Gamma Shielding Efficiency of Sedimentary Rock-Based Bricks for Low-Energy Applications

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Abstract
Ensuring human safety requires understanding the radiation shielding capabilities of building materials alongside their strength and durability. This study investigates the potential of concrete made from two types of sedimentary rocks, shale and calcareous, for shielding against Co-60 gamma rays at energy levels of 960 keV and 1180 keV. The sedimentary rocks were sourced from the Global Geopark region in Satun Province, Thailand. The shielding performance of sedimentary rock-based concrete is compared with standard construction concrete, with both having identical dimensions of 15 cm × 15 cm × 15 cm and a cement-to-sand-to-stone ratio of 1:2:4. Engineering properties such as density and compressive strength are analyzed. Gamma shielding efficiency is assessed using the linear attenuation coefficient (μ_l), mass attenuation coefficient (μ_m), mean free path (MFP), half-value layer (HVL), and tenth-value layer (TVL). The results indicate that standard concrete exhibits the highest compressive strength, while shale-based concrete provides superior attenuation of gamma rays at the studied energy levels. The effectiveness of gamma radiation shielding in construction materials is influenced by the internal composition of the stone or concrete mixture.

Keywords: gamma radiation shielding, sedimentary rocks, concrete against radiation

1. Introduction

Gamma radiation, a form of ionizing radiation, poses significant risks to human health and the environment due to its high energy and strong penetrating ability. Effective shielding against gamma radiation is therefore essential in a wide range of sectors, including medical facilities, nuclear power plants, and radiation-related construction applications. Traditionally, radiation shielding has relied heavily on materials such as lead and concrete, which are known for their high attenuation capacity. However, these conventional materials present notable drawbacks, including high costs, substantial weight, and environmental concerns related to their production, handling, and disposal.

In recent years, there has been a growing interest in the development of alternative shielding materials that are more sustainable, lightweight, cost-effective, and environmentally friendly. Among these alternatives, sedimentary rocks have garnered attention due to their natural abundance, compositional diversity, and potential radiation attenuation properties. Sedimentary rocks are formed through the long-term accumulation, compaction, and lithification of mineral and organic particles. Their distinct physical and chemical characteristics—such as density, mineral composition, and porosity—may make them viable candidates for radiation shielding applications.

Rocks are fundamental materials commonly used in construction, both for coating and flooring. The scientific definition of rocks encompasses a solid aggregate naturally formed from one or more minerals, volcanic glass, or organic materials (Kadir Günoğlu et al., 2024). Concrete, a widely used composite material, consists of a mixture of cement paste and aggregates. The mechanical and gamma radiation attenuation properties of concrete can be altered by varying the types of aggregate used. Concrete composites are well-recognized for their adaptability and effectiveness in shielding applications in sectors such as nuclear power plants, radioactive waste disposal, and nuclear medicine (R.S. Aita et al., 2024).

Incorporating cement into a composite material with sedimentary rocks presents a promising approach to enhance radiation shielding efficiency. Cement-based composites have been extensively studied for their mechanical strength, durability, and cost-effectiveness in construction. When combined with sedimentary rocks such as sandstone and shale, these composites may further improve gamma radiation attenuation while maintaining the desired structural integrity. The versatility of composite materials allows them to be molded into various forms, which makes them applicable for radiation shielding in medical and nuclear settings as well as in construction.

The addition of cement to sedimentary rocks also optimizes the porosity and density of the composite, which directly influences its ability to reduce gamma radiation penetration. Moreover, these composite materials are relatively cost-effective and can be locally produced, making them an attractive option for countries where traditional shielding materials are either prohibitively expensive or difficult to obtain. In particular, composite materials align with the growing demand for eco-friendly and sustainable building materials, as they can be designed to minimize environmental impact during production and disposal.

This study investigates the feasibility of utilizing bricks made from sedimentary rocks—specifically shale and calcareous—as effective shielding materials against gamma radiation. The goal is to evaluate the shielding efficiency of these sedimentary rock-based bricks by analyzing key parameters, such as their density, composition, and compressive strength, and comparing them to traditional shielding materials. This research aims to contribute to the development of practical, sustainable alternatives for gamma radiation shielding, particularly in contexts where accessibility, cost, and environmental impact are key considerations.

2. Material and Methods

2.1. Samples preparation

This study investigates the effectiveness of solid concrete, derived from sedimentary rocks, in shielding low-energy gamma radiation. The research evaluates key physical properties, including density, compressive strength, and gamma-ray shielding performance. Two types of sedimentary rocks, shale and calcareous, were selected for the study. These rocks were sourced from the UNESCO Global Geopark in Satun Province, Thailand. The rocks were then mixed with cement in a proportion of 1:2:4 by weight (cement: sand: rock), which is an optimal concrete mix ratio for construction in Thailand as shown in Figure 1.

The mixture was thoroughly blended in a concrete mixer to ensure uniformity. Subsequently, the mixture was poured into a 15 cm × 15 cm × 15 cm concrete mold and compacted to ensure density. The concrete was then cured in water for a minimum of 28–30 days, following standard curing procedures for construction-grade concrete. After curing, the physical and mechanical properties, including density, compressive strength, and gamma-ray shielding performance, were assessed. The gamma-ray shielding efficacy was tested using a NaI(Tl) detector and a Geiger-Muller counter, with a standard Co-60 gamma radiation source at energy levels of 960 keV and 1180 keV. Measurements were recorded over a period of 300 seconds.

Figure 1 Preparation of sedimentary rock blocks of size 15 cm x15 cm x15 cm

2.2. Rock-Based Bricks Characteristics

2.2.1 Chemical Composition

To analyse the elemental composition and compounds of the shale and calcareous samples, X-ray fluorescence (XRF) analysis was performed to quantify the concentration of individual elements present in the samples. This analysis was conducted using the Zetium X-ray fluorescence spectrometer (PANalytical, Netherlands). In addition, X-ray diffraction (XRD) analysis was employed to examine the crystallographic structure of the samples, utilizing the Empyrean X-ray diffractometer (PANalytical, Netherlands). The results, including the elemental composition and identified compounds, are provided.

2.2.2 Physical and Mechanical properties

The density of the prepared concrete samples was evaluated by dividing the dry weight (M) of each specimen by its calculated volume (V). The mass measurements were obtained using a digital precision balance, while the sample volumes were derived from dimensional measurements of the concrete cubes. The density was then computed in accordance with equation (1). Compressive strength refers to the maximum axial load that concrete can endure before structural failure occurs, such as cracking or crushing as shown figure 2. It serves as a critical parameter in evaluating the material's mechanical performance under compressive stress. For the testing procedure, two steel bearing platens with hardened surfaces were mounted on the testing machine to ensure uniform load distribution during compression testing and determined in equation (2) (Aita et al., 2024).

$$\rho = \frac{M}{V} \quad (1)$$

$$F_c = \frac{P}{A} \quad (2)$$

2.2.3 Gamma Ray Attenuation Coefficient

The intensity of gamma radiation (I_0) decreases when it passes through a shielding material of thickness x. The reduction in radiation intensity (I) is directly proportional to the intensity of the incident radiation as it travels through the medium. The attenuation coefficient (μ) can be determined using the following equations 3 and 4 (Wisarut Rungcharoenkit and Withit Pansuk, 2021 and Kadir Günoğlu et al., 2024):

$$I = I_0 e^{-\mu x} \quad (3)$$

Figure 2 Assessment of Compressive Strength

Alternatively, the equation can be expressed in terms of the mass attenuation coefficient as:

$$I = I_0 e^{-(\frac{\mu}{\rho})(\rho x)} \quad (4)$$

where:

I = intensity of gamma radiation after transmission through the material (in counts per second or other suitable units),

I_o = initial intensity of gamma radiation before interaction with the material,

x = thickness of the shielding material (cm),

ρ = density of the material (kg/m³),

μ = linear attenuation coefficient $(cm^2)^{-1}$,

$\frac{\mu}{\rho}$ = mass attenuation coefficient (cm²/g).

Several factors influence the attenuation coefficient (μ), which measures the amount of radiation absorbed by a material:

The characteristics of radiation or particles: Various forms of radiation interact with matter in unique ways. Alpha particles have a significant attenuation coefficient owing to their considerable mass and strong electric charge, resulting in a higher propensity for absorption by materials. On the other hand, gamma rays can penetrate much better and have no charge, so they usually have lower μ values and require denser or thicker materials to reduce their strength.

The atomic number of a substance primarily determines its efficacy in attenuating radiation. Elements with high atomic numbers, such as lead, are better at blocking radiation because their tightly packed atoms make it more likely for radiation to hit them. Materials with lower atomic numbers are often less efficient in absorbing energetic particles and light.

The energy level of incoming radiation correlates positively with its penetrating capability. High-energy gamma rays may traverse several materials with minimum contact, leading to less attenuation. Conversely, under identical circumstances, lower-energy radiation absorbs more efficiently, leading to an elevated value.

Once the attenuation coefficient is determined, it can be used to calculate the Mean Free Path (MFP), Half Value Layer (HVL), and Tenth Value Layer (TVL) as follows:

MFP (Mean Free Path) refers to the average distance that radiation travels before interacting with the shielding material.

$$MFP = \frac{1}{\mu} \quad (5)$$

HVL (Half Value Layer) is the thickness of the shielding material required to reduce the intensity of radiation to 50% of its initial value from the source.

$$HVL = \frac{ln\,(2)}{\mu} \quad (6)$$

TVL (Tenth Value Layer) is the thickness of the shielding material required to reduce the intensity of radiation to 10% of its initial value from the source.

$$TVL = \frac{ln\,(10)}{\mu} \tag{7}$$

Figure 3 Examination of the radiation shielding characteristics of sedimentary rock block bricks

3. Results and Discussion

3.1. Chemical Composition

Table 1 Elemental and Compound Composition Analysis of Sedimentary Rocks (XRF)

Calcareous		Shale	
compound	Concentration (%)	compound	Concentration (%)
Al_2O_3	11.418	Al_2O_3	10.823
SiO_2	30.756	SiO_2	28.461
K_2O	4.370	K_2O	3.892
CaO	22.826	CaO	24.965
Fe_2O_3	3.081	Fe_2O_3	3.472

Table 2 Types of Compounds and Chemical Formula of Sedimentary Rocks (XRD)

Calcareous		Shale	
Mineral/compound name	Chemical Formular	Mineral/compound name	Chemical Formular
Quartz	SiO_2	Calcite	$Ca(CO_3)$
Calcite	$Ca(CO_3)$	Quartz	SiO_2
Pyrite	FeS_2	Dolomite	$CaMg(CO_3)_2$
Orthoclase	$K(AlSi_3O_8)$	Pyrite	FeS_2
Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$	Orthoclase	$K(AlSi_3O_8)$
Dolomite	$CaMg(CO_3)_2$	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$

Tables 1 and 2 present the analysis results regarding the elements, compounds, and structure of shale and calcareous. The research indicates that both rock types include identical elements and chemicals, although they vary in their concentrations. The researcher identified the five most common elements and compounds present in both categories of rocks as follows: SiO_2 CaO Al_2O_3 K_2O and Fe_2O_3

3.2. Physical and Mechanical properties

An investigation of the physical and mechanical properties of concrete made from shale and calcareous. This study examines the physical and mechanical characteristics of concrete produced using sedimentary rocks, specifically shale and calcareous. Two key properties were assessed:

1. The density of solid concrete samples made from each rock type, and
2. Their respective compressive strengths.

According to the data presented in Table 3, the density and compressive strength of concrete blocks made from both types of sedimentary rocks were compared to those of standard construction concrete. The highest values were observed in typical construction concrete, with a density of 2,194.66 kg/m^3 and a compressive strength of 259.69 Ksc.

Shale-based concrete blocks followed, with a density of 1,993.72 kg/m^3 and a compressive strength of 138.72 Ksc. The lowest values were recorded for concrete made from calcareous, at 1,883.37 kg/m^3 and 53.20 Ksc, respectively.

Table 3 Physical and Mechanical properties of Sedimentary Rock-Based Bricks

Type concrete	m (kg)	Volume (m^3)	Density (kg/ m^3)	Compressive strength (Ksc)
Calcareous	6.375	0.0034	1,883.37	53.20
Shale	6.789	0.0034	1,993.72	138.72
concrete	7.526	0.0034	2,194.66	259.69

3.3. Radiation shielding properties

This research examines the efficacy of solid concrete as a gamma radiation shield by incorporating sedimentary rock samples with cement. The analysed sedimentary rocks consist of two varieties: shale and calcareous, combined with cement in a ratio of 1:2:4 for cement, sand, and stone, respectively. The sedimentary rock samples included in the study were sourced from the La-Ngu District in Satun Province, which is included in the Satun Geopark. Next, the effectiveness of the dense concrete in blocking radiation was tested by using it to measure how well it reduced gamma radiation with a Geiger-Muller counter and a standard gamma radiation source, Co-60, which has an intensity of 74 kBq and a half-life of 5.3 years. The measurement duration was 300 seconds to ascertain the attenuation coefficient of thick concrete from both varieties of sedimentary rock samples and to compare it with standard building concrete. The experimental findings are shown in Table 4.

Table 4 Radiation Shielding properties

Energy (keV)	Type concrete	μ_l (cm^2)$^{-1}$	μ_m (cm^2/g)	MFP (cm)	HVL (cm)	TVL (cm)
960	Calcareous	0.15	0.08	6.90	4.78	15.90
	Shale	0.18	0.09	5.59	3.87	12.86
	Concrete	0.17	0.08	5.88	4.08	13.54
1180	Calcareous	0.07	0.04	13.51	9.37	31.12
	Shale	0.08	0.04	12.05	8.35	27.74
	Concrete	0.04	0.02	27.78	19.25	69.79

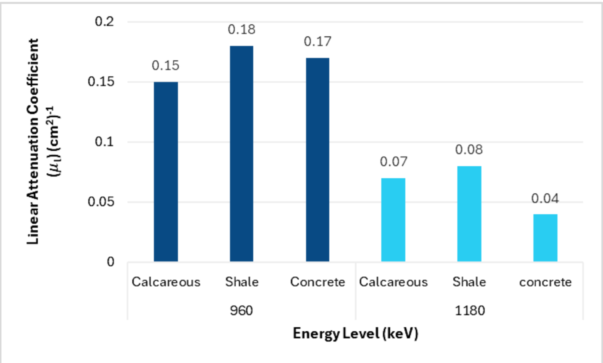

Figure 4 A graph shows the relationship between the linear attenuation coefficient and the energy levels of each kind of brick block.

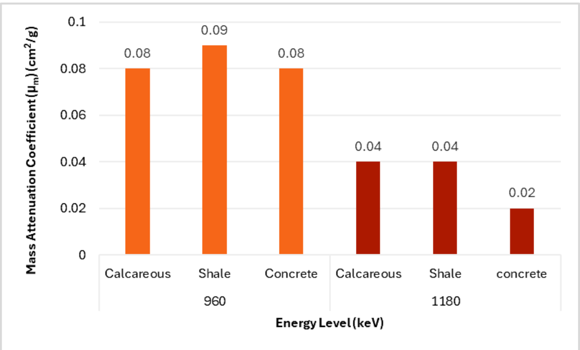

Figure 5 A graph shows the relationship between the mass attenuation coefficient and the energy levels of of each kind of brick block.

From Figures 4 and 5, the graphs illustrate the relationships between the linear attenuation coefficient and the gamma-ray energy levels, and between the mass attenuation coefficient and the gamma-ray energy levels, respectively. The values of both the linear (μ_l) and mass (μ_m) attenuation coefficients presented in these graphs were calculated using Equation (4).

The results indicate that shale brick blocks exhibited the highest linear attenuation coefficients for gamma rays at energy levels of 960 keV and 1180 keV, with values of 0.18 (cm^2)$^{-1}$ and 0.08 (cm^2)$^{-1}$, respectively. Standard concrete showed a slightly lower linear attenuation coefficient at 960 keV, measured at 0.17 (cm^2)$^{-1}$ while the calcareous brick blocks had the lowest value of 0.15 (cm^2)$^{-1}$. At 1180 keV, the calcareous brick blocks outperformed standard concrete, with linear attenuation coefficients of 0.07 (cm^2)$^{-1}$ and 0.04 (cm^2)$^{-1}$, respectively.

Regarding mass attenuation coefficients (μ_m) at 960 keV, shale brick blocks again demonstrated the highest value at 0.09 cm^2/g. Both the calcareous bricks and standard concrete had equal mass attenuation coefficients of 0.08 cm^2/g.

At 1180 keV, shale and calcareous brick blocks had the same mass attenuation coefficient of 0.04 cm^2/g, while standard concrete showed the lowest value of 0.02 cm^2/g.

The radiation attenuation coefficient of shielding materials serves as an indicator of their ability to absorb or reduce radiation intensity. Higher attenuation coefficients signify greater shielding effectiveness, making the material more suitable for radiation protection applications.

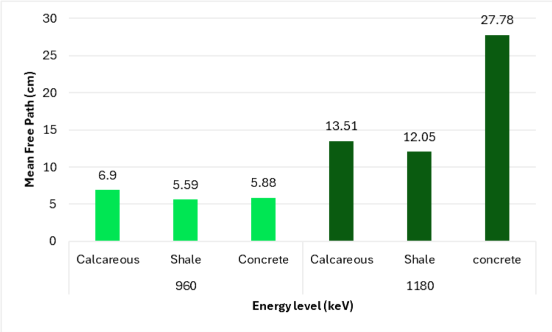

Figure 6 A graph showing the relationship between the mean free path and energy levels of each kind of brick block.

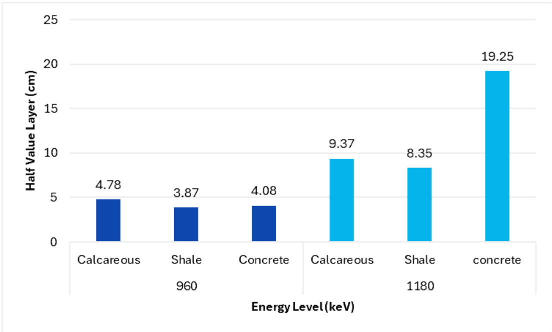

Figure 7 A graph showing the relationship between the half value layer and energy levels of each kind of brick block.

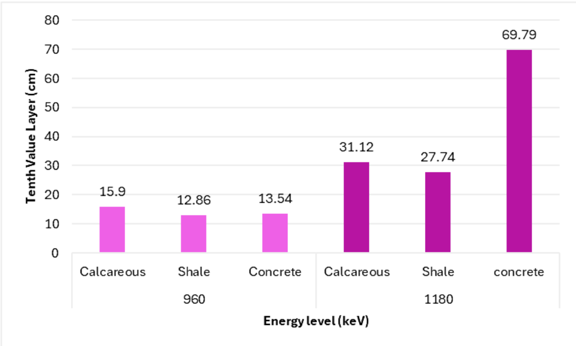

Figure 8 A graph showing the relationship between the tenth value layer and energy levels of each kind of brick block.

Analysis of radiation shielding parameters in concrete blocks made from shale and calcareous under Co-60 gamma ray energies.

Figures 6 through 8 present the graphs of three key thickness parameters—Mean Free Path (MFP), Half Value Layer (HVL), and Tenth Value Layer (TVL)—plotted against gamma-ray energy levels from Co-60 at 960 keV and 1180 keV, respectively. At 960 keV, the MFP, HVL, and TVL values for shale-based concrete blocks were 5.59 cm, 3.87 cm, and 12.86 cm. For blocks made from calcareous, the corresponding values were 6.90 cm, 4.78 cm, and 15.90 cm. Conventional standard concrete showed slightly higher values of 5.88 cm, 4.08 cm, and 13.54 cm. When the energy increased to 1180 keV, shale blocks showed values of 12.05 cm (MFP), 8.35 cm (HVL), and 27.74 cm (TVL). The calcareous blocks recorded 13.51 cm, 9.37 cm, and 31.12 cm, respectively. In contrast, standard concrete demonstrated significantly larger values of 27.78 cm, 19.25 cm, and 69.79 cm for the same parameters.

All three parameters were calculated according to the formulas provided in equations (5) through (7). The results clearly indicate that shale blocks had the lowest values across both energy levels, suggesting their superior ability to attenuate gamma radiation. Calcareous blocks performed moderately well, while standard concrete showed the least effectiveness in radiation shielding.

In practical terms, lower values of MFP, HVL, and TVL imply that a thinner material layer is needed to reduce radiation intensity. Hence, materials with lower values in these parameters are more efficient in shielding against gamma rays, particularly in applications where compactness and material economy are important.

3.4 Discussion

1. Physical and mechanical properties from density and compressive strength. This study focuses on concrete made from two types of sedimentary rocks: shale and calcareous. The mix ratio used was a fixed 1:2:4 ratio by weight of cement, sand, and aggregate. This ratio was chosen based on Surapong Daram's (2019) research, which recommends this standard mix for public construction and small-scale buildings. The highest density was found in standard concrete, at 2,194.66 kg/m^3. Concrete made with shale had a density of 1,993.72 kg/m^3, while the lowest density was observed in calcareous blocks, at 1,883.37 kg/m^3. These density values correlate closely with compressive strength, which generally increases with higher density. The compressive strengths measured were 259.69 Ksc for standard concrete, 138.72 Ksc for shale blocks, and 53.20 Ksc for calcareous blocks. While standard concrete met standard expectations, the sedimentary rock-based blocks showed lower results. This decrease may be due to the uneven nature of the aggregate mix. As noted in Surapong Daram's (2019) work, sedimentary rocks like shale and calcareous tend to have higher porosity compared to granite, which is typically used in standard concrete mixes. This porosity likely weakens the overall concrete structure, reducing both density and strength.

2. Radiation shielding properties in relation to the chemical composition of sedimentary rocks in this study, the radiation shielding performance of concrete blocks made from shale and calcareous was examined in connection with the chemical makeup of these rocks. Based on Table 1, both rock types share several chemical components. Importantly, both contain metallic compounds such as Al_2O_3 and Fe_2O_3. These compounds may play a part in improving the radiation attenuation capability of the blocks compared to those made from ordinary concrete. Previous research by Shamsan S. Obaid et al. (2017) investigated gamma-ray shielding in rocks at energy levels from 122 to 1330 keV. Rocks tested included feldspathic basalt, volcanic rock, granite, and sandstone. Among them, sandstone—also a sedimentary rock—had attenuation coefficients that are comparable to the results found here. For example, at 960 keV, the values for calcareous, and shale in this study were 0.15 (cm^2)$^{-1}$ and 0.18 (cm^2)$^{-1}$. At 1180 keV, the values were 0.07 (cm^2)$^{-1}$ and 0.08 (cm^2)$^{-1}$. These are in the same range as sandstone from the earlier study, which had a coefficient of 0.056 (cm^2)$^{-1}$ at 1170 keV. The difference in this study lies in the chemical composition. The calcareous used here contains 11.419% Al_2O_3 and 10.823% Fe_2O_3, while the shale contains 3.081% and 3.472%, respectively. This characteristic may help explain why these blocks perform better at radiation shielding. Although lead is well-known for its radiation shielding effectiveness, its toxicity makes it less desirable. This study explores safer alternatives. The presence of metallic oxides and the density of the resulting concrete appear to significantly affect shielding performance. According to R.S. Aita et al. (2024), both factors—chemical makeup and density—play a role in how well a material can block radiation. In conclusion, the findings suggest that blocks made from these sedimentary rocks, especially due to their chemical content, can offer better shielding than conventional concrete blocks.

In the study conducted by R.S. Aita et al. (2024), the team explored how concrete mixed with siltstone—a type of sedimentary rock—could block gamma radiation. Tests were done at three energy levels: 0.662 MeV (662 keV), 1.173 MeV (1173 keV), and 1.332 MeV (1332 keV). Siltstone was added to the concrete in different amounts, ranging from 0% to 40% by weight. The results showed that when the amount of siltstone increased, the concrete became better at absorbing radiation. This enhancement was seen in the higher values of the linear attenuation coefficient (μ_l). The improvement was mainly due to two factors: the concrete's electron density increased, and the cross-sectional area for interaction between the radiation and the material became larger. Them used cylindrical concrete blocks for this part of the experiment. Another significant finding was that adding more siltstone increased the MnO content. This made the concrete denser. As a result, the effective atomic number of the concrete also increased. These factors together suggest that siltstone can improve the radiation shielding ability of concrete, especially when used in higher amounts.

In both the findings of this study and the review of related literature, it can be seen that the effectiveness of gamma radiation shielding, particularly at low energy levels, in materials made from cement and sedimentary rocks depends on a few key factors. First, the density and compressive strength of the material are directly related to how well it can block radiation. Materials with higher density and compressive strength tend to perform better in terms of shielding low-energy gamma rays. Second, the chemical makeup of the material is important. If the material contains compounds with heavy metals or elements with relatively high atomic numbers, it tends to show improved shielding capabilities at lower energies. Based on this study, there are several directions for future research. For instance, varying the proportion of sedimentary rock by weight in the mix could help better understand how the composition affects shielding. It would also be valuable to compare different types of sedimentary rock to other types of stone used in construction materials. Finally, exploring additional parameters that relate to shielding across different energy levels—beyond those examined here—could further improve the development of radiation-resistant materials.

4. Conclusions

This study aimed to investigate how well concrete blocks made from sedimentary rocks in La-ngu District, within the Satun UNESCO Global Geopark, can shield against gamma radiation. The research focused on examining the physical and mechanical properties, as well as the radiation attenuation parameters, of the concrete blocks. These blocks, measuring 15 cm × 15 cm × 15 cm, were mixed using a fixed ratio of cement, sand, and rock at 1:2:4 by weight. The study compared the radiation levels before and after shielding using blocks made from shale and calcareous. Next, the effectiveness of shielding against gamma rays from a Co-60 source was contrasted with that of regular concrete used in construction. The results from the study are as follows: The concrete used in general construction showed the highest density and compressive strength, followed by the shale-based blocks and then the calcareous blocks. The study looked at how well different materials block gamma radiation at energy levels of 960 keV and 1180 keV by measuring the linear attenuation coefficient (μ_l), mass attenuation coefficient (μ_m), mean free path (MFP), half-value layer (HVL), and tenth-value layer (TVL). At 960 keV, the shale blocks provided the best radiation shielding, followed by standard concrete and calcareous blocks. At 1180 keV, the shale blocks again offered the most effective shielding, followed by calcareous, with standard concrete providing the least.

5.Acknowledgements

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