

Article

Comprehensive Study of Natural Radioactivity in Building Materials: A Case Study in Ica, Peru

Rafael Liza ^{1,2,*}, Patrizia Pereyra ¹, Daniel Muñoz ¹, Victor Viera ¹, Maria Elena López Herrera ¹, Jhonny Rojas ¹, Daniel Palacios ¹, Félix Díaz ³, Nhell Cerna ⁴, Segundo Rojas ⁵ and Laszlo Sajó-Bohus ^{6,7}

¹ Departamento de Ciencias, Sección Física, Pontificia Universidad Católica del Perú, San Miguel 15088, Peru; ppereyr@pucp.edu.pe (P.P.); daniel.munozg@pucp.edu.pe (D.M.); victor.viera@pucp.edu.pe (V.V.); mlopez@pucp.edu.pe (M.E.L.H.); palaciosf@pucp.edu.pe (D.P.)

² Facultad de Ingeniería, Universidad Tecnológica del Perú, Lima 15046, Peru

³ Vicerrectorado de Investigación, Universidad Autónoma del Perú, Lima 15842, Peru; fediazdes@autonoma.edu.pe

⁴ Facultad de Ciencias de la Salud, Escuela Académico Profesional de Medicina Humana, Universidad Privada Norbert Wiener, Lima 15072, Peru

⁵ Escuela de Ingeniería Mecánica Eléctrica, Universidad Señor de Sipán, Chiclayo 14000, Peru; rfloressegundoj@uss.edu.pe

⁶ Laboratorio de Física Nuclear, Universidad Simón Bolívar, Caracas 1080 A, Venezuela; lsajo@usb.ve

⁷ Alba Regia Technical Faculty, Óbuda University, 8000 Szekesfehervar, Hungary

* Correspondence: raliza@pucp.edu.pe

Abstract: This study evaluates radon exhalation rates and assesses the potential radiological risks of external exposure to primordial radionuclides in building materials employed in the Ica region of Peru, particularly those with high uranium content. The radon exhalation rates are currently measured using a combination of a closed chamber and an active monitor. We proposed a novel method that effectively ensured a hermetic seal for the closed chamber and guaranteed that the efficient maintenance of secular equilibrium. The obtained results ranged from below the detection limit (BDL) to a maximum of $52.3 \text{ mBq} \cdot \text{kg}^{-1} \text{h}^{-1}$. Gamma spectrometry was employed to measure the concentrations of radionuclides by utilizing a $3' \times 3'$ NaI detector. The analysis of cement samples revealed a strong positive correlation between the activity concentration of radium and the radon exhalation rate. The activity concentrations for radionuclides varied, with values ranging from BDL to $60.6 \text{ mBq} \cdot \text{kg}^{-1} \text{h}^{-1}$ for ^{226}Ra , BDL to $22.3 \text{ mBq} \cdot \text{kg}^{-1} \text{h}^{-1}$ for ^{232}Th , and BDL to $1074 \text{ mBq} \cdot \text{kg}^{-1} \text{h}^{-1}$ for ^{40}K . These findings contribute valuable insight to decision-making processes in the Peruvian construction industry, particularly regarding material safety and radiological risk management.

Keywords: building materials; natural radioactivity; radon exhalation rate; gamma index



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1. Introduction

Radioactive isotope content in soil, rocks, and building materials is a significant source of environmental radiation that may impact human health [1,2]. Natural internal and external exposure includes the inhalation of radon progeny and gamma radiation from natural radioactive materials (NORMs) [3]. Both indoor and outdoor external exposures are mainly caused by gamma rays emitted by ^{40}K , ^{226}Ra (^{238}U), and ^{232}Th decay series [4,5]. The production of building materials requires the extraction of raw materials from quarries, and the resulting materials, such as bricks, cement, and gypsum, can present variations in their activity concentrations [6]. Known types of ionizing radiation induce damage that alters the molecular structure in living tissues quantified in terms of the effective dose. That takes into account the type of radiation and the sensitivity of different tissues and organs. In short, it is a way of expressing the overall risk of harm from ionizing radiation exposure, to which radioactive elements in construction materials may contribute remarkably; their impact on indoor radiation levels may have a significant human health

risk, although it depends on various factors such as the specific materials used, local geology, and building design. Considering that in Perú, 77% of the population are living in urban areas, and, therefore, a large group of individuals dwells indoors for most of their time, the assessment of radiation emitted by building materials is deemed important for the estimation of potential radiation risks to inhabitants. Monitoring and controlling the activity concentration of radionuclides in building materials is essential, especially in Peru, which to date has relied on international recommendations for regulatory criteria application. This monitoring is valuable to assess the increase in health risk due to relatively high dose rates on long-term radiation exposure. The UNSCEAR report (2000) indicates that radon and its decay products all contribute to an average inhaled dose of 1.26 mSv/y, which is approximately half of an annual effective dose that individuals receive (2.4 mSv/y) from natural sources [7–10]. The International Commission on Radiological Protection (ICRP) and the World Health Organization (WHO) recognize radon problems and external irradiation from building materials as significant factors that affect public health. Radon gas tends to accumulate in low-ventilated spaces such as homes, and it is the most significant contributor to radon levels indoors [11]. This accumulation occurs through a process known as radon exhalation, which begins with radon emanation. Radon emanation is the term used to describe the proportion of radon atoms generated within the structure of a material (soils and/or building materials) that can escape to its pores [12,13]. Radon exhalation from materials depends on intrinsic factors (such as radium content and other physical properties of the material) and extrinsic factors (such as air pressure, temperature, relative humidity, etc.) [14]. Measuring the radon exhalation rate from building materials is essential for monitoring risk levels from a radiological point of view. Ensuring proper ventilation and performing air quality tests are vital for the safety and regulatory compliance of a dwelling. Even for existing buildings, measuring the radon exhalation rate can help determine appropriate mitigation strategies, especially if radon levels are found to be above the standards set by the country's regulatory body. In most cases, building materials have a negligible influence on the radon concentration within residences, although some specific materials can significantly increase indoor radon exposure [15]. In Peru, research on radon exposure has gained significant interest in recent years, thus featuring studies such as [16,17]. However, regulations that limit the dose of exposure to construction materials have not yet been established. In the latest update of the Radiation Protection Regulation, approved by D.S. No. 009-97-EM on 20 May 1997 [C], no reference is made to an action level concerning building materials. This study aims to evaluate and provide experimental data on the natural radioactivity concentration, the radon exhalation rate, and the radiological risk indexes (gamma index, radium equivalent activity, external hazard index, and internal hazard index) of the most common construction materials available commercially in Ica, Peru. With this study, we hope to inform public policy, improve building practices, and increase public awareness of the impact of building materials on radon exposure. This advice should regulate and establish safe limits for radionuclides in building materials for the purpose of efficient supervision and control. Additionally, the effectiveness of one method with three different settings for hermetically sealing the container used in gamma ray spectrometry was also studied.

2. Materials and Methods

2.1. Sample Collection and Preparation

Fourteen samples of building materials were collected from Ica, a city on the Peruvian coast. Samples were prepared for gamma radiation measurements and radon mass exhalation rate determination following the recommended protocol: First, samples were crushed and ground to a 1 mm mesh size, dried at 110 °C for 24 h, then stored in a dry environment until their analysis. Cement and brick samples were obtained from main factories on the Peruvian coast. Aggregates for concrete (sand and rock) and gypsum samples were sourced from geographical areas in the Ica region near locations with potential significant uranium

concentration anomalies [18]. Figure 1 illustrates the extraction areas for gypsum and aggregates, with red circles indicating areas of potential uranium exploitation.

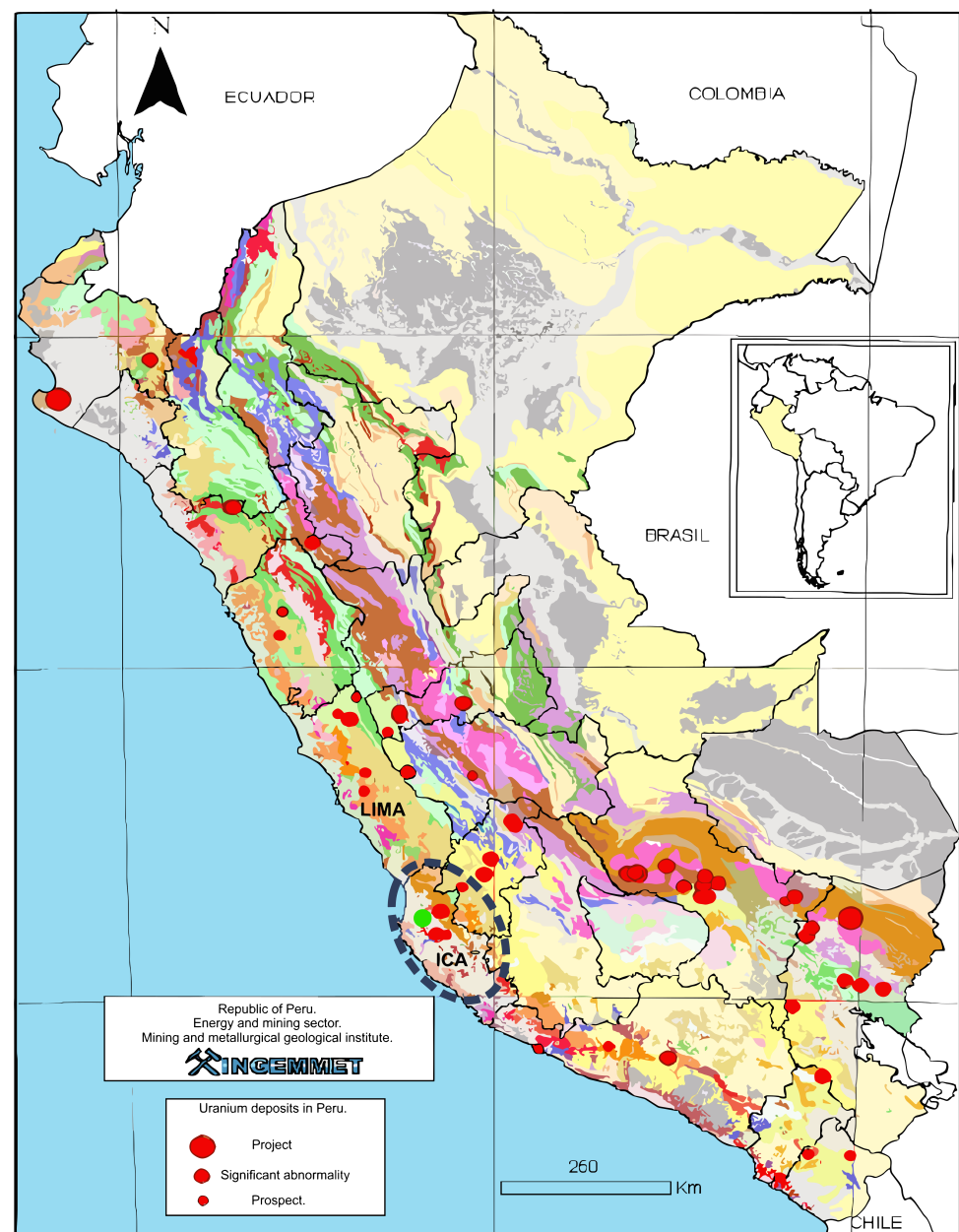


Figure 1. The dotted blue curve indicates the extraction area of natural mineral materials used as raw materials for the construction products evaluated in this study. The green dot points to the primary raw material extraction area for brick production located in Ica, which is southwest of Lima on the central coast of Peru [18].

2.2. Measurement of Natural Radioactivity

Building materials from various manufacturers were collected. Processed samples were subsequently stored in high-density plastic containers with screw caps. Container dimensions were 85.40 mm (external diameter), 139.98 mm (filling height), 1.96 mm (side thickness), and 2.20 mm (base thickness).

A radon leak test was performed to ensure the tightness of the cylindrical plastic container designated for gamma spectrometry measurements. The AlphaGUARD (AG) equipment in diffusion configuration was used as a radon monitor for the leak test, which was conducted inside a methacrylate accumulation chamber (Figure 2D). A uranium ore

sample was placed inside the cylindrical container, and three sealing methods were tested (Figure 2).

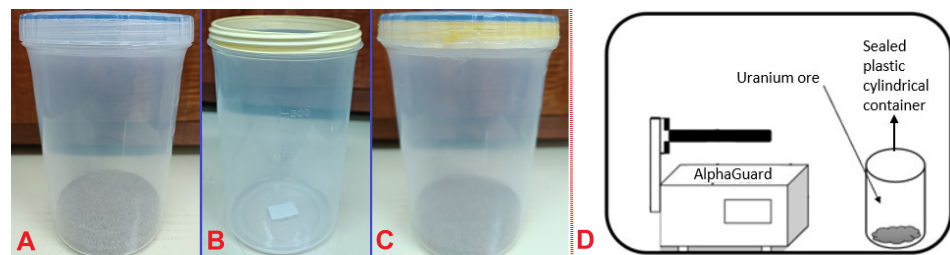


Figure 2. Sealing methods and leakage setup experiment are displayed. On the left, three methods are shown: (A) tightening the screw cap to its limit, (B) using Teflon tape on the thread, and (C) applying high-vacuum grease to the internal contour of the screw cap and covering the thread with Teflon tape. Depicted on the right, (D) is the setup inside the accumulation chamber for measuring container leakage.

Then, the containers were sealed using a method that ensured negligible radon leakage, thereby maintaining secular equilibrium between ^{226}Ra , ^{222}Rn , and their short-lived progeny. Upon achieving secular equilibrium, samples were analyzed using a gamma spectrometer with a $3'' \times 3''$ NaI(Tl) scintillation detector. The detector had a resolution $\leq 8.5\%$ at the 662 keV peaks of ^{137}Cs . Cylindrical plastic containers containing the building material were positioned on a low-density plastic support to standardize measurements. Natural radionuclides ^{40}K , ^{226}Ra , and ^{232}Th were identified through their respective energy peaks, as depicted in Figure 3.

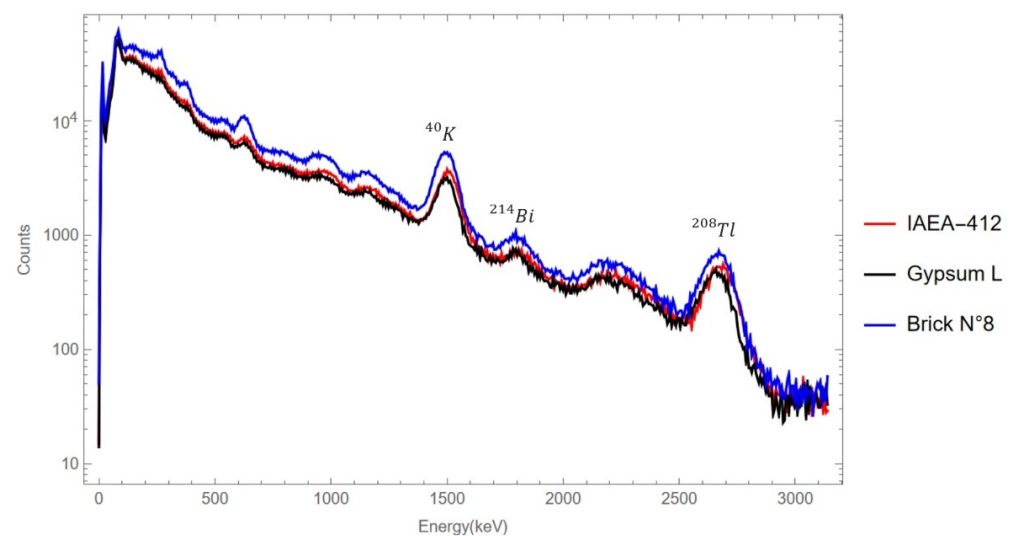


Figure 3. Gamma spectrum of various materials such as gypsum, brick, and the IAEA reference sample.

Gamma spectra for the background, samples, and reference material were acquired over 86,400 s. Full energy peaks were identified, regions of interest (ROIs) were set, and net peak areas were determined using the MAESTRO[®]-32 MCA emulation software (ORTEC/AMETEK, Oak Ridge, TN, USA). The minimum detectable activity (MDA) by the system was estimated at a 95% confidence level. Energy calibration was typically performed using point sources, while efficiency calibration was done using reference materials. However, energy calibration was deemed unnecessary for this study due to the similarity in radionuclides between building material samples and the IAEA-412 (ocean sediment) reference material.

For quantification, an extended relative method of activity determination (ERMAD) similar to that developed by [19] was employed. Instead of full Monte Carlo simulations, in our approach, we used the ETNA (EfficiencyTransfer for Nuclide Activity) software for

the efficiency transfer calculations [20]. This calculation remains consistent as long as there are negligible differences in geometry and composition between them. Summing-up and loss effects by coincidence were not considered because the radionuclides and energies were identical for samples and the reference material; also, the discrepancies in container sizes and volumes occupied by them were minimal.

2.3. Measurement of Radon Mass Exhalation Rates

Determining radon exhalation from surface area of granular materials like soil, rock, or building materials is indeed a complex task due to the multiple factors that can influence the process. It often requires a combination of experimental techniques and modeling approaches to obtain accurate and meaningful results. Their granular nature means that the total exhalation surface is not just the external area, but includes the surfaces of individual particles. Additionally, variability in grain size, shape, and radon content, combined with the presence of intergranular spaces, complicates the measurement process. Therefore, in these cases, it is common to determine the radon exhalation rate as a function of mass [21,22]. In practical scenarios, building materials often degrade into smaller particles, where knowledge of the contribution of various components of building materials to the exhalation rate is required. A custom-designed cylindrical stainless steel accumulation chamber was used, in which the radon leakage rate was negligible, as confirmed in [16]. This chamber was connected to a RAD7 instrument through two valves to form a closed circuit, as shown in Figure 4.

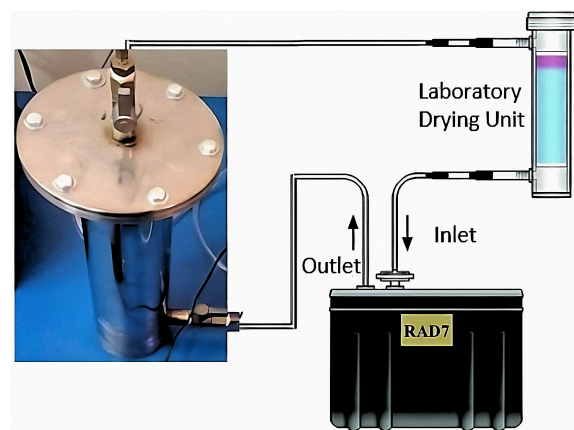


Figure 4. Radon exhalation experimental setup: RAD7 instrument measuring the radon exhalation rate of the sample contained in the stainless steel accumulation chamber.

The radon concentration, denoted as $C(t)$, within the stainless steel accumulation chamber is regulated by the subsequent radon mass transfer equation [23]:

$$\frac{dC(t)}{dt} = \frac{E(t)S}{V_c} - \lambda_{Rn}C - \lambda_L C - \lambda_{BD}C \quad (1)$$

E represents the radon exhalation rate, S represents the exhalation surface area, V_c defines the available volume within the enclosed chamber (including the volume of RAD7 measurement mechanism), λ_{BD} is the back-diffusion rate, λ_L is the radon leak rate, and λ_{Rn} is the radon decay constant. Then, for a short sampling duration, during which the linear growth of radon concentration governs the radon accumulation process within the closed chamber for the first 24 h [24,25], it is possible to consider λ_{BD} and λ_L as negligible [26]:

$$E_M = (m + \lambda_{Rn}C_0) \frac{V_c}{M} \quad (2)$$

Here, m ($\text{Bq} \cdot \text{m}^{-3} \cdot \text{h}^{-1}$) denotes the initial slope of the increase in radon within the accumulation chamber, and M denotes the mass of the sample.

The emanation fraction refers to the proportion of ^{222}Rn atoms generated within the grains of materials that successfully escape the pore space. We can obtain the radon emanation fraction according to the following [27]:

$$f = \frac{E_M}{C_{Ra}\lambda_{Rn}} \quad (3)$$

where f represents the radon emanation fraction, E_M is the radon mass exhalation rate ($\text{Bq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$), and C_{Ra} is the ^{226}Ra concentration ($\text{Bq}\cdot\text{kg}^{-1}$).

2.4. Radiological Parameters

To assess the radiation hazard associated with the building materials used, radiological parameters such as the gamma index (I_γ), the radium equivalent activity (Ra_{eq}), and the external and internal hazard index (H_{ex} and H_{in} , respectively) were determined.

2.4.1. Gamma Index I_γ

The European Commission [28] and several authors [27,29] have proposed some indices to assess the excess gamma radiation from building materials and its relationship to the annual dose rate. In this sense, the gamma index is an important measure for assessing the potential radiological risk posed by the presence of ^{226}Ra , ^{232}Th , and ^{40}K in building materials. It quantifies the cumulative impact of these radioisotopes, thereby providing a comprehensive understanding of their contribution to the annual dose rate and ensuring safety and compliance with health standards.

$$I_\gamma = \frac{C_{226Ra}}{300} + \frac{C_{232Th}}{200} + \frac{C_{40K}}{3000} \quad (4)$$

Building materials with a gamma index equal to or greater than 1 have the capacity to produce annual effective doses exceeding 1 mSv. In contrast, a gamma index value < 1 means that the analyzed material is safe to use [28].

2.4.2. External Hazard Index H_{ex}

The external hazard index H_{ex} estimates the radiation dose expected due to the emitted γ rays by building materials and assumes thick walls without windows and doors [30]. The values of the H_{ex} index can be calculated according to [30] to determine if the radiation hazard is insignificant. It is required that the values be lower than 1.

$$H_{ex} = \frac{C_{226Ra}}{370} + \frac{C_{232Th}}{259} + \frac{C_{40K}}{4810} \quad (5)$$

2.4.3. Internal Hazard Index H_{in}

The internal hazard index (H_{in}) represents the internal exposure to radon and its progeny, in addition to the external hazard index (H_{ex}). According to [31], the maximum permissible concentration for ^{226}Ra needs to be lowered to half of the standard limit ($185 \text{ Bq}\cdot\text{kg}^{-1}$) to mitigate this risk.

$$H_{in} = \frac{C_{226Ra}}{185} + \frac{C_{232Th}}{259} + \frac{C_{40K}}{4810} \quad (6)$$

Keeping the values of this index below 1 is necessary to ensure that radiation risks can be considered negligible.

2.4.4. Absorbed Gamma Dose Rate

The absorbed gamma dose rate, attributed to gamma emissions from radionuclides such as (^{226}Ra , ^{232}Th , and ^{40}K) and NORMs in building materials, was computed using the

methodologies delineated in the European Commission Report [28,32] and is calculated by the following:

$$D_R(\text{nGy}\cdot\text{h}^{-1}) = 0.92C_{Ra} + 1.1C_{Th} + 0.08C_K \quad (7)$$

The global average absorbed gamma dose rate has been reported as $55 \text{ nGy}\cdot\text{h}^{-1}$ [33]:

2.4.5. Annual Effective Doses Rate (AED)

The estimation of annual effective dose rate indoors (AED) incorporates a conversion coefficient from the absorbed dose rate in air (D_R) to an annual effective dose value of $0.7 \text{ Sv}\cdot\text{Gy}^{-1}$. This calculation also factors in an indoor occupancy rate of 0.8, thereby reflecting the typical scenario where individuals reside indoors for approximately 80% of their daily duration, and T denotes the number of hours in a year ($8760 \text{ h}\cdot\text{y}^{-1}$) [7].

$$AED(\text{mSv}\cdot\text{y}^{-1}) = D_R \times T \times 0.8 \times 0.7 \times 10^{-6} \quad (8)$$

3. Results and Discussion

3.1. Testing of Sealing Methods for Cylindrical Plastic Containers Used in Gamma Spectrometry Measurements

The radon concentration was monitored inside a methacrylate accumulation chamber over 15 days to assess the radon leakage from cylindrical plastic containers, with collected data every 15 min. The AlphaGUARD (AG) instrument in the diffusion configuration was used as a radon monitor for the leak test conducted inside the chamber (Figure 2D). The average background radon concentration within the accumulation chamber was $(13.4 \pm 10.2) \text{ Bq}\cdot\text{m}^{-3}$ after being hermetically closed. However, it is important to understand that the thickness of the container and, consequently, the value of its diffusion coefficient are significant factors to consider to prevent leakage through diffusion. Additionally, from other tests conducted in the laboratory, it has been verified that the best seal for the plastic container is achieved when the cap is equipped with an O-ring that ensures an enhanced sealing effect. On the other hand, the accurate measurement of radon at the bottom inside the chamber must take into account that the accumulation chamber, whether made of methacrylate or another material, ensures hermeticity. This is crucial because potential leakage from the container with NORM sample could be so minor that it might be mistaken for the background and lead to an erroneous measurement of leakage from the plastic container.

The results in Figure 5 indicate that radon leakage for the first sealing method was inefficient, since the radon concentration after 15 days was about 97 times larger than the average background radon concentration. The second method yielded a leak of a smaller magnitude; however, it still surpassed the background concentration by a factor of 15. The last sealing method, using Teflon tape and high-vacuum grease, showed a practically hermetic sealing, so it can be considered to be a negligible leak. The average radon concentration in this method was $(17.9 \pm 9.5) \text{ Bq}\cdot\text{m}^{-3}$, which is statistically comparable to the average background radon concentration. This result demonstrates that the third method of sealing is effective for achieving air-tightness of the containers, which has been the subject of numerous studies for measuring ^{226}Ra activity via the gamma ray spectrometry of natural samples [34–36].

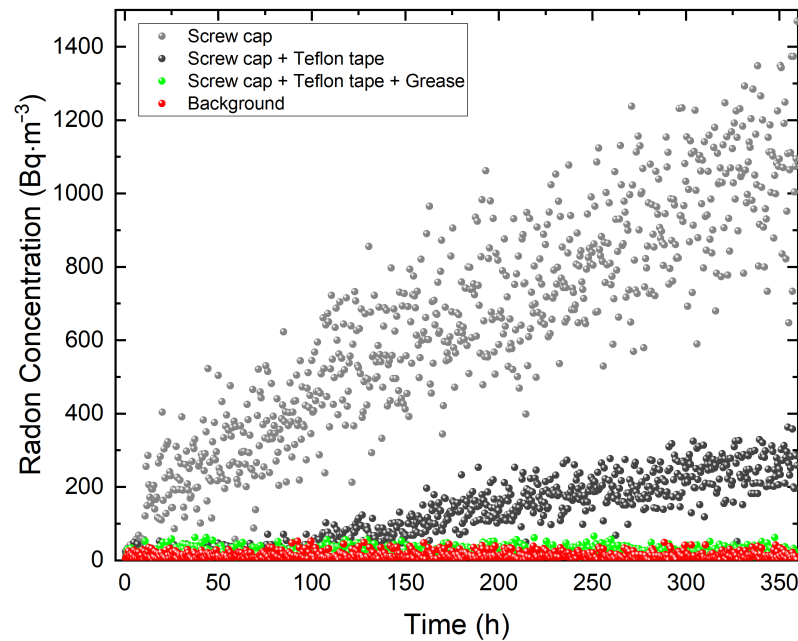


Figure 5. Comparison of the time evolution of radon leakage for the three sealing methods vs. background concentration for the plastic cylindrical containers.

3.2. Activity Concentrations of ^{226}Ra , ^{232}Th , and ^{40}K

The minimum detectable activity (MDA) was determined as $6.6 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{226}Ra , $6.2 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{232}Th , and $32 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{40}K . Table 1 presents the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in $\text{Bq}\cdot\text{kg}^{-1}$. The activity concentrations of ^{226}Ra were found to vary from below the detection limit (BDL) to $60.6 \text{ Bq}\cdot\text{kg}^{-1}$, with an average of $39.4 \text{ Bq}\cdot\text{kg}^{-1}$. For ^{232}Th , it was found in the range of BDL to $22.3 \text{ Bq}\cdot\text{kg}^{-1}$, with a mean value of $13 \text{ Bq}\cdot\text{kg}^{-1}$. For ^{40}K , it was found in the range from BDL to $1074 \text{ Bq}\cdot\text{kg}^{-1}$, with a mean value of $702 \text{ Bq}\cdot\text{kg}^{-1}$.

Table 1. Activity concentration of ^{226}Ra , ^{232}Th , and ^{40}K in pulverized samples of building materials from the Peruvian central coast.

Sample Building Materials *		Activity Concentration ($\text{Bq}\cdot\text{kg}^{-1}$)					
		$C_{^{40}\text{K}}$	Uncertainty ($\pm$)	$C_{^{226}\text{Ra}}$	Uncertainty ($\pm$)	$C_{^{232}\text{Th}}$	Uncertainty ($\pm$)
1	Cement S	405	19	33.3	1.0	7.8	0.8
2	Cement PR	579	27	42.5	1.6	10.8	1.0
3	Cement A	347	16	31.8	1.2	7.8	0.8
4	Cement PV	356	17	43.8	1.7	9.9	1.0
5	Cement Y	821	39	30.0	1.1	9.5	0.9
6	Sand G	924	44	40.9	1.5	15.4	1.5
7	Sand F1	898	43	23.8	0.9	7.7	0.7
8	Sand F2	834	40	42.1	1.6	13.4	1.3
9	Gypsum M	BDL	—	BDL	—	BDL	—
10	Gypsum L	BDL	—	BDL	—	BDL	—
11	Concrete	667	33	44.4	1.7	19.6	1.9
12	Rock	452	21	28.7	1.1	10.8	1.0
13	Brick P8	1067	51	60.6	2.3	21.4	2.1
14	Brick P9	1074	51	50.6	1.9	22.3	2.2

BDL: Below the detection limit. * The letters accompanying the construction materials indicate the brands of these products.

According to UNSCEAR [7], the average global activity levels of ^{226}Ra , ^{232}Th , and ^{40}K have been measured at $35 \text{ Bq}\cdot\text{kg}^{-1}$, $30 \text{ Bq}\cdot\text{kg}^{-1}$, and $400 \text{ Bq}\cdot\text{kg}^{-1}$, respectively. Cement PR, cement PV, sand G, sand F2, concrete, and both brick samples had values slightly higher than the global average for ^{226}Ra . For ^{40}K , only cement A and cement PV had values lower than the global average. On the other hand, the concentration of ^{232}Th in all samples was

always lower than the global average. Gypsum samples had the lowest content of all primary radionuclides, while brick samples had the highest content of ^{226}Ra ($60.6 \text{ Bq}\cdot\text{kg}^{-1}$), ^{232}Th ($22.3 \text{ Bq}\cdot\text{kg}^{-1}$), and ^{40}K ($1074 \text{ Bq}\cdot\text{kg}^{-1}$). The low values of these radionuclides in a macroregion of potential interest for uranium exploitation have shown that they do not automatically imply high concentrations of natural radioactivity in construction materials derived from these areas. Therefore, radiological safety assessments should not be based solely on proximity to uranium-rich zones but on a detailed analysis of specific geological characteristics and direct measurements of radioactivity in building materials. In Figure 6, the averages of the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K for the sample groups of cement, sand, and brick are shown.

3.3. Radon Mass Exhalation Rate and Radon Emanation Fraction

Table 2 summarizes the radon mass exhalation rate for all samples, the slope “ m ”, which represents the linear growth of the radon concentration during the first 24 h of measurement, and the radon emanation fraction f . A good correlation between the total radium and radon mass exhalation rate from cement samples was found as shown in Figure 7 ($R^2 = 0.99$). The radon mass exhalation rate (E_M) varied from $(4.50 \pm 0.42) \text{ mBq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ to $(22.34 \pm 1.30) \text{ mBq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$, with an average value of $(14.01 \pm 1.04) \text{ mBq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$. The average radon mass exhalation rates from the cement and gypsum samples were comparable with the values reported by [37]. The radon exhalation rate from the bricks was higher than from other samples. Gypsum samples did not show significant radon exhalation, which is consistent with the amount of radium in these samples. The radon emanation fraction for each building material was determined using Equation (3). The average values were 5.9% for cement, 8.6% for sand, 7.1% for concrete, 5.1% for rock, and 11.6% for bricks. Figure 7 shows a strong positive correlation (0.99) between the radium activity concentration and the radon exhalation rate for cement samples.

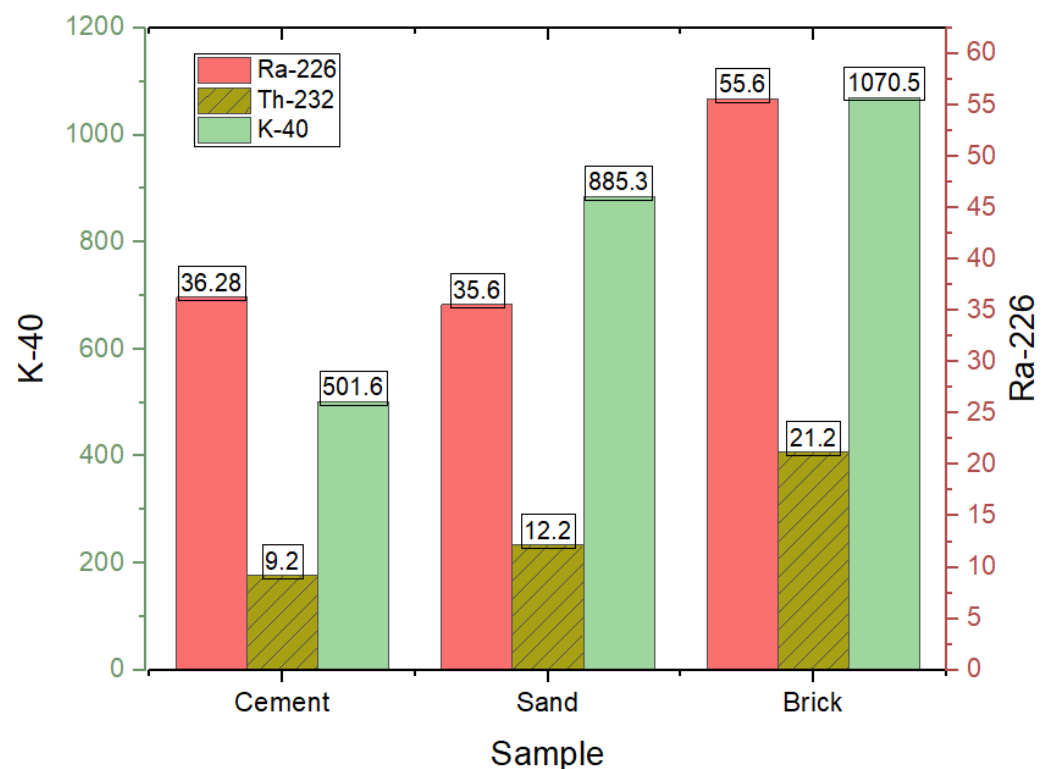


Figure 6. Averages of activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K for cement, sand, and bricks.

Table 2. The radon mass exhalation rate E_M , the initial slope of radon growth in the accumulation chamber m , and the radon emanation fraction f of the building material samples.

Samples	$m \pm \Delta m$ (Bq·m ⁻³ ·h ⁻¹)	$E_M \pm \Delta E_M$ (mBq·kg ⁻¹ ·h ⁻¹)	f (%)
Cement S	0.98 ± 0.07	13.1 ± 0.9	5.2
Cement PR	1.77 ± 0.06	20.8 ± 1.4	6.5
Cement A	1.30 ± 0.07	14.5 ± 1.1	6.0
Cement PV	1.34 ± 0.07	21.0 ± 1.3	6.4
Cement Y	0.93 ± 0.08	12.9 ± 1.1	5.7
Sand G	2.40 ± 0.07	29.8 ± 1.8	9.6
Sand F1	1.44 ± 0.08	13.7 ± 1.1	7.6
Sand F2	1.04 ± 0.07	18.8 ± 1.1	5.9
Gypsum M	0.21 ± 0.09	BDL	BDL
Gypsum L	0.25 ± 0.09	BDL	BDL
Concrete 1	1.75 ± 0.07	23.9 ± 1.5	7.1
Rock C	1.15 ± 0.08	11.1 ± 0.9	5.1
Brick P8	2.45 ± 0.05	52.3 ± 2.4	13.6
Brick P9	1.25 ± 0.06	44.2 ± 2.1	11.6

3.4. Radiological Parameters

The range and average $\pm$ SD values of the gamma index I_γ , external hazard H_{ex} , internal hazard H_{in} , absorbed gamma dose rate D_R , and annual effective dose (AED) are summarized in Table 3. Building materials such as cement, sand, concrete, and gypsum demonstrated gamma index values of ≤ 0.5 , thereby corresponding to the exemption dose criterion of $0.3 \text{ mSv} \cdot \text{y}^{-1}$ and indicating that these types of materials can be considered exempt and can be used without restrictions. On the other hand, the I_γ of the brick samples exceeded this criterion but met the $I_\gamma \leq 1$ criterion, thereby indicating that it did not exceed the $1 \text{ mSv} \cdot \text{y}^{-1}$ and therefore can be used for building construction. The values of the external hazard index H_{ex} and internal hazard index H_{ix} were < 1 for the studied building materials, thus ensuring negligible radiation risk due to their use. Of all the samples, only the brick ones exceed the dose level of $55 \text{ nGy} \cdot \text{h}^{-1}$. Meanwhile, the annual effective doses were below the recommended limit of $1 \text{ mSv} \cdot \text{y}^{-1}$, as suggested by [38].

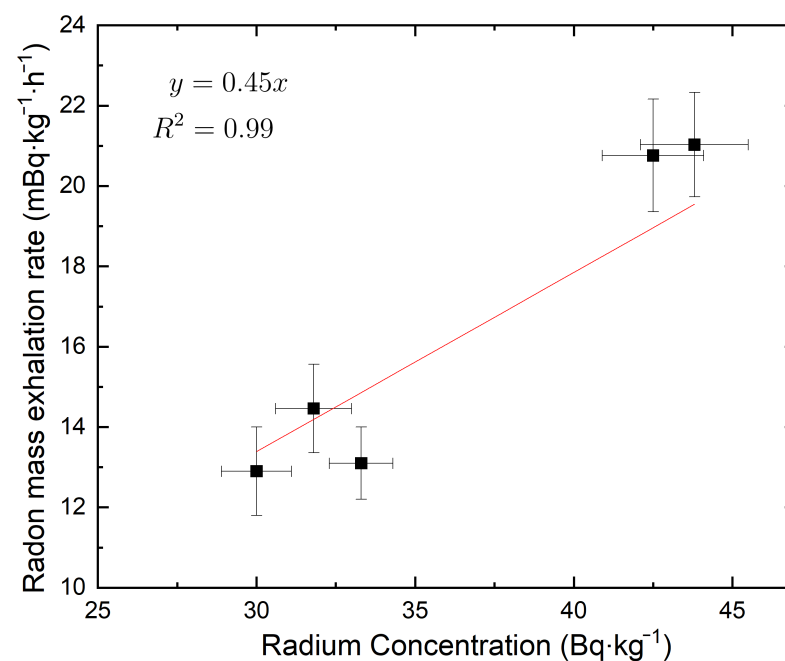
**Figure 7.** Correlation between radon mass exhalation rate and radium concentration of cement samples.

Table 3. Range and average of the different radiological hazard indices for the analyzed building material samples.

Building Material	No.		I_γ	H_{ex}	H_{in}	$D(\text{nGy}\cdot\text{h}^{-1})$	$AED(\text{mSv}\cdot\text{y}^{-1})$
Cement	5	Range	0.26–0.42	0.19–0.29	0.27–0.39	33.87–53.83	0.17–0.26
		Average $\pm$ SD	0.33 ± 0.07	0.24 ± 0.04	0.34 ± 0.05	43.21 ± 8.57	0.21 ± 0.04
Sand	3	Range	0.42–0.52	0.28–0.36	0.35–0.47	53.09–66.73	0.26–0.33
		Average $\pm$ SD	0.47 ± 0.05	0.33 ± 0.04	0.42 ± 0.07	60.71 ± 6.96	0.30 ± 0.03
Gypsum	2	-	-	-	-	-	-
Concrete	1	-	0.52	0.38	0.54	67.37	0.33
Rock	1	-	0.30	0.21	0.29	38.63	0.19
Brick	2	Range	0.64–0.66	0.45–0.47	0.58–0.63	81.63–85.42	0.40–0.42
		Average $\pm$ SD	0.65 ± 0.02	0.46 ± 0.02	0.61 ± 0.03	83 ± 2.68	0.41 ± 0.01

The concentration of ^{226}Ra , ^{232}Th , and ^{40}K varied considerably among countries. It is important to note that the results of the ^{40}K measurements in this study were higher than those of previous works. Radiological H_{in} and H_{ex} indices varied but generally remained at comparable levels. It is also evident that the radiological index values were sufficiently low for gypsum to be considered negligible. The annual effective dose (AED) varied, thereby being the lowest in India and highest in the European Union. The building materials in the present study showed concentrations and AEDs in a medium range compared to other countries, as shown in Table 4. Variations may be due to material features, local geology, and regional technical norms regarding building materials. In addition, countries such as Ecuador and Colombia are carrying out similar work to characterize the natural radioactivity of any building materials in the region [39,40].

Table 4. Measured activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K , calculated indices and AEDs for building materials from various country studies. Average value are provided in parenthesis; notation for no range is (NR) and for unavailable data is (ND).

Country/Reference	Samples	^{226}Ra (Bq·kg ⁻¹)	^{232}Th (Bq·kg ⁻¹)	^{40}K (Bq·kg ⁻¹)	H_{in}	H_{ex}	I_γ	AED (mSv·y ⁻¹)
Hungary [41]	Cement	19–251 (108)	7–25 (17)	36–110 (69)	0.14–1.47 (0.67)	0.09–0.79 (0.38)	0.11–0.98 (0.47)	0.4–1.29 (0.61)
	Brick	31–32 (32)	NR (31)	473–484 (479)	0.39–0.40 (0.40)	0.30–0.31 (0.31)	NR (0.42)	0.49–0.50 (0.50)
	Concrete	9–13 (11)	5–7 (6)	115–169 (142)	0.11–0.12 (0.12)	0.08–0.09 (0.09)	0.11–0.12 (0.12)	0.13–0.15 (0.14)
Iran [42]	Cement	24–38 (31)	11–18 (15)	145–312 (231)	0.24–0.31 (0.27)	0.17–0.20 (0.19)	0.23–0.27 (0.25)	0.28–0.33 (0.30)
	Brick	20–39 (30)	19–34 (28)	167–536 (338)	0.25–0.40 (0.34)	0.18–0.29 (0.26)	0.24–0.39 (0.35)	0.28–0.46 (0.42)
	Gypsum	10–13 (12)	11–17 (14)	66–172 (116)	0.13–0.15 (0.14)	0.10–0.11 (0.11)	0.14–0.15 (0.15)	0.16–0.17 (0.17)
Poland [43–45]	Cement	21.7–75.6 (48)	12.3–47.3 (29)	123–430 (238)	0.35–0.67 (0.51)	0.22–0.44(0.32)	0.33–0.61 (0.47)	0.40–0.74 (0.57)
	Brick	(35.6)	(31.75)	(546.41)	ND	ND	ND	(0.098)
	Sand	2–49(13.5)	2.3–90.0 (9.4)	26–770 (206)	ND	ND	ND	ND
European Union [46–49]	Cement	4–422 (45)	3–266 (67)	4–846 (216)	ND	ND	ND	0.10–3.01 (1.03)
	Brick	2–148 (47)	2–164 (48)	12–1169 (598)	ND	ND	ND	0.15–2.34 (1.01)
	Gypsum	22–668 (318)	5–55 (19)	3–151 (58)	ND	ND	ND	ND
India [50]	Sand	42.6–92.7 (70.81)	45.2–95.6 (77.10)	409.5–777.10 (575.20)	0.61–0.95 (0.80)	0.46–0.70 (0.61)	0.63–0.93 (0.81)	0.10–0.15 (0.12)
	Cement	35.8–69.5 (55.26)	45.0–77.4 (64.61)	55.8–133.3 (97.83)	0.35–0.64 (0.52)	0.28–0.50 (0.41)	0.40–0.71 (0.58)	0.06–0.10 (0.08)
	Brick	36.4–80.9 (63.0)	35.7–73.2 (53.78)	292.6–492.3 (405.02)	0.43–0.81 (0.62)	0.32–0.61 (0.47)	0.41–0.81 (0.61)	0.07–0.13 (0.10)
Brazil [51,52]	Sand	40.3–134.0 (66.7)	15.1–136.0 (40.6)	289.0–1019.0 (647.0)	ND	ND	ND	0.33–1.06 (0.51)
	Cement	NR (62)	NR (59)	NR (564)	ND	ND	ND	ND
	Brick	9.5–70.0 (46.8)	12.7–488.6 (119.9)	149–553 (349)	ND	ND	ND	ND
Argentina [53]	Cement	6.4–34.0(16.3)	11.6–14.1 (13.0)	199–247 (228.8)	ND	ND	ND	ND
	Sand	3.7–45.8 (20.1)	4.7–90.0 (33.8)	85–1168 (522)	ND	ND	ND	ND
	Gypsum	1.6–9.5 (5.8)	<2	6–59.7 (25.7)	ND	ND	ND	ND
Present study	Cement	30–43.8 (36.28)	7.8–10.8 (9.16)	347–821 (501.6)	0.27–0.39 (0.34)	0.19–0.29 (0.24)	0.26–0.42 (0.33)	0.17–0.26 (0.21)
	Brick	50.6–60.6 (55.8)	21.4–22.3 (21.85)	1067–1074 (1070.5)	0.58–0.63 (0.61)	0.45–0.47 (0.46)	0.64–0.66 (0.65)	0.40–0.42 (0.41)
	Concrete	(44.7)	(19.6)	(667)	0.58–0.63 (0.61)	0.45–0.47 (0.46)	0.64–0.66 (0.65)	0.40–0.42 (0.41)
	Sand	23.8–42.1 (35.6)	7.7–15.4 (12.16)	834–924 (885.3)	0.35–0.47 (0.42)	0.28–0.36 (0.33)	0.42–0.52 (0.47)	0.26–0.33 (0.30)

4. Conclusions

The findings of this study offer a comprehensive assessment of the effectiveness of various sealing techniques for cylindrical plastic containers in gamma spectrometry. Among the methods evaluated, the use of Teflon tape combined with high-vacuum grease was proven to be the most efficient, as evidenced by its performance under the minimum detectable

concentration (MDC) criteria set at $44 \text{ Bq}\cdot\text{m}^{-3}$. This novel sealing method is especially effective in maintaining air-tightness, which is crucial to ensure the secular equilibrium between ^{226}Ra and its radon progeny. This equilibrium is vital for the indirect estimation of the radium content in samples. Hermetic sealing is paramount in gamma spectrometry, particularly for measuring the natural radioactivity in naturally occurring radioactive material (NORM) and technically enhanced naturally occurring radioactive material (TENORM); it also directly impacts the precision and reliability of these measurements. Therefore, the results of this study can contribute to determining the best practices for air-tight sealing containers containing construction material, thereby avoiding radon leakage for gamma spectrometry and enhancing the accuracy of radioactivity measurements in various materials, as well as provide a more reliable and safer handling of radioactive substances in research and industrial applications.

The analysis of the measurements of the primary radioisotopes, in various materials (including ^{226}Ra , ^{232}Th , and ^{40}K), reveals important findings about their levels. The content of ^{226}Ra was close to or slightly above the global average. Additionally, the levels of ^{232}Th did not exceed the global average in any sample, while ^{40}K was above the average in two samples. When evaluating radiological risks using indices such as the gamma index (I_γ), only brick samples surpassed the exemption criterion of $0.3 \text{ mSv}\cdot\text{y}^{-1}$, although they remained below the more flexible criterion of $1 \text{ mSv}\cdot\text{y}^{-1}$. This pattern was observed for indices including the external hazard index (H_{ex}) and internal hazard index (H_{in}). Moreover, when calculating gamma dose rates, sand, concrete, and brick exhibited higher levels than the global average of $55 \text{ nGy}\cdot\text{h}^{-1}$, but they were still within the UNSCEAR's recommended limits. The latter could be attributed to the geographical proximity of the raw material extraction areas for brick fabrication to regions known for uranium production. Additionally, the study identified a significant correlation between radon mass exhalation and radon exhalation rates in cement samples, thus suggesting a uniform distribution of ^{226}Ra in the raw material zones used for cement production.

Based on the radiological indices, we conclude that generally all the building materials studied could be considered safe for use, as their values were found to be below the thresholds recommended by the UNSCEAR.

The data from this research are crucial in forming the foundation for national guidelines in Peru. These guidelines aim to regulate radiation exposure from building materials, ensure public safety, and adhere to international standards. In conclusion, this study has significant implications for public health and safety regulations in the construction industry.

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