural variability in site conditions and challenges in precise moisture control. In this study, the density at both 3% and 4% moisture content was found to be virtually equal (2.917 g/cm³), suggesting a performance plateau rather than a narrow optimum point. This supports the idea of a workable compaction range rather than a single precise value. Although hydraulic conductivity (k) was not measured as part of this study, the small density variation and consistent compaction trend within this moisture range suggest that the permeability behavior would likely remain within acceptable limits, as reported in similar filler-based studies [18]. Further experimental evaluation of permeability within this range is recommended for site-specific applications. The authors fully agree that low hydraulic conductivity is a critical parameter for backfill materials in radioactive waste disposal systems, where impermeability must be ensured to prevent water ingress and radionuclide migration. Since this study focused exclusively on radiation attenuation behavior, permeability testing was not conducted. However, considering that barite is a coarse-grained material, its intrinsic hydraulic conductivity may be too high for direct application in engineered barriers without modification. Future work should include detailed permeability testing under varying moisture and compaction levels, and also explore blending barite with low-permeability additives such as bentonite to achieve both shielding efficiency and hydraulic isolation—an approach supported in bentonite-barrier literature [8,9]. At lower moisture levels (1%–2%), there isn't enough water to facilitate proper lubrication between particles, limiting their ability to compact efficiently. As the moisture content rises to 3% and 4%, water acts as a lubricant, improving particle arrangement and achieving the highest density. However, at 5%, the excess water begins to disrupt compaction by creating water pockets, reducing the packing efficiency and slightly lowering the density. Overall, the density increases by 2.8% from 1% to 3%, reflecting the improvement in compaction with optimal moisture. The reduction from 4% to 5% is minimal at 0.48%, showing that the material is sensitive to excessive water. This behavior is characteristic of a Proctor test curve, which typically shows a parabolic relationship between density and moisture content.

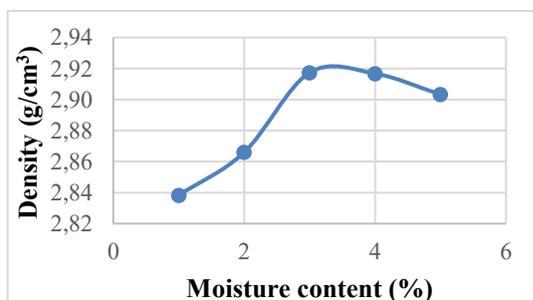


Figure 2. Proctor test results

3.2 Linear attenuation capabilities of fillers for gamma rays and neutrons

The results presented in Figure 3 illustrate the linear attenuation coefficient and its variations for gamma rays, as

well as the linear attenuation factor and its changes for neutrons across different moisture contents.

In Figure 3(a), the linear attenuation coefficient (μ) for gamma rays is shown for three different photon energies: 662 keV, 1173 keV, and 1332 keV. As moisture content increases from 1% to 5%, there is a clear decreasing trend in μ for all three energies. At 662 keV, the coefficient declines from 0.2590 cm⁻¹ at 1% moisture to 0.2533 cm⁻¹ at 5%, representing a decrease of approximately 2.2%. For 1173 keV, the attenuation drops from 0.1835 cm⁻¹ to 0.1801 cm⁻¹ (a 1.85% reduction), while for 1332 keV, the values decrease from 0.1712 cm⁻¹ to 0.1693 cm⁻¹, reflecting a smaller change of about 1.1%. The coefficients exhibit a clear inverse correlation with moisture content, with R² values of 0.6556, 0.5553, and 0.5478 for the respective energies, indicating a moderate negative correlation. This suggests that with the increase of moisture content, the gamma ray attenuation property of the soil decreases up to 5% moisture content.

In Figure 3(b), the relative changes in the linear attenuation coefficient for gamma rays are illustrated as percentages. At 1% moisture, all three energies are normalized to 100%. As moisture increases, relative attenuation for 662 keV drops to 98.7% at 5% moisture, while 1173 keV and 1332 keV experience similar declines to 99.0% and 98.2%, respectively. The steepest relative decline occurs for the lowest photon energy (662 keV), suggesting a greater sensitivity of lower-energy gamma rays to moisture-induced attenuation. This indicates that the gamma ray attenuation property of the soil continues to decrease with increasing moisture content up to 5%. However, even at these higher energies, the variations remain relatively small, confirming that the material maintains its shielding capability across different moisture levels. This behavior aligns well with established principles in radiation shielding [19], where high-density materials primarily dictate attenuation rather than moisture content.

Figure 3(c) examines the linear attenuation factor (μ) for neutrons at two energies: thermal (2.54 meV) and fast (4 MeV). Unlike gamma attenuation, neutron attenuation shows a strong positive correlation with moisture content, with both thermal and fast neutrons exhibiting near-linear increases. Thermal neutron attenuation rises from 0.1948 cm⁻¹ at 1% moisture to 0.8881 cm⁻¹ at 5%, an increase of 356%. Similarly, fast neutron attenuation grows from 0.1806 cm⁻¹ to 0.8719 cm⁻¹, marking a 383% rise. The high R² values of 0.9998 for both data sets confirm the robustness of this linear relationship. This reveals that with the increase of moisture content, the neutron attenuation property of the soil increases significantly up to 5%. This trend suggests that as moisture content increases, neutron absorption capacity improves substantially [20, 21], which is a well-documented phenomenon in neutron physics. Water molecules, containing hydrogen atoms, serve as effective neutron moderators by reducing neutron energy through elastic scattering interactions, thereby enhancing neutron attenuation [22].

The results indicate that neutron attenuation is far more sensitive to moisture content than gamma attenuation, with fast neutrons exhibiting a marginally higher sensitivity than

thermal neutrons. The neutron attenuation property of the soil consistently increases with moisture content up to 5%, showing a strong dependence on hydrogen interaction. This is expected, as thermal neutrons interact more effectively with hydrogen-rich materials like water, leading to significant attenuation improvements. The results indicate that the presence of moisture plays a crucial role in neutron shielding efficiency, making the material highly suitable for applications where neutron radiation protection is required. While the results demonstrate that increased moisture content significantly enhances the neutron shielding performance of barite-based fillers due to hydrogen-rich water molecules, it is acknowledged that the long-term stability of this shielding effect may be challenged by moisture loss or ingress resulting from environmental fluctuations, ventilation effects, or hydrostatic changes. Over time, desiccation can reduce hydrogen content, diminishing neutron moderation efficiency, whereas unintended water intrusion may destabilize compacted layers or increase back pressure. This sensitivity has been highlighted in several studies investigating moisture-dependent shielding media [20,22,23]. To address this, the authors recommend that in-situ filler applications should be complemented with protective barriers (e.g., vapor-retardant membranes, clay liners) and regular monitoring systems (e.g., dielectric or neutron moisture sensors) to maintain effective shielding conditions [9,21]. Moreover, when designing repository systems or radiation facilities, the use of hygroscopic additives, bentonite-based barriers, or sealed enclosures may be considered to limit undesirable moisture variations [8]. Therefore, while moisture-enhanced neutron shielding is an

advantage of this method, the long-term performance is contingent upon proper environmental control and design foresight. The observed trends align with findings in the literature, where higher moisture content is known to reduce gamma attenuation due to reduced density, whereas neutron attenuation increases with moisture due to enhanced hydrogen atom interaction (primarily via elastic scattering). Studies have similarly reported stronger moisture sensitivity for fast neutrons than for thermal neutrons, reflecting their different cross-sectional interaction mechanisms. These trends suggest that with the increase of moisture content, the contrasting behavior of gamma ray and neutron attenuation persists steadily up to 5% moisture content.

The connection between the graphs becomes apparent when comparing the inverse gamma attenuation trends with the direct neutron attenuation trends. The interplay between moisture-induced hydrogen content and radiation interaction mechanisms suggests a complementary behavior: as gamma ray attenuation weakens, neutron attenuation strengthens, highlighting the duality of moisture's impact on radiation transport properties. This synergistic relationship could be particularly useful in moisture sensing applications where gamma and neutron techniques are used in tandem to enhance measurement accuracy. Thus, the property of the soil is shown to decrease in gamma ray attenuation and increase in neutron attenuation up to 5% moisture content. Overall, the figures collectively illustrate a clear and scientifically consistent pattern, with inverse gamma ray attenuation trends and direct neutron attenuation trends, reflecting the contrasting effects of moisture on photon and neutron interactions with matter.

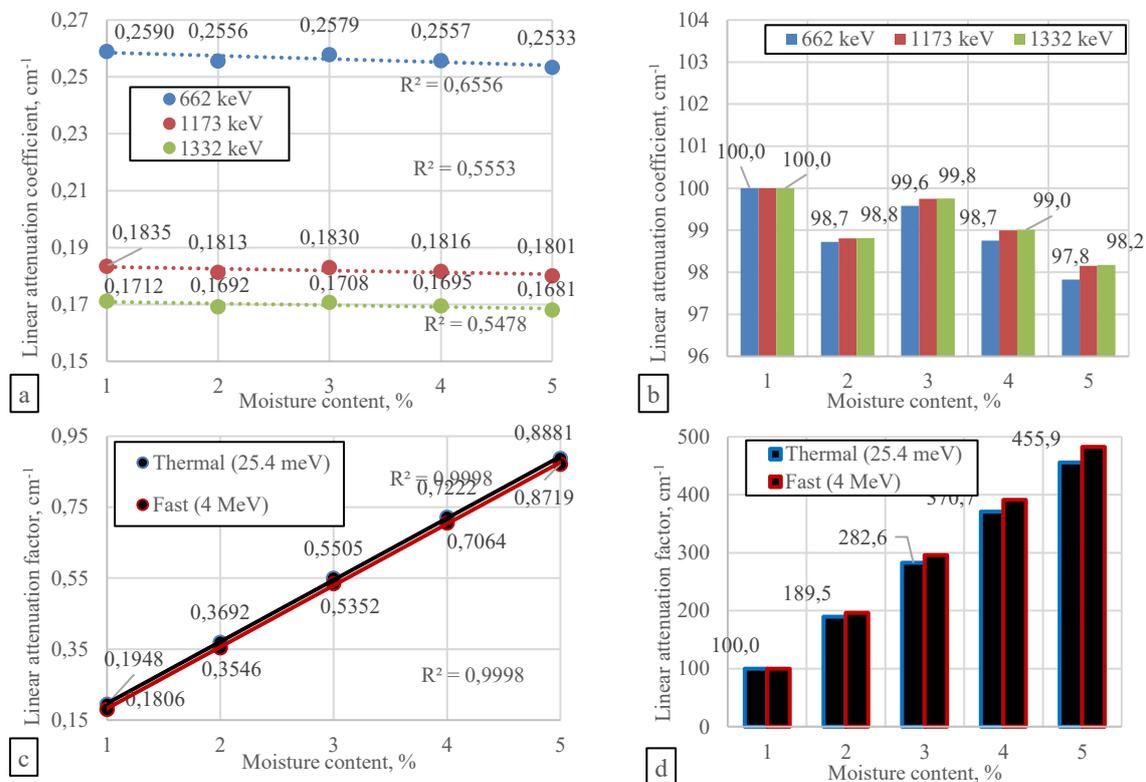


Figure 3. (a) Linear attenuation coefficient and (b) its relative changes for gamma rays; and (c) linear attenuation factor and (d) its relative changes for neutrons

3.3 Gamma ray shielding thickness of filler materials

The data presented in Table 2 provides an insightful analysis of the gamma-ray shielding properties of the studied materials by evaluating the MFP, HVL, and TVL at different moisture contents and energy levels.

These parameters are essential in assessing the material's ability to attenuate gamma radiation, where lower values of MFP, HVL, and TVL signify superior shielding effectiveness. As energy levels increase, the MFP, HVL, and TVL values generally show an upward trend, reflecting the well-established principle that higher-energy gamma rays penetrate deeper into materials, requiring thicker shielding to achieve the same level of attenuation. At 662 keV, the MFP increases by 2.33%, from 3.86 cm at 1% moisture to 3.95 cm at 5%. Similarly, at 1173 keV, MFP increases by 2.24%, from 2.68 cm to 2.74 cm, and at 1332 keV, MFP rises by 2.25%, from 8.89 cm to 9.09 cm.

A similar pattern can be observed for HVL, which shows a slight increase with moisture content. At 662 keV, HVL increases by 1.83% (from 5.45 cm at 1% to 5.55 cm at 5%), at 1173 keV, HVL rises by 1.85% (from 3.78 cm to 3.85 cm), and at 1332 keV, the increase is 1.85% (from 3.78 cm to 3.85 cm). These increases suggest that higher moisture content, while slightly affecting the material's shielding properties, does not drastically alter the overall performance. Similarly, TVL values also show slight increases: a 1.88% rise at 662 keV (from 12.55 cm to 12.79 cm), a 1.91% increase at 1173 keV (from 12.55 cm to 12.79 cm), and a 1.86% rise at 1332 keV (from 13.45 cm to 13.70 cm).

The slight increases in MFP, HVL, and TVL values with increasing moisture content suggest that water molecules may marginally reduce the material's density, leading to a slight decrease in the attenuation coefficient. However, these changes are minimal, implying that the material's inherent gamma-ray attenuation properties dominate, maintaining a relatively stable shielding performance across different moisture contents. The data demonstrates that as moisture content increases, the shielding effectiveness decreases only slightly. The relationship between the attenuation coefficient and shielding thickness parameters (MFP, HVL, and TVL) supports this conclusion, as a material with a higher attenuation coefficient will naturally exhibit lower MFP, HVL, and TVL values.

These findings are significant in practical applications, as materials with lower MFP, HVL, and TVL values are more

desirable for radiation shielding. Such materials provide effective protection with thinner layers, thus reducing material usage and cost. The relatively small changes observed across moisture contents suggest that the studied material maintains stable shielding performance even under varying environmental conditions. This stability makes it suitable for applications where moderate moisture exposure is anticipated, without significantly affecting its gamma-ray attenuation properties.

In conclusion, the analysis of the data indicates that the studied material has good gamma-ray attenuation properties, as evidenced by its relatively low MFP, HVL, and TVL values. While moisture content causes slight variations in these values, the material's overall shielding capability remains largely unaffected, demonstrating its potential for use in radiation shielding applications where consistent performance is required.

4. Conclusions

This study investigated the gamma-ray and neutron shielding properties of barite-filled materials under different moisture contents and compaction conditions. Key findings are summarized as follows:

1. The optimum water content (OMC) was determined to be between 3% and 4%, where the maximum density of 2.917 g/cm³ was achieved. Beyond this point, an increase in water content led to reduced density due to water pockets disrupting particle packing efficiency, with a slight decrease to 2.903 g/cm³ at 5% water content.
2. The gamma-ray LAF exhibited a slight decline with increasing moisture content. At 0.662 MeV, the LAF peaked at 0.259 cm⁻¹ for samples with 1% and 2% water content and decreased to 0.253 cm⁻¹ at 5% water content. This reduction is attributed to the dilution effect of water's lower density compared to barite, slightly lowering the overall attenuation properties of the material.
3. The neutron attenuation performance improved with increasing water content, with the LAF for thermal neutrons increasing from 0.1948 cm⁻¹ at 1% water content to 0.8881 cm⁻¹ at 5%, representing a significant enhancement. This trend highlights the critical role of hydrogen in water for effective neutron moderation.

Table 2. MFP, HVL and TVL for gamma rays

Characteristic	Energy level (keV)	Moisture content				
		1%	2%	3%	4%	5%
MFP (cm)	662	3.86	3.91	3.88	3.91	3.95
	1173	2.68	2.71	2.69	2.71	2.74
	1332	8.89	9.01	8.93	9.00	9.09
HVL (cm)	662	5.45	5.52	5.46	5.51	5.55
	1173	3.78	3.82	3.79	3.82	3.85
	1332	12.55	12.70	12.58	12.68	12.79
TVL (cm)	662	5.84	5.91	5.86	5.90	5.95
	1173	4.05	4.10	4.06	4.09	4.12
	1332	13.45	13.61	13.48	13.58	13.70

4. The study demonstrated that radiation shielding efficiency for both gamma rays and neutrons is optimized under controlled moisture conditions. Excessive moisture reduces shielding performance for gamma rays but enhances neutron shielding due to hydrogen's role in neutron capture.
5. While this study focused on the radiation shielding performance of barite filler, future research should address the material's hydraulic conductivity, especially for applications in nuclear waste isolation where long-term impermeability is essential. Integration with low-permeability materials such as bentonite may be required to meet engineering criteria for both radiation shielding and hydraulic performance [8,9].
6. The long-term geotechnical behavior of the compacted barite filler—such as consolidation, swelling, or time-dependent volume change—was not within the scope of this study. However, for practical implementation in buried shielding systems or engineered barriers, these properties are highly relevant and must be evaluated. Future research should include long-term monitoring and testing of volume stability, mechanical degradation, and compatibility with surrounding materials to ensure reliable performance under field conditions and over operational timescales.

Recommendations for future work

This study was designed to isolate and evaluate the radiation shielding performance of compacted barite filler under varying moisture contents and compaction conditions, without the influence of a host soil matrix. While this approach provides clear insight into the shielding capacity of pure barite, it does not fully capture the behavior of composite backfill systems in practical field conditions.

For future research, it is strongly recommended to expand the experimental program by investigating barite blended with fine-grained soils such as clays or silts. Such mixtures could further enhance neutron attenuation performance due to the natural hydrogen content of plastic fines. In addition, incorporating low-permeability additives such as bentonite could help to achieve the necessary hydraulic isolation required in radioactive waste repositories or other critical shielding applications [8,9].

It is also suggested that future studies include comprehensive geotechnical characterization of the blended systems. This should cover grain size distribution (sieve and hydrometer analysis), Atterberg limits, specific gravity (Gs), porosity (n), void ratio (e), dry unit weight, minimum and maximum dry density, relative density, and hydraulic conductivity (k). Moreover, long-term behavior such as consolidation, swelling potential, and time-dependent volumetric stability should be assessed to ensure practical viability under changing field conditions.

Finally, the effects of environmental exposure, water ingress, or moisture loss on the long-term shielding efficiency and structural integrity of compacted barite-based

systems should be examined through field-scale mock-ups and continuous monitoring.

These additional investigations will support the development of more robust design guidelines for the safe and effective use of barite-based radiation shielding materials in diverse engineering and nuclear infrastructure projects.

Conflict of Interest

The authors declare that they have no conflict of interest.

Similarity rate (Turnitin): % 17

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