

Radiation Physics and Engineering 2027; ?(?):?–?

Natural radioactivity in building materials used in Baghdad, Iraq: An environmental risk assessment

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HIGHLIGHTS

- Building materials may include natural radionuclides that cause ionizing radiation.
- Natural radionuclides in Iraqi building materials were evaluated using gamma spectrometry.
- All selected building materials comply with international radiological standards.
- A database of radiation levels in frequently used building materials was established.

ABSTRACT

Natural radionuclides in building materials can expose residents to both internal and external radiation. In the present study, gamma-ray spectroscopy is employed to assess the natural radioactivity of locally available building materials, namely brick, sand, gravel, gypsum, and cement that are frequently used in Baghdad, Iraq. The radiological hazard indices were also computed to evaluate the radiation risks to individuals living in dwellings constructed from the analyzed materials. The activity concentration of Ra-226, Th-232, and K-40 in the analyzed building materials varies from 10.63 ± 0.70 to 33.57 ± 1.09 , 3.80 ± 0.54 to 21.41 ± 1.55 , and 107.90 ± 9.15 to 223.27 ± 12.51 Bq.kg⁻¹, respectively. These results were compared to the global mean values for building materials as well as the results of similar studies conducted in other countries. The radium-equivalent activities of all the analyzed materials are less than the permissible limit of 370 Bq.kg⁻¹, with a range of 24.37-77.17 Bq.kg⁻¹. Similarly, indoor absorbed dose rates (22.59 - 68.42 nGy.h⁻¹) and annual effective doses (0.11 - 0.34 mSv.y⁻¹) of all materials remained below recommended limits of 84 nGy.h⁻¹ and 1 mSv.y⁻¹, respectively. The other radiological hazard indices, including internal hazard index, external hazard index, gamma index, alpha index, and excess lifetime cancer risk, did not exceed the worldwide recommended limits with ranges of 0.09-0.29, 0.07-0.21, 0.09-0.28, 0.05-0.17, and $(0.388 - 1.175) \times 10^{-3}$, respectively. These results indicate that the residents are not exposed to any significant radiation hazards as a result of using the analyzed building materials.

KEYWORDS

Natural radioactivity
Building materials
Gamma spectrometry
Radiological hazards

HISTORY

Received:
Revised:
Accepted:
Published:

1 Introduction

Radionuclides of natural origin are present in all building materials and are considered primary sources of radiation exposure for people living in dwellings (Penabei et al., 2018). In addition to cosmic rays and nuclear medicine, building materials are the main source of radiation exposure for residents, since most individuals spend around

80% of their daily activities indoors. Residents are exposed to radiation via natural radioactivity in building materials, which are mostly caused by U-238, Th-232, and their products as well as K-40 (Majid et al., 2013). Since the decay chain segment beginning with radium (Ra-226) in the U-238 series has the most significant radiological consequences, Ra-226 is often referred to rather than U-238 (Abd El-Mageed et al., 2014). The internal and exter-

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nal radiation exposures of individuals residing in dwellings are affected by the radionuclides present in building materials, with variations influenced by regional geology and the geochemical properties of the materials used (Muntean et al., 2014). Gamma radiation can expose the human body externally. In contrast, the inhalation of radioactive gases, namely radon (Rn-222) and thoron (Rn-220), along with their short-lived byproducts exposes the respiratory tract to alpha particles internally (Turhan, 2008). According to UNSCEAR (UNSCEAR, 2000), the global average value for the gamma absorbed dose rate in the air due to terrestrial sources is 59 nGy.h^{-1} , while the absorbed dose rate in the air inside homes is 84 nGy.h^{-1} . The ratio of indoor to outdoor dose is 1.4, which is attributed to the contribution of construction materials. Individuals exposed to materials containing elevated levels of natural radionuclides may incur significant health risks. Thus, the monitoring of radionuclides in environmental samples is essential for preserving radiation safety (Hassan et al., 2010).

Assessment of radioactivity levels in building materials is a vital step in evaluating potential radiological hazards to human health, especially when they contain primordial radionuclides exceeding normal levels. Therefore, several studies have been conducted to assess the radioactivity of various building materials used in different countries (Abdullahi et al., 2019; El-Taher, 2012; Kobeissi et al., 2013; Lu et al., 2014; Omogunloye et al., 2025; Turhan and Varinlioglu, 2012; Upadhyay et al., 2025). The fast growth of construction activities, due to the increasing urbanization of Iraq, led to the use of a diverse array of local and imported resources for the construction of buildings. The study is performed to determine the activity concentrations of Ra-226, Th-232 and K-40 in various local building materials such as brick, sand, gravel, gypsum and cement. This research aims to establish baseline data on the activity concentration of natural radionuclides in the essential building materials with the objective of evaluating the possible radiological risk to the health of the occupants.

2 Materials and Methods

2.1 Sample collection and preparations

Samples of building materials were collected from commercial suppliers in Baghdad. These included raw materials (sand and gravel) and manufactured products (brick, gypsum, and cement). Although acquired within the capital, the materials were sourced from 17 distinct factories and quarries across 11 Iraqi governorates. To ensure adequate representation of origins, 1-3 samples were collected per factory or quarry source, for a total of 32 samples. Table 1 summarizes all collected samples with their material types, names of origin and the corresponding governorates. During sample preparation, the materials were crushed, ground, and sieved to a particle size of $\leq 0.1 \text{ mm}$. The samples were then dried in an oven at 105°C for 5 hours to ensure the moisture was effectively removed. Samples were stored in 750 mL Marinelli beakers. Before the gamma

spectrometric analysis, the containers were sealed hermetically and stored for one month to reach radioactive equilibrium between Ra-226 and Ra-228 and their short-lived decay products (Alsaffar and Kabir, 2024).

Table 1: Types and origins of building materials collected in this study.

Material	Name/ Origin	Governorate	No. of samples
Brick	Nahrawan	Baghdad	3
	Aziziyah	Wasit	2
	Hillah	Babylon	2
Cement	Al-Jesr	Sulaymaniyah	1
	Bazyani	=	1
	Mass	=	1
	Tasluja	=	1
	Al-Qa'im	Anbar	1
	Kubaisa	=	1
	Najmat Al-Samawa	Muthanna	1
Gravel	Balad Ruz	Diyala	2
	Sidor	=	2
	Nibai	Saladin	2
Gypsum	Fallujah	Anbar	3
	Najaf	Najaf	2
Sand	Karbala	Karbala	2
	Najaf	Najaf	2
	Nibai	Saladin	2
	Amarah	Maysan	1

2.2 Analytical technique

A high-purity germanium (HPGe) detector with a coaxial configuration (Model: GX4020, Canberra Inc.) was employed to analyze the gamma spectra of the samples. This detector has a resolution of 2.0 keV for the 1332.2 keV gamma-ray emission of Co-60, and its relative efficiency is 40%. The detector was coupled to a high-voltage power supply (DSA 1000), a shaping amplifier, and a preamplifier to transform event energy into a pulse height spectrum. A personal computer is employed to process the information from the MCA card. Spectra of gamma rays were displayed and analyzed with the Genie 2000 software. The detector crystal was cooled to around 77 K using liquid nitrogen to minimize thermal noise and leakage current. The background level of radiation in the surrounding areas is reduced by shielding the detector with 10 cm of lead on all sides. Standard gamma point sources (Am-241, Cs-137, Co-60, and K-40) were used to conduct energy calibration for the detector. The efficiency calibration of the system is performed using mixed calibration standard sources, MBSS2, within an optimal geometry for sample counting. These sources cover an energy range of 59.5-1836.1 keV, with a composition of Am-241, Cd-109, Co-57, Ce-139, Sn-113, Sr-85, Cs-137, Co-60, and Y-88. At a specific gamma-ray energy E , the full-energy peak efficiency $\varepsilon(E)$ of the detector can be calculated using the following equation (Almayahi et al., 2012):

$$\varepsilon(E) = \frac{N}{T \cdot p_{\gamma} \cdot A} \quad (1)$$

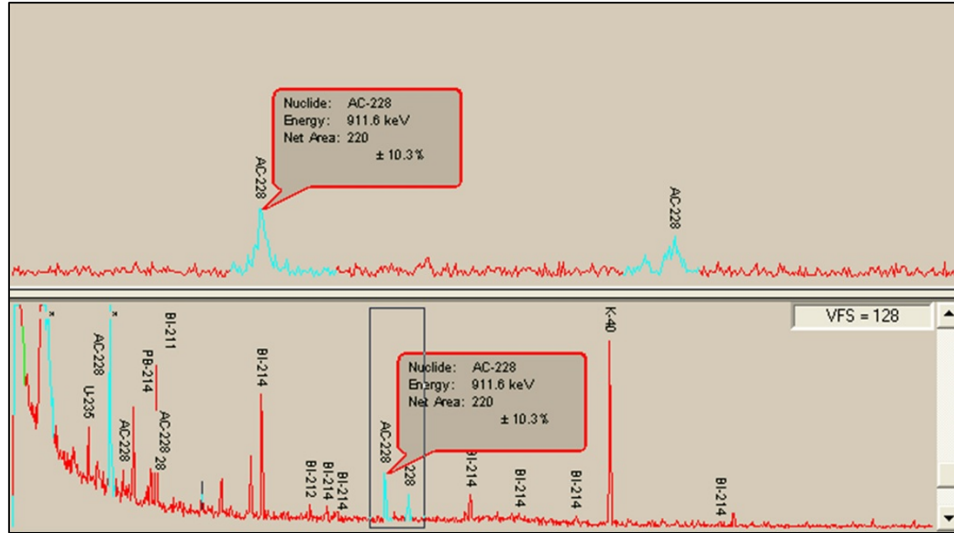


Figure 1: Gamma-ray spectrum of the brick sample (Nahrawan - Br1).

where N denotes the net count above the background. T is the duration of counting (s). p_γ is the probability of gamma emission at a particular energy E . A is the activity of the source (Bq) at the time of measurement, and is expressed by $A = A_0 e^{-\lambda t}$, where A_0 is the initial activity, λ is the decay constant which is expressed as the ratio of $\ln 2$ to $T_{1/2}$, $T_{1/2}$ is the half-life of the radionuclide, and t is the decay time.

The photopeaks of 351.9 keV from Pb-214 and 609.3 keV from Bi-214 were used to calculate the Ra-226 concentration. The photopeaks of 238.6 keV from Pb-212 and 911.6 keV from Ac-228 were employed to determine the concentration of Th-232. The gamma transition at 1461.8 keV was used to calculate the K-40 content. The samples were counted for 18,000 s, and the photopeaks corresponding to Ra-226, Th-232 decay products, and K-40 were analyzed from the spectra. The background spectrum obtained during the same counting time is subtracted from the respective sample count rate to determine the net count rate under the specific photopeaks. Subsequently, the activity concentration of the aforementioned radionuclides was estimated by analyzing their energy photo peaks. Figure 1 illustrates the energy photo peaks in the spectrum of a sample analyzed during this research.

2.3 Radioactivity measurements

The following equation was employed to determine the activity concentration of each radionuclide (Hassan et al., 2010):

$$C = \frac{N}{T \cdot P_\gamma \cdot \varepsilon(E) \cdot M} \quad (2)$$

where C represents the activity of the isotope in Bq.kg⁻¹. N denotes the net count above the background. T is the duration of counting (s). P_γ is the probability of gamma emission at a certain energy. $\varepsilon(E)$ is the absolute efficiency of the detector and M is the net weight of the sample (kg). The minimum detectable activity (MDA) at a 95% con-

fidence level was determined as follows (Abdullahi et al., 2019):

$$MDA = \frac{2.71 + 4.66\sqrt{N_b}}{T \cdot P_\gamma \cdot \varepsilon(E) \cdot M} \quad (3)$$

where N_b denotes the background counts within the region of interest. For a 750 g dry-weight sample and a 18,000 s counting time, the minimum detectable activities (MDAs) were determined to be 1.43, 1.36, and 19.27 Bq.kg⁻¹ for Ra-226, Th-232, and K-40, respectively.

2.4 Calculations of radiological hazards

2.4.1 Radium equivalent activity

The distribution of natural radionuclides is not uniform for the samples under investigation. Therefore, a standard radiological index was developed to assess the actual level of Ra-226, Th-232, and K-40 activity in the samples, as well as the radiation hazards associated with these radionuclides. Typically, this index is referred to as radium equivalent (Ra_{eq}) activity and is quantified as follows (Turhan, 2008):

$$Ra_{eq} = C_{Ra} + \left(\frac{10}{7}\right)C_{Th} + \left(\frac{10}{130}\right)C_K \quad (4)$$

where C_{Ra} , C_{Th} , and C_K denote the specific activity of Ra-226, Th-232, and K-40, respectively, in Bq.kg⁻¹. The definition of Ra_{eq} makes the assumption that the gamma-ray dose rate of 10 Bq.kg⁻¹ of Ra-226, 7 Bq.kg⁻¹ of Th-232, and 130 Bq.kg⁻¹ of K-40 is equivalent. For safe use, the maximum value of Ra_{eq} in building materials and products must be less than 370 Bq.kg⁻¹, which is equivalent to maintaining the external dose below 1.5 mSv.y⁻¹ (UNSCEAR, 2000).

2.4.2 Absorbed dose rate

The indoor air absorbed dose rate (D_{in}) due to the gamma radiation emitted by Ra-226, Th-232, and K-40 in building materials was calculated using the formula given by

EC (EC, 1999). In this report, the standard room model was applied to calculate the dose conversion coefficients. The room dimensions are 4 m × 5 m × 2.8 m. The density of the buildings is 2,350 kg m⁻³ and the thickness of the walls, floor, and ceiling is 20 cm. The coefficients for Ra-226, Th-232 and K-40 are 0.92, 1.1 and 0.08 nGy.h⁻¹ per Bq.kg⁻¹ respectively. The indoor air absorbed dose rate was obtained using the following formula (Krstić et al., 2007; Lu et al., 2013):

$$D_{in} \text{ (nGy.h}^{-1}\text{)} = 0.92C_{Ra} + 1.1C_{Th} + 0.08C_K \quad (5)$$

where C_{Ra} , C_{Th} , and C_K stand for the activity concentrations of Ra-226, Th-232, and K-40 in Bq.kg⁻¹, respectively. The average global absorbed dose rate was 84 nGy.h⁻¹ due to natural sources indoors, as reported by UNSCEAR (UNSCEAR, 2000).

2.4.3 Annual effective dose equivalent

The annual effective dose equivalent (AEDE) should be calculated in order to assess the effects of such absorbed dose rates on health. As suggested in UNSCEAR (UNSCEAR, 2000), the conversion coefficient from the absorbed dose in air to the effective dose (0.7 Sv.Gy⁻¹) and the indoor occupancy factor (0.8) imply that 80% of the time is spent indoors. The annual effective dose equivalent is calculated by the following formula (Mavi and Akkurt, 2010):

$$AEDE = D_{in} \text{ (nGy.h}^{-1}\text{)} \times 8760 \text{ (h)} \times 0.8 \times 0.7 \text{ (Sv.Gy}^{-1}\text{)} \times 10^{-6} \quad (6)$$

According to UNSCEAR (UNSCEAR, 2000), the average dose value from external terrestrial radiation is 0.48 mSv.y⁻¹.

2.4.4 Internal and external hazard indices

The internal hazard index (H_{in}) quantifies the internal health hazard that is associated with radon and thoron inhalation as well as the deposition of their short-lived progenies on the lung tissues. This index is given by the following equation (Pourimani et al., 2023):

$$H_{in} = \left(\frac{C_{Ra}}{185} \right) + \left(\frac{C_{Th}}{259} \right) + \left(\frac{C_K}{4810} \right) \quad (7)$$

where C_{Ra} , C_{Th} , and C_K denote the activity concentration of Ra-226, Th-232, and K-40, respectively, in Bq.kg⁻¹. For materials containing radionuclides, this index must be less than unity to ensure the safe use of building materials in residential dwellings.

The index due to external gamma radiation (H_{ex}) is another indicator that might be used to calculate the external hazards of radiation exposure. In addition to external risk assessment, the Hex index is crucial for limiting the external gamma radiation exposure in building materials to a maximum of 1.5 mSv.y⁻¹. The following relationship may be used to calculate the external hazard index (Muntean et al., 2014):

$$H_{ex} = \left(\frac{C_{Ra}}{370} \right) + \left(\frac{C_{Th}}{259} \right) + \left(\frac{C_K}{4810} \right) \quad (8)$$

The external index should exhibit a value that is lower than unity to ensure the lowest possible risk. Nevertheless, the maximum value of H_{ex} must be less than 370 Bq.kg⁻¹ in order for Hex to have a maximum value under the unit.

2.4.5 Gamma index

Since the building materials under consideration are widely utilized in the construction industry, the gamma index (I_γ) is another useful index that may be used to assess the fulfillment of the dose criteria. The gamma index was calculated in accordance with the EC (EC, 1999) proposal. The EC recommends that building materials be exempt from radioactivity constraints if the annual excess effective dose from gamma radiation does not exceed 0.3 mSv.y⁻¹. This relationship can be defined as follows:

$$I_\gamma = \left(\frac{C_{Ra}}{300} \right) + \left(\frac{C_{Th}}{200} \right) + \left(\frac{C_K}{3000} \right) \quad (9)$$

For the gamma radiation of construction materials, EC establishes two dosage criteria: an upper limit of 1 mSv.y⁻¹ and an exemption threshold of 0.3 mSv.y⁻¹. Considering the exemption level of 0.3 mSv.y⁻¹, the I_γ values for bulk materials (e.g., brick and cement) should be below 0.5; however, if the maximum limit of 1 mSv.y⁻¹ is taken into account, the I_γ values for these materials should be below 1 (Muntean et al., 2014).

2.4.6 Alpha index

The alpha index has been suggested to evaluate the exposure level arising from radon inhalation from building materials. The following formula was used in the current investigation to calculate the alpha index (Kayakökü et al., 2016; Medhat, 2009):

$$I_\alpha = \left(\frac{C_{Ra}}{200 \text{ Bq.kg}^{-1}} \right) \quad (10)$$

where C_{Ra} represents the activity concentration of Ra-226 in Bq.kg⁻¹. There is a possibility that the radon exhalation from a building material could lead to an internal radon concentration exceeding 200 Bq.m⁻³ if the Ra-226 activity concentration of the material exceeds 200 Bq.kg⁻¹. Conversely, it is improbable that the radon exhalation from the building materials could result in internal radon concentrations exceeding 200 Bq.m⁻³ when the Ra-226 activity concentration is below 100 Bq.kg⁻¹ (Righi and Bruzzi, 2006; Viruthagiri et al., 2013). The maximum permissible activity concentration of Ra-226 in building materials is 200 Bq.kg⁻¹, with a recommended exemption threshold of 100 Bq.kg⁻¹, as suggested by the radiation protection authorities in Denmark, Finland, Iceland, Norway, and Sweden (Åkerblom et al., 2000). A maximal threshold of 200 Bq.kg⁻¹ for Ra-226 can be specified when I_α is equal to 1.

Table 2: Activity concentration of Ra-226, Th-232 and K-40 in building materials.

Material	No. of samples	Activity (Bq.kg^{-1})								
		Ra-226			Th-232			K-40		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Brick	7	21.19 $\pm$ 1.28	44.01 $\pm$ 1.91	29.36 $\pm$ 1.38	16.02 $\pm$ 1.28	31.15 $\pm$ 1.77	21.41 $\pm$ 1.55	145.20 $\pm$ 9.63	312.23 $\pm$ 16.45	223.72 $\pm$ 12.51
Cement	7	24.18 $\pm$ 0.81	40.47 $\pm$ 1.42	33.57 $\pm$ 1.09	5.21 $\pm$ 0.49	13.34 $\pm$ 1.02	8.73 $\pm$ 0.67	93.10 $\pm$ 8.04	203.54 $\pm$ 13.06	133.73 $\pm$ 9.93
Gravel	6	8.31 $\pm$ 0.59	14.01 $\pm$ 1.02	11.60 $\pm$ 0.77	6.20 $\pm$ 0.42	12.06 $\pm$ 1.02	8.45 $\pm$ 0.64	84.85 $\pm$ 8.56	199.38 $\pm$ 13.70	131.95 $\pm$ 9.85
Gypsum	5	7.66 $\pm$ 0.60	13.97 $\pm$ 0.91	10.63 $\pm$ 0.70	3.02 $\pm$ 0.47	5.13 $\pm$ 0.88	3.80 $\pm$ 0.54	90.10 $\pm$ 8.02	125.41 $\pm$ 11.81	107.90 $\pm$ 9.15
Sand	7	8.24 $\pm$ 0.63	17.16 $\pm$ 1.40	12.35 $\pm$ 0.93	7.01 $\pm$ 0.83	10.05 $\pm$ 1.63	8.30 $\pm$ 1.00	109.01 $\pm$ 8.01	369.01 $\pm$ 16.14	221.94 $\pm$ 11.96
Mean			19.50 $\pm$ 0.97			10.14 $\pm$ 0.88			163.78 $\pm$ 10.68	

2.4.7 Excess lifetime cancer risk

In order to predict the probability that an individual will develop cancer during their lifetime due to exposure to natural ionizing radiation in the building materials, the estimated values of the annual effective doses were employed to calculate the indoor excess lifetime cancer risks (ELCR), as given by the following relation (Kayo et al., 2021):

$$ELCR = AEDE (\text{Sv.y}^{-1}) \times HL \times RF \quad (11)$$

where HL is the typical human lifetime, which is 70 years, RF is the fatal risk factor, which is equal to 0.05 Sv^{-1} according to the ICRP (ICRP, 2008), and AEDE is the annual effective dose equivalent for particular samples under evaluation. Based on a maximum allowable annual effective dose of 1 mSv.y^{-1} , the acceptable threshold for this index cannot exceed 3.5×10^{-3} .

3 Results and discussions

3.1 Evaluation of natural radioactivity

Table 2 summarizes the activity concentrations and mean values of Ra-226, Th-232, and K-40 in the analyzed building materials. The activity concentration of Ra-226 in the samples was determined to range from 10.63 ± 0.70 to $33.57 \pm 1.09 \text{ Bq.kg}^{-1}$. The maximum value was observed for cement, whereas the minimum value was found for gypsum. For Th-232, the activity concentration in the samples ranged from 3.80 ± 0.54 to $21.41 \pm 1.55 \text{ Bq.kg}^{-1}$. The highest value was determined for brick, and the lowest value was noted for gypsum. The activity concentration of K-40 in the samples ranged from 107.90 ± 9.15 to $223.72 \pm 12.51 \text{ Bq.kg}^{-1}$. The maximum and minimum values were observed for brick and gypsum, respectively. The levels of Ra-226, Th-232, and K-40 in the evaluated building materials are shown in Figs. 2, 3 and 4, respectively. The concentrations of these radionuclides differ among various building materials. The geological structure of building materials, which varies depending on the location, may contribute to variations in radiation levels. The worldwide average concentrations of Ra-226, Th-232, and K-40 in building materials are 50, 50, and 500 Bq.kg^{-1} , respectively, as per UNSCEAR (UNSCEAR, 1993). In this study, the mean concentrations of the aforementioned radionuclides in building materials are 19.50 ± 0.97 , 10.14 ± 0.88 , and $163.78 \pm 10.68 \text{ Bq.kg}^{-1}$, respectively. Thus, the concentrations of the specific radionuclides in building materials are consistent with the globally suggested levels and do not provide a substantial risk to human health.

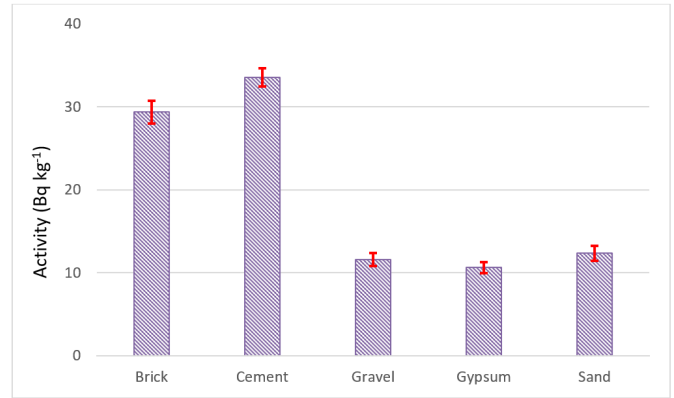
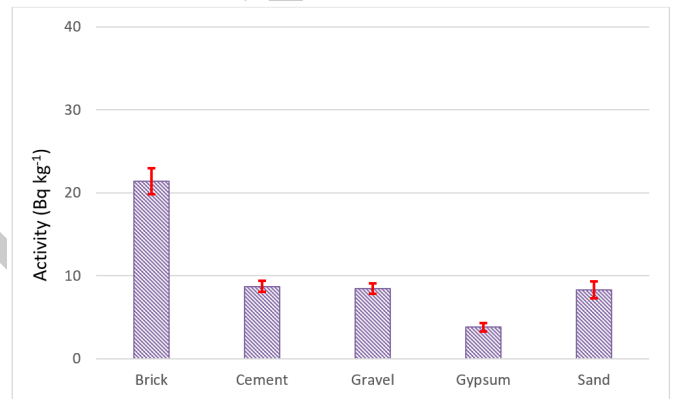
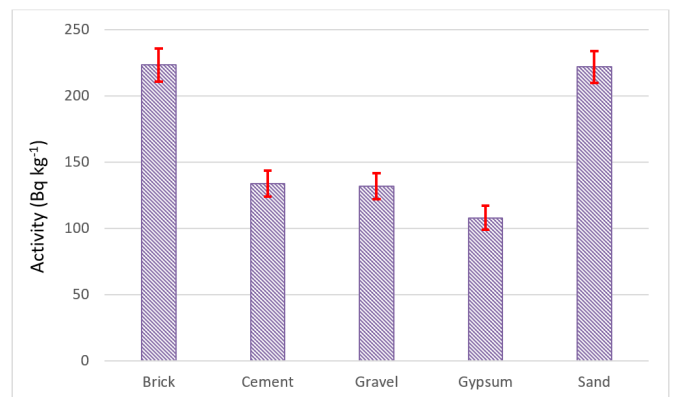
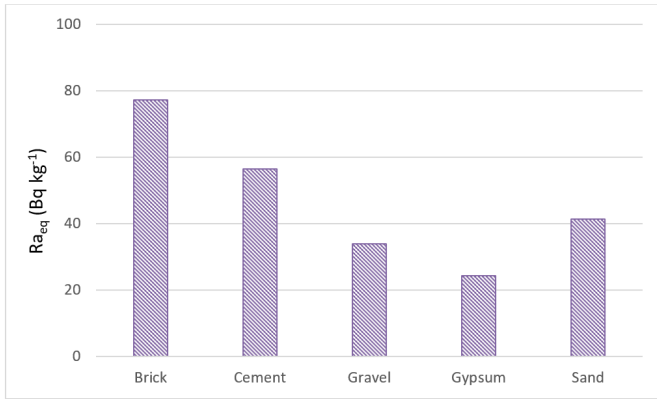
**Figure 2:** Activity concentration of Ra-226 in building materials.**Figure 3:** Activity concentration of Th-232 in building materials.**Figure 4:** Activity concentration of K-40 in building materials.

Table 3: Radium equivalent activity, indoor absorbed dose rate, annual effective dose equivalent, internal and external hazard indices, gamma and alpha indices, and excess lifetime cancer risks for building materials.

Material	Ra_{eq} (Bq.kg ⁻¹)	D_{in} (nGy.h ⁻¹)	$AEDE$ (mSv.y ⁻¹)	H_{in}	H_{ex}	I_γ	I_α	$ELCR \times 10^{-3}$
Brick	77.17	68.42	0.34	0.29	0.21	0.28	0.15	1.175
Cement	56.35	51.19	0.25	0.24	0.15	0.20	0.17	0.879
Gravel	33.84	30.52	0.15	0.12	0.09	0.12	0.06	0.524
Gypsum	24.37	22.59	0.11	0.09	0.07	0.09	0.05	0.388
Sand	41.31	38.25	0.19	0.14	0.11	0.16	0.06	0.657
Mean	46.61	42.19	0.21	0.18	0.13	0.17	0.10	0.724

**Figure 5:** Radium equivalent activity for building materials.

3.2 Evaluation of radiological hazard indices

The radium equivalent activity (Ra_{eq}), indoor absorbed dose rates (D_{in}), annual effective dose equivalent ($AEDE$), internal hazard index (H_{in}), external hazard index (H_{ex}), gamma index (I_γ), alpha index (I_α), and excess lifetime cancer risk ($ELCR$) for building materials are all calculated in Table 3. The radium equivalent activity levels derived from the present investigation vary from 24.37 to 77.17 Bq.kg⁻¹. The brick showed the highest value, whereas the gypsum showed the lowest. In Fig. 5, the radium equivalent activity values are depicted. The radium-equivalent activity values in any of the evaluated samples do not surpass the prescribed limit of 370 Bq.kg⁻¹ by UNSCEAR (UNSCEAR, 2000). The average indoor absorbed dose rate for the investigated building materials is 42.19 nGy.h⁻¹, ranging from 22.59 nGy.h⁻¹ in gypsum to 68.42 nGy.h⁻¹ in brick, as presented in Table 3. However, the absorbed dose rates for all evaluated building materials remained below the worldwide average of 84 nGy.h⁻¹ (UNSCEAR, 2000). According to the calculations, the annual effective dose for the evaluated building materials varies between 0.11 and 0.34 mSv.y⁻¹. Brick had the highest value of the materials, and gypsum had the lowest. The average annual effective dose of building materials was 0.21 mSv.y⁻¹ which is less than the UNSCEAR (UNSCEAR, 2000) recommended level of 0.48 mSv.y⁻¹. The average internal hazard index of the building materials was 0.18, ranging from 0.09 to 0.29. The highest value was for brick while the lowest value was for gypsum. However, the internal hazard index values are less than unity for all samples and are within the globally recommended range. The mean of the external hazard index was 0.13,

with values ranging from 0.07 to 0.21. Among the materials, brick showed the highest values, and gypsum showed the lowest. Nevertheless, the results of the external hazard index for all building materials are below unity and satisfy the globally recommended standards. The average gamma index value for building materials was 0.17, ranging from 0.09 to 0.28. The highest value was observed in the brick, while the lowest was observed in the gypsum. As shown in Table 3, all gamma index values are less than 0.5, which corresponds to an annual effective dose of 0.3 mSv.y⁻¹ (EC, 1999). The average alpha index for building materials was 0.10, with values ranging from 0.05 to 0.17. The cement demonstrated highest alpha index value, while the gypsum showed the lowest. However, the alpha index values for all evaluated building materials are less than unity, falling well within internationally recommended safety. The range of excess lifetime cancer risk ($ELCR$) for all samples is $(0.388 - 1.175) \times 10^{-3}$, with a mean of 0.724×10^{-3} . Among the samples, brick had the highest values, and gypsum had the lowest. The $ELCR$ results suggest that the probability of cancer incidence among residents using the analyzed building materials is almost insignificant.

Table 4 presents a comparison of radionuclide activity results from this investigation with those from other countries. This comparison clearly indicates that there are considerable variations in the levels of radioactivity present in building materials among various countries. The differences in the activity concentrations of Ra-226, Th-232 and K-40 in building materials are directly related to the variations in the dominant bedrock geology and rock types of Iraq and other countries. The geology across most of Iraq consists primarily of alluvial sediments, clays, and limestones associated with the Tigris and Euphrates river basins. The sedimentary rocks created by physical and chemical weathering instead of magmatic crystallization are characterized by low to moderate baseline levels of the primordial radionuclides (Ra-226, Th-232 and K-40) (Hussian and Ali, 2024). Other regions are characterized by granitic bedrock or soils, such as those reported in China (Yang et al., 2005) and India (Sandesh et al., 2022). These areas are naturally enriched in high concentrations of Ra-226, Th-232 and K-40 during igneous crystallization, which may be the reason for the significantly higher radioactivity in local granitic gravels and clay bricks compared to their sedimentary counterparts in Iraq.

According to Table 4, the mean radium equivalent activity (Ra_{eq}) value observed for Iraqi brick samples (77.17 Bq.kg⁻¹) is closest to the values measured in Egypt (82

Table 4: Comparison of activity concentrations between the building materials under investigation and those from other countries.

Material	Country	Ra-226	Th-232	K-40	Ra_{eq}	Ref.
Brick	Algeria	47±6	35±4	425±3	130±7.8	(Amrani and Tahtat, 2001)
	Chad	56.31	15.92	283.33	100.89	(Penabei et al., 2018)
	China	47.3	61.6	821.8	199	(Lu et al., 2013)
	Cuba	57±16	12±10	857±759	140±68	(Flores et al., 2008)
	Egypt	30±4.5	21±2.4	289±10.5	82	(Medhat, 2009)
	India	63.74	38.6	313.71	143.094	(Raghu et al., 2017)
	Iran	37.0±1.5	12.2±0.7	851.4±15	120.00	(Mehdizadeh et al., 2011)
	Jordan	7.48±0.18	1.23±0.26	6±0.14	9.70	(Sharaf and Hamideen, 2013)
	Pakistan	23 ± 7	35 ± 11	431 ± 131	106 ± 30	(Faheem et al., 2008)
	Turkey	21	29	534	104	(Tufan and Dişci, 2013)
	Syria	38	29	331	105	(Othman and Mahrouka, 1994)
	Baghdad, Iraq	29.36±1.38	21.41±1.55	223.27±12.51	77.17	Present work
Cement	Algeria	41±7	27±3	422±3	112±8.2	(Amrani and Tahtat, 2001)
	Chad	5.85	5.73	81.31	20.31	(Penabei et al., 2018)
	China	63.3	68.7	303.4	185	(Lu et al., 2013)
	Cuba	23±7	11±3	467±85	74±12	(Flores et al., 2008)
	Egypt	48±5.8	22±3.9	220±8.9	96	(Medhat, 2009)
	India	35.73	37.75	159.83	102.01	(Raghu et al., 2017)
	Iran	39.6±1.4	28.9±0.9	290.8±12	103.32	(Mehdizadeh et al., 2011)
	K.S.A	38.4±3.8	45.3±1.2	86±4	108	(El-Taher, 2012)
	Pakistan	25 ± 10	37 ± 9	245 ± 95	69 ± 25	(Faheem et al., 2008)
	Turkey	29	25	147	77	(Tufan and Dişci, 2013)
	Syria	29	29	80	47	(Othman and Mahrouka, 1994)
	Baghdad, Iraq	33.57±1.09	8.73±0.67	133.73±9.93	56.35	Present work
Gravel	Algeria	24±3	10±1	259±2	58±3.7	(Amrani and Tahtat, 2001)
	Chad	3.29	1.51	52.7	9.51	(Penabei et al., 2018)
	China	37.2	48.5	678	159	(Lu et al., 2013)
	Cuba	20±3	13±9	134±70	49±12	(Flores et al., 2008)
	Egypt	12	5±1.8	159±3.8	31	(Medhat, 2009)
	Iran	20.4±1.2	6.3±0.3	450.7±14	64.11	(Mehdizadeh et al., 2011)
	K.S.A	14.7±1.3	24.2±1.7	195±6	65.7	(El-Taher, 2012)
	Baghdad, Iraq	11.60±0.77	8.45±0.64	131.95±9.85	33.84	Present work
Gypsum	Egypt	39±3.2	25±1.4	226±2.9	92	(Medhat, 2009)
	India	41.88	57.39	527.533	164.56	(Raghu et al., 2017)
	Iran	8.1±0.9	2.2±0.2	116.2±12	20.19	(Mehdizadeh et al., 2011)
	K.S.A	33.28±4.7	47.2±2.8	88±4.4	107	(El-Taher, 2012)
	Kuwait	2.81±0.4	0.55±0.1	13.9±1	17.4	(Bou-Rabee and Bem, 1996)
	Turkey	8	11	35	27	(Tufan and Dişci, 2013)
	Syria	14	2	31	19	(Othman and Mahrouka, 1994)
	Baghdad, Iraq	10.63±0.70	3.80±0.54	107.90±9.15	24.37	Present work
Sand	Algeria	12±1	7±1	74±7	28±7.1	(Amrani and Tahtat, 2001)
	Chad	3.99	3.08	158.04	20.56	(Penabei et al., 2018)
	China	13.1	19	851.7	106	(Lu et al., 2013)
	Cuba	17±4	16±6	208±104	55±14	(Flores et al., 2008)
	Egypt	33±3.7	27±4.2	385±8.9	101	(Medhat, 2009)
	India	90.27	101.67	280.71	257.273	(Raghu et al., 2017)
	K.S.A	12.3±2.3	24.2±1.3	195±4	60.35	(El-Taher, 2012)
	Pakistan	20 ± 9	29 ± 8	383 ± 142	91 ± 29	(Faheem et al., 2008)
	Turkey	17	19	152	55	(Tufan and Dişci, 2013)
	Syria	9	2	21	13	(Othman and Mahrouka, 1994)
	Baghdad, Iraq	12.35±0.93	8.30±1.00	221.94±11.96	41.31	Present work

Bq.kg⁻¹) and slightly lower than the values measured in Chad (100.89 Bq.kg⁻¹), Turkey (104 Bq.kg⁻¹) and Syria (105 Bq.kg⁻¹). The mean Ra_{eq} of Iraqi cement was 56.35 Bq.kg⁻¹, which is within the range reported for Syria (47 Bq.kg⁻¹), Pakistan (69 Bq.kg⁻¹) and Cuba (74 Bq.kg⁻¹). The Ra_{eq} level for gravel in Iraq (33.84 Bq.kg⁻¹) is close to reported values for Egypt (31 Bq.kg⁻¹), Cuba (49 Bq.kg⁻¹) and Algeria (58 Bq.kg⁻¹). The low Ra_{eq} value

of the Iraqi gypsum (24.37 Bq.kg⁻¹) is comparable with the results of the neighboring countries, such as Kuwait (17.4 Bq.kg⁻¹), Syria (19 Bq.kg⁻¹), Iran (20.19 Bq.kg⁻¹), and Turkey (27 Bq.kg⁻¹). The Ra_{eq} for Iraqi sand (41.31 Bq.kg⁻¹) is in agreement with the lower range concentrations reported in Algeria (28 Bq.kg⁻¹), Cuba (55 Bq.kg⁻¹) and Turkey (55 Bq.kg⁻¹). Overall, building materials in Iraq exhibit relatively low Ra_{eq} values that are consistent

with data from regional Middle Eastern neighbors, mainly Syria, Egypt, Kuwait and Turkey, as well as some international studies from Cuba and Algeria.

4 Conclusions

The activity concentrations of Ra-226, Th-232, and K-40 in common building materials used in Baghdad, Iraq, were evaluated by gamma-ray spectrometry. The concentrations of the aforementioned radionuclides in the analyzed materials are lower than the worldwide averages for building materials (50, 50, and 500 Bq.kg⁻¹, respectively) as reported by UNSCEAR (UNSCEAR, 1993). On average, cement had the highest concentration of Ra-226, while brick had the highest levels of Th-232 and K-40. The activity concentration of gypsum was the lowest among the three radionuclides. Although brick and cement samples had higher activity concentrations than other studied materials, all their radiological hazard indices, such as radium equivalent activity, absorbed dose rate, annual effective dose, internal and external hazard indices, gamma and alpha indices, and excess lifetime cancer risk, were below international safety limits. Thus, their application as building materials does not require any radiological restrictions. The results, therefore, show that the analyzed building materials meet the standards of radiation safety and do not represent a significant health hazard for the inhabitants. While the dataset of this study does not contain a full inventory of all materials and commercial brands, the results provide a representative baseline screening of building materials in the Iraqi market. Future studies should involve sampling of other materials and brands to enhance regional radioecological evaluations.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

Funding

The authors declare that no funds, grants, or other financial support were received during the preparation of this manuscript.

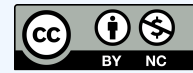
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To cite this article:

M.S. Al-Ghuraibawi, I.S. Mustafa, N.M. Ahmed, F. Mizban, Sh.K. Al-attafi. Natural radioactivity in building materials used in Baghdad, Iraq: An environmental risk assessment. *Radiation Physics and Engineering*, In Press.

DOI:

To link to this article:

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