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Gamma shielding efficiency of sedimentary rock-based concrete blocks under Co-60 irradiation

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ABSTRACT

Ensuring human safety requires understanding the radiation shielding capabilities of building materials alongside their strength and durability. Common conventional radiation shielding materials include lead and concrete. However, lead is costly, toxic, and raises environmental concerns, prompting increased interest in alternative shielding materials. Therefore, this research investigates the potential of concrete made from two types of sedimentary rocks, shale and calcareous, for shielding against Co-60 irradiation. 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. All concrete blocks were 15 cm × 15 cm × 15 cm and were prepared with a cement:sand:stone ratio of 1:2:4. Concrete cube specimens were prepared to evaluate radiation attenuation properties. The linear attenuation coefficient (μ_l) was calculated from the reduction in count rate after transmission through the concrete block. Engineering properties, including density and compressive strength, were also analyzed. Radiation 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), All of these parameters were calculated from the measured count rates. The study found that standard concrete had the highest compressive strength at 25.45 MPa, followed by shale concrete at 13.59 MPa, and calcareous concrete at 5.21 MPa. However, shale concrete performed best in radiation shielding, showing a linear attenuation coefficient (μ_l) of 0.18 cm^{-1}, a mass attenuation coefficient (μ_m) of 0.09 cm^2/g, a mean free path of 5.59 cm, a half-value layer of 3.87 cm, and a tenth-value layer of 12.86 cm. The improved shielding performance of shale concrete may be related to its mineral composition and internal structure. Analysis by XRD and XRF indicated that the main heavy metal compounds present were Al_2O_3 and Fe_2O_3.

Keywords: Radiation attenuation, Co-60 radiation, Radiation shielding concrete

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 [1]. Therefore, effective protection against gamma radiation is important in many fields, such as hospitals, nuclear power plants, and construction sites that deal with radiation [2]. In the past, radiation shielding has mostly used materials like lead and concrete, which are known for their ability to attenuate gamma radiation effectively [3]. But these traditional materials have several limitations, such as high costs, heavy weight, and environmental issues associated with their production, handling, and disposal [4].

Recent studies have focused on developing lightweight, economical, and environmentally sustainable alternative materials for radiation shielding. Sedimentary rocks are promising candidate materials because they are naturally abundant and have varied chemical compositions. [6]. Mineral particles and organic matter build up, compact, and solidify over a long period of time to form sedimentary rocks. Sedimentary rocks are suitable for shielding against radiation because they exhibit a wide range of physical and chemical properties, including density, mineral composition, and porosity [7].

Natural rocks are widely used as construction materials because of their availability, durability, and mineral diversity. Concrete is a common composite material composed of cement and aggregate. Changing the aggregate type can affect the radiation attenuation performance of concrete [9]. People know that concrete composite materials are useful and can be used in many different ways. They work well to block radiation and can be used in nuclear power plants, handling radioactive waste, and nuclear medicine [10].

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Mixing cement with sedimentary rock is an interesting way to improve radiation shielding [11]. Researchers have studied cementitious composite materials extensively to determine their mechanical strength, durability, and cost-effectiveness for building [12]. These composite materials can effectively reduce gamma radiation when combined with sedimentary rocks like sandstone, limestone, or shale [13]. Different kinds of composite materials can be shaped into different shapes without losing their strength. This makes them suitable for radiation shielding applications in hospitals, nuclear facilities, radioactive waste management, and industrial radiation areas.

The incorporation of sedimentary rock aggregates can affect the density, porosity, and microstructure of concrete [14], thereby influencing gamma-ray attenuation. Also, these composite materials are relatively inexpensive and can be made locally [15]. This makes them a suitable choice for places where it's difficult to locate or too expensive to buy normal shielding materials. There is a growing need for building materials that are environmentally sustainable and durable, and composite materials are a beneficial choice for that [15]. This is because they can be made and disposed of in an eco-friendly way.

Gamma-ray shielding materials have been widely investigated due to their important role in radiation protection in medical, industrial, and nuclear applications. Conventional shielding materials such as lead and heavy concrete are commonly used because of their high density and effective attenuation capability. However, the use of lead raises environmental and health concerns, while heavy concrete materials often involve higher production costs and limited availability of suitable aggregates.

In recent years, several studies have explored alternative materials for gamma-ray shielding, including natural rocks, industrial by-products, and modified concrete composites. Despite these efforts, few studies have focused on the use of sedimentary rock-based materials as a primary component in developing concrete blocks with enhanced gamma attenuation properties under Co-60 gamma irradiation.

Therefore, the present study aims to investigate the radiation shielding efficiency of concrete blocks produced from sedimentary rock. The rock's elemental composition was analyzed to identify metal oxides that may improve attenuation performance. The novelty of this work lies in the development and evaluation of sedimentary rock-based concrete blocks as a potential alternative shielding material, along with a detailed assessment of their linear attenuation coefficient and radiation protection efficiency under Co-60 irradiation.

This research aims to evaluate sedimentary rock-based concrete blocks as potential alternatives or supplementary shielding materials for applications requiring moderate gamma-ray attenuation and construction compatibility.

MATERIALS AND METHODS

Sample preparation

Concrete blocks were prepared using two types of sedimentary rocks: shale and calcareous rock, in attenuating Co-60 gamma radiation. The study examines key physical properties, including density, compressive strength, and gamma-ray shielding performance. The study focused on two types of sedimentary rocks: shale and calcareous. These rocks were collected from the UNESCO Global Geopark region in Satun Province, Thailand. Then, the rocks were mixed with Portland cement in a 1:2:4 weight ratio (cement: sand: rock). This ratio is commonly used as a nominal concrete mix for general construction, as shown in Figure 1.

Figure 1 Preparation of sedimentary rock-based concrete blocks size 15 cm x15 cm x15 cm.

To ensure the mixture was even, it was mixed thoroughly in a concrete mixer. The mixture was homogenized using a concrete mixer, placed into 15 cm × 15 cm × 15 cm molds, and compacted. The specimens were then cured in water for 28-30 days before density, compressive strength, and gamma-ray shielding tests were performed. A Geiger-Muller detector and counter were used to measure the incident and transmitted count rates. The detector was operated at 960 V. A standard Co-60 source with an activity of 74 kBq was used as the gamma-ray source. The measurements were taken over a period of 300 seconds.

X-ray fluorescence (XRF) analysis was used to determine the concentration of each element in the shale and calcareous samples. This study was done to analyze the elemental composition and compounds of the samples. The Zetium X-ray fluorescence spectrometer (PANalytical, Netherlands) was used to do this analysis. The Empyrean X-ray diffractometer (PANalytical, Netherlands) was also used to analyze

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the samples' crystallographic structures using X-ray diffraction (XRD). The elemental and mineralogical compositions are presented in Tables 1 and 2.

Property analysis

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 is the maximum axial load that concrete can withstand before structural failure, such as cracking or crushing. It serves as a critical parameter in evaluating the material's mechanical performance under compressive stress. For the testing procedure, two steel bearing plates with hardened surfaces were mounted on the testing machine to ensure uniform load distribution. The compressive strength was calculated using Equation (2) [10].

$$\rho = M/V \tag{1}$$

$$F_c = P/A \tag{2}$$

where ρ, M, and V are density, mass and volume, respectively. F_c, P and A are compressive strength, load and loaded area, respectively.

Radiation shielding

The transmitted count rate, C, decreases when gamma radiation passes through a shielding material of thickness x. The reduction in the transmitted count rate is related to the incident count rate and the material's attenuation properties. The attenuation coefficient (μ) can be determined using the following equations (3) and (4) [8, 16]:

$$C = C_0 e^{-\mu x} \tag{3}$$

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

$$C = C_0 e^{(-\frac{\mu}{\rho})(\rho x)} \tag{4}$$

where:

C = transmitted count rate after shielding (counts/s),
C_0 = initial count rate before shielding (counts/s),
x = thickness of the shielding material (cm),
ρ = density of the material (g/cm^3),
μ = linear attenuation coefficient (cm)$^{-1}$,
μ/ρ = mass attenuation coefficient (cm^2/g).

Several factors influence the attenuation coefficient (μ), which describes the ability of a material to attenuate gamma radiation.

The atomic number of a substance primarily determines its efficacy in attenuating radiation. Elements with higher atomic numbers generally increase the probability of gamma-ray interactions within the material. Materials with lower atomic numbers are often less efficient in attenuating gamma photons.

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.

$$MFP = 1/\mu \tag{5}$$

HVL (Half Value Layer) is the thickness required to reduce the transmitted count rate to 50% of the initial count rate.

$$HVL = \ln 2/\mu \tag{6}$$

TVL (Tenth Value Layer) is the thickness required to reduce the transmitted count rate to 10% of the initial count rate.

$$TVL = \ln 10/\mu \tag{7}$$

To provide a quantitative evaluation of the radiation shielding performance, the radiation protection efficiency (RPE) of the developed concrete blocks was calculated using the relation:

$$RPE(\%) = \left(\frac{C_0 - C}{C_0}\right) \times 100 \tag{8}$$

where C_0 and C are the initial count rate before shielding and the transmitted count rate after shielding, respectively. The calculated RPE values indicate the effectiveness of the developed blocks in attenuating Co-60 gamma radiation. Higher RPE values correspond to greater shielding capability.

RESULTS AND DISCUSSION

Figure 2 Experimental setup for gamma-ray shielding measurements using a Co-60 source and a Geiger-Muller detector. The system was used to measure incident and transmitted count rates for evaluating the shielding performance of the concrete samples.

DOI: 10.60101/jarst.2026.263233

Tables 1 and 2 present the elemental oxide composition and mineral phases of the shale and calcareous rocks. Both rock types contained similar major oxide compounds, but their concentrations differed. The five major oxide compounds identified in both rock types were SiO_2 CaO Al_2O_3 K_2O and Fe_2O_3.

The physical and mechanical properties of concrete made from shale and calcareous rock were also investigated. This study examines the physical and mechanical characteristics of concrete produced from sedimentary rocks, specifically shale and calcareous rock. Two key properties were assessed:

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

Table 3 summarizes the density and compressive strength of the concrete blocks. Conventional concrete showed the highest density and compressive strength, followed by shale concrete and calcareous concrete. The highest values were observed in typical construction concrete, with a density of 2.19 g/cm^3 and a compressive strength of 25.45 MPa. Shale-based concrete blocks followed, with a density of 1.99 g/cm^3 and a compressive strength of 13.59 MPa. The lowest values were recorded for concrete made from calcareous, at 1.88 g/cm^3 and 5.21 MPa, respectively.

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	$KAl_2Si_3AlO_{10}(OH)_2$

Table 3 Physical and mechanical properties of sedimentary rock-based concrete blocks.

Concrete type	**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

Table 4 Radiation shielding properties.

Operating Voltage (V)	**Concrete type**	**μ_l $(cm)^{-1}$**	**μ_m (cm^2/g)**	**MFP (cm)**	**HVL (cm)**	**TVL (cm)**
960	Calcareous	0.13	0.07	7.59	5.26	17.47
	Shale	0.18	0.09	5.56	3.86	12.81
	Concrete	0.15	0.07	6.89	4.78	15.88

Table 5 presents the radiation protection efficiency (RPE) of the different concrete types. Shale concrete block is found to exhibit the highest RPE, followed by conventional concrete and calcareous concrete block, respectively.

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Table 5 Radiation shielding efficiency (RPE) of all concrete types.

Concrete type	C_0	C	RPE (%)
Calcareous	6,311.60	874.25	86.15
Shale	6,311.60	425.75	93.25
concrete	6,311.60	716.75	88.64

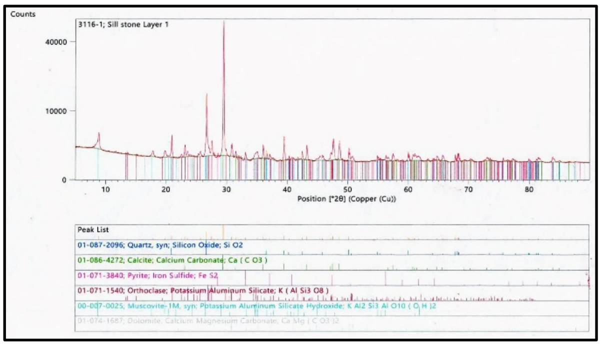

Figure 3 XRD pattern of calcareous is shown, where quartz is identified as the dominant phase, with minor calcite, pyrite, orthoclase, and muscovite.

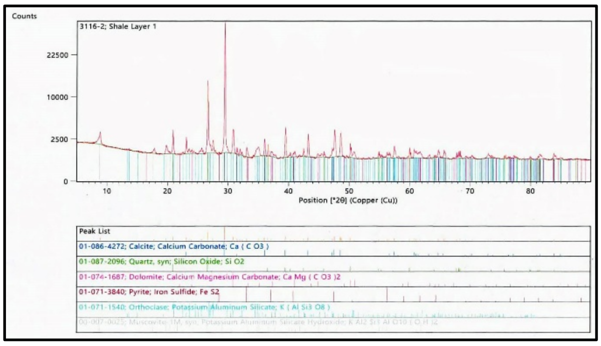

Figure 4 XRD pattern of shale is presented, in which calcite is identified as the dominant phase, with quartz, dolomite, pyrite, and orthoclase detected as minor constituents.

This research examines the efficacy of solid concrete as a gamma radiation shield by incorporating sedimentary rock samples with Portland cement. The analyzed sedimentary rocks consist of two varieties: shale and calcareous, combined with Portland cement, sand, and stone in a ratio of 1:2:4, respectively. The sedimentary rock samples used in the study were sourced from the La-Ngu District in Satun Province, which is part of the Satun Geopark. Next, the effectiveness of the dense concrete in blocking radiation was tested by measuring its ability to reduce radiation with a Geiger-Müller counter and a standard radiation source, Co-60 (shown in figure 2), which had an activity of 74 kBq and a half-life of 5.3 years. The measurement duration was 300 seconds to determine 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. The Co-60 attenuation measurements were done with the source at the bottom of the arrangement. It was set that the source and the concrete block would be 3 cm apart. The detector was just next to the 15 cm thick concrete block. In this setup, the source, sample, and detector were aligned vertically. So, the total distance from the source to the detector (C_0 measurement position) was 18 cm. The average value was utilized in the analysis after each measurement was taken three times for 300 seconds. Background radiation was measured separately and subtracted from all measured count values.

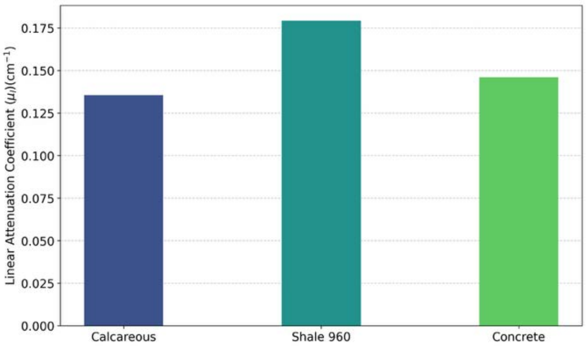

Figure 5 Linear attenuation coefficient (LAC) values of calcareous concrete, shale concrete, and conventional concrete under Co-60 gamma irradiation.

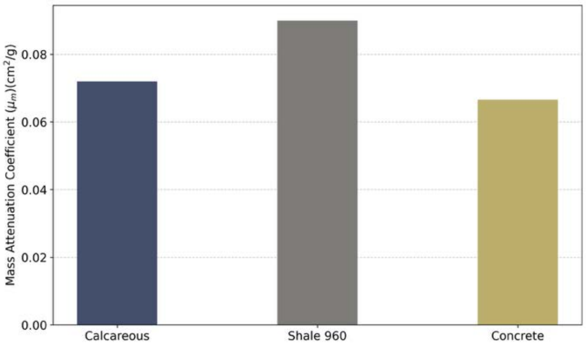

Figure 6 Mass attenuation coefficient (MAC) values of calcareous concrete, shale concrete, and conventional concrete under Co-60 gamma irradiation.

From Figures 5 and 6, the graphs illustrate the relationships between the linear and mass attenuation coefficients for the three concrete types. 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 concrete blocks exhibited the highest linear attenuation coefficient, 0.18 $(\text{cm})^{-1}$. Standard concrete showed a lower linear attenuation coefficient of 0.15 $(\text{cm})^{-1}$, while the calcareous brick blocks had the lowest value of 0.13 $(\text{cm})^{-1}$.

Regarding mass attenuation coefficients (μ_m), shale concrete blocks again demonstrated the highest

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value at 0.09 cm^2/g. Both the calcareous concrete block and standard concrete had equal mass attenuation coefficients of 0.07 cm^2/g.

For the mass attenuation coefficient, shale concrete also showed the highest value of 0.09 cm^2/g, whereas calcareous concrete and conventional concrete showed values of 0.07 cm^2/g. These results indicate that shale concrete had the best shielding performance among the tested materials under the present Co-60 irradiation condition.

The radiation attenuation coefficient indicates how effectively a material reduces radiation count rate. Materials with higher values provide better shielding and are more suitable for radiation protection.

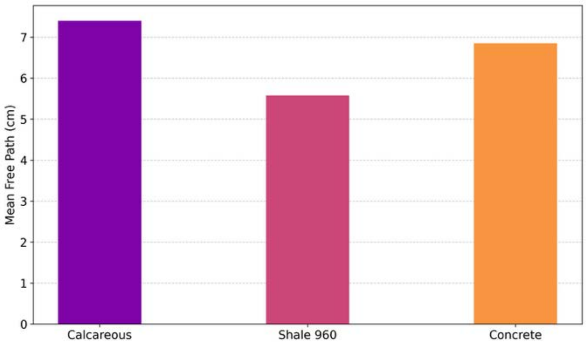

Figure 7 Mean free path (MFP) values of calcareous concrete, shale concrete, and conventional concrete calculated from the linear attenuation coefficient.

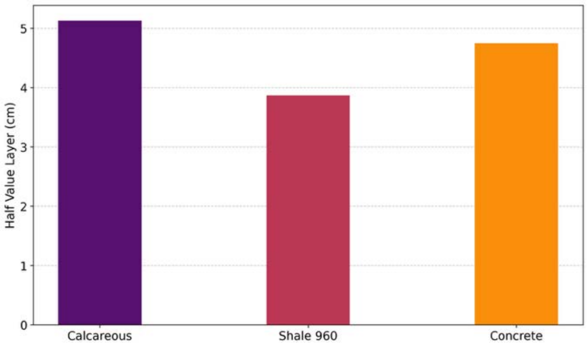

Figure 8 Half-value layer (HVL) values of calcareous concrete, shale concrete, and conventional concrete calculated from the linear attenuation coefficient.

Analysis of radiation shielding parameters in concrete blocks made from shale and calcareous under Co-60 irradiation. Figures 7 through 9 present the graphs of three key thickness parameters-Mean Free Path (MFP), Half Value Layer (HVL), and Tenth Value Layer (TVL). The MFP, HVL, and TVL values for shale concrete were 5.56 cm, 3.86 cm, and 12.81 cm, respectively. For calcareous concrete, the corresponding values were 7.59 cm, 5.26 cm, and 17.47 cm. Conventional concrete showed values of 6.89 cm, 4.78 cm, and 15.88 cm.

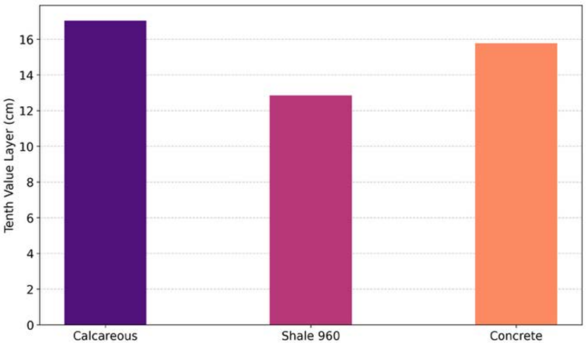

Figure 9 Tenth-value layer (TVL) values of calcareous concrete, shale concrete, and conventional concrete calculated from the linear attenuation coefficient.

All three parameters were calculated according to the formulas provided in equations (5) through (7). The results indicate that shale concrete had the lowest MFP, HVL, and TVL values, suggesting the best attenuation performance among the tested materials. Conventional concrete showed intermediate shielding performance, while calcareous concrete showed the lowest.

Lower MFP, HVL, and TVL values indicate that less material is required to reduce radiation count rate. Thus, materials with lower values are more efficient for Co-60 gamma-ray shielding, particularly in applications where space and material efficiency are important.

Discussion

1. Physical and Mechanical Properties: Density and Compressive Strength. This study examines how sedimentary rocks, specifically shale and calcareous rock, affect the basic properties of concrete. A mix ratio of 1:2:4 (cement: sand: aggregate by weight) was used, following previous studies [17] for general construction. The results show that conventional concrete had the highest density at 2.19 g/cm^3. When shale was used, the density decreased to 1.99 g/cm^3, and the lowest density, 1.88 g/cm^3, was found in the mix with calcareous rock. Compressive strength showed the same pattern. Conventional concrete had a strength of 25.45 MPa, the shale mix had 13.59 MPa, and the calcareous mix had the lowest strength at 5.21 MPa. These results suggest that rock type affects both density and strength. Shale and calcareous rock are more porous than granite, which is commonly used in conventional concrete. Higher porosity leads to lower density and weaker structure. Overall, the results indicate that shale and calcareous concrete blocks have lower mechanical strength than conventional concrete. Therefore, their use should be limited to non-load-bearing or low-load shielding applications unless further mechanical optimization is performed.

2. Effect of Chemical Composition on Radiation Shielding. This study examines how the chemical

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composition of calcareous and shale rocks affects the radiation shielding performance of concrete blocks. Table 1 shows that both rocks contain elements such as iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3), which are known to improve radiation attenuation. As a result, shale-based concrete may provide slightly better shielding than conventional concrete under the present experimental conditions, while calcareous concrete showed lower attenuation performance. Previous research [18] studied gamma-ray attenuation in several types of rock, including granite, sandstone, volcanic rocks, and feldspathic basalt, over an energy range of 122 to 1330 keV. Sandstone, another sedimentary rock, showed attenuation values similar to those reported in this study. The attenuation coefficients were 0.15 cm^{-1} for calcareous rock and 0.18 cm^{-1} for shale. These findings are consistent with previous studies, but this study focuses more clearly on the role of chemical composition. Calcareous rock collected in this study contains higher Al_2O_3 (11.419%) and Fe_2O_3 (10.823%) than shale (3.081% and 3.472%). This difference may explain its better shielding performance, especially at higher energies. Although lead is highly effective for radiation shielding, it is toxic and poses environmental risks. Therefore, safer alternative materials are needed. This study shows that using shale aggregate can slightly improve attenuation performance compared with conventional concrete, although this improvement cannot be attributed solely to density. These materials may serve as supplementary shielding materials in applications where moderate attenuation, low cost, and local availability are important. A related study [10] found that adding siltstone (0-40% by weight) increased concrete's shielding capacity. Higher siltstone content led to higher attenuation coefficients, mainly due to increased electron density, MnO content, density, and effective atomic number. Overall, sedimentary rocks can enhance the radiation shielding performance of concrete.

The results of this study and related literature show that radiation shielding depends on a few key factors. Density is generally an important factor in gamma-ray attenuation. However, the present results show that shale concrete had higher attenuation than conventional concrete despite its lower density. This suggests that chemical composition, mineral phases, aggregate distribution, and internal structure also contributed to the measured shielding performance. Compressive strength should be considered mainly as a mechanical suitability parameter rather than a direct indicator of radiation shielding ability. Chemical composition is also important because materials containing higher atomic-number elements generally exhibit improved gamma-ray attenuation. This study also suggests directions for future work. Adjusting the proportion of sedimentary rock in the mix could help better understand its effect on shielding. It would also be useful to compare different types of sedimentary rocks with other common construction materials. In addition, studying other factors that affect shielding could help further improve radiation-resistant materials [19].

CONCLUSIONS

This study aims to evaluate the effectiveness of concrete blocks made from sedimentary rocks in La-ngu District, part of the Satun UNESCO Global Geopark, for radiation shielding. The study focuses on both physical and mechanical properties, as well as radiation attenuation performance. Concrete blocks in a cubic shape (15 × 15 × 15 cm) were prepared using a 1:2:4 mix ratio of cement, sand, and rock by weight. Radiation levels were measured before and after placing shale and calcareous concrete blocks as shielding materials. Their performance was then compared with conventional concrete under Co-60 gamma irradiation. The results show that conventional concrete had the highest density and compressive strength, followed by shale blocks and then calcareous blocks. Radiation shielding was evaluated 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). Shale blocks provided the best shielding, followed by conventional concrete and calcareous blocks.

DECLARATION OF AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the authors used ChatGPT and QuillBot for language editing and grammar improvement. The authors reviewed and edited the content and take full responsibility for the final manuscript.

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