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Assessment of Exposure Due to Technologically Enhanced Natural Radioactivity in Various Samples of Moroccan Building Materials

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Abstract

The aim of our present work is to measure the specific activities of the radionuclides ^{226}Ra, ^{232}Th, ^{40}K and the exhalation rates in terms of area and mass of ^{222}Rn in some samples of building materials commonly used in Morocco in order to evaluate the radiological risk caused by natural radioactivity. To this end, the analyses were carried out, using two nuclear techniques, namely high resolution gamma spectrometry and alpha dosimetry based on the use of LR115, on 50 samples collected from large commercial suppliers in Morocco. The results of these analyses show that the average specific activities of ^{226}Ra, ^{232}Th and ^{40}K in these materials vary from 9 to 52 Bq/kg, 3 to 63 Bq/kg and 68 to 705 Bq/kg respectively. These activities remain within the permissible limits of 35 Bq/kg, 30 Bq/kg and 370 Bq/kg respectively, with the exception of a few samples of red brick, gray cement, ceramic and granite. The activity of the radium equivalent (Ra_{eq}), the internal (H_{in}) and external (H_{ex}) hazard indices, the absorbed dose rate ($\dot{D}$), the total annual effective dose ($\dot{E}_{tot}$), the excess lifetime cancer risk (ELCR) as well as volumic activities, exhalation rates in terms of area (E_S) and mass (E_M) are calculated for the samples analyzed in this work in order to assess the radiological risks resulting from the use of these materials in various construction activities. It seems that the values of these indices vary from 19 to 196 Bq/kg, 0.08 to 0.67, 0.05 to 0.53, 9 to 91 nGy/h, 0.05 to 0.56 mSv/y, 0.19×10^{-3} to 1.96×10^{-3}, 72 to 350 Bq/m^3, 56 to 273 mBq·m^{-2}·h^{-1} and 3 to 15 mBq·kg^{-1}·h^{-1} respectively. The lowest values are identified for gypsum, while the highest are attributed to granite. All of the obtained results of these indices respect the permissible limits except for the Ra_{eq} in some granite samples, the ELCR index in all samples except gypsum and the radon volumic activity in some gray cement samples, ceramic and granite. As a result, the different types of building materials analyzed in our work do not present a health risk to the public and can be used in various construction activities, with the exception of a few samples of red brick, gray cement, ceramic and granite. The choice of the use of red brick, gray cement and ceramic should be monitored and adapted according to the criteria of the limitation of the doses whereas the use of the granite must be moderate in order to limit over time the health risk which increases with the duration of exposure of humans to these building materials.

Keywords

Building Materials, Natural Radioactivity, Radionuclide, Radon Exhalation Rate, Radium Equivalent, Annual Effective Dose

1. Introduction

Since 1970, indoor air quality has become a major preoccupation for public health, due in part to the time we spend indoors (on average 87%) [1] and the high diversity of the airborne contaminants found therein, biological, chemical and physical [2]. Building materials represent a continuous source of natural radiation because it is produced from rocks and soils that contain radioactivity at varying levels depending on their origins [3] [4]. Radioactive exposure to building materials can be divided into internal and external exposure. This latter is due to gamma radiation from the different radionuclides of the three radioactive decay chains (^{238}U, ^{235}U, ^{232}Th) and ^{40}K. Internal exposure is due to the inhalation of radon and its progeny. ^{222}Rn is now considered the main source of human exposure to natural radiation [5]. It is a naturally occurring radioactive gas from the disintegration of ^{226}Ra, itself part of the ^{238}U disintegration chain. When disintegrating, radon emits alpha particles and generates solid progeny, which are also radioactive (polonium, bismuth, lead, etc.). These descendants continue to disintegrate and emit radiation, in particular of the α and β type. Once inhaled, it dissipates their energies into the surrounding lung tissue, thereby damaging the lung cells, and altering their atomic structure. In 1987, the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) recognized radon as a pulmonary carcinogen for humans [5].

In Morocco, the building materials industry is currently experiencing significant growth. A growing demand means the creation or expansion of several production units (cement works, brickworks, etc.). In recent years, the building industry uses a raw material, large quantities of waste with a technologically enhanced natural radioactivity (coal ash, phosphogypses, etc.) [6] [7] [8]. The use of these materials in building materials has economic advantages but may affect the doses received by humans inside buildings as has been demonstrated in various studies [9] [10] [11]. Hence, the knowledge of the natural radioactivity in buildings materials from the three radioactive decay chains (^{238}U, ^{235}U, ^{232}Th) and ^{40}K, is necessary and important for the assessment of the radiological impact on the public and the environment. To evaluate the radiological impact of these materials on the population and the environment, and through these specific activities, we calculated several radiological risk indices, namely radium equivalent (Ra_{eq}), internal (H_{in}) and external (H_{ex}) hazard indices, total annual effective dose ($\dot{E}_{tot}$) as well as the excess lifetime cancer risk (ELCR).

2. Materials and Methods

2.1. Sample Preparation

The building materials samples to be analyzed are collected from large and important commercial suppliers in Morocco. As regards sand, samples are taken from seven different quarries in the Doukkala region. Before any analysis and to obtain homogeneous samples, these building materials are dried in an oven at 40˚C for 24 hours and then ground and sieved through a 100 µm mesh screen. The screened samples are packaged in radon-tight containers for at least 4 weeks to establish the secular equilibrium corresponding to seven half-lives of ^{222}Rn.

2.2. Spectroscopic Analysis

The measurement of the natural radioactivity in the prepared samples is carried out by gamma ray spectrometer using the Broad Energy Germanium detector (BEGe) at Pluridisciplinary Institute Hubert Curien in Strasbourg, France. It is a planar type Hyper-Pure Germanium HPGe detector associated with a set of electronic modules for shaping the pulses, amplifying and storing the pulses delivered during the passage of the gamma rays through the detector. Its energy measurement range is 30 to 3000 keV with a resolution of 0.633 keV to 122 keV and from 1.934 keV to 1332 keV [12].

As regards the energy and efficiency calibration of the BEGe detector, a multi-energy certified standard is analyzed under the same conditions and geometry as the samples studied. This standard contains several γ-emitting radionuclides such as ^{241}Am (60 keV), ^{109}Cd (88 keV), ^{57}Co (122, 136 keV), ^{139}Ce (165 keV), ^{51}Cr (320 keV), ^{113}Sn (391 keV), ^{85}Sr (514 keV), ^{137}Cs (661 keV), ^{88}Y (898, 1836 keV) and ^{60}Co (1173, 1332 keV). Samples of building materials are packaged in SG50 geometry and counted for 172.800 seconds. The treatment of the amplitude spectra is carried out using automatic analysis software Genie 2000 [12] allowing to give directly the mass activity of each radioelement present in the sample.

The volumetric activities and the exhalation rate in terms of area and mass of the radon in the prepared samples are carried out using the alpha dosimetry. For this purpose, several pieces of 2 × 2 cm^2 of Solid State Nuclear Track Detector (SSNTD) LR115 type 2 non strippable, Kodak brand 12 µm thick, are exposed in sealed cylindrical "cans" of 5.5 cm diameter and 9.5 cm height by 50 g of each sample of building materials. After two months of irradiation, the LR115 are chemically treated in a 2.5 N sodium hydroxide solution during 100 min at a temperature of 60˚C. The developed films are read using an optical microscope. The density of traces per unit area and per unit time in LR115 and the volume activity of radon A_V^{Rn} are determined according to [13].

3. Results and Discussions

3.1. Specific Activities

The specific activities of the radionuclides ^{226}Ra, ^{232}Th and ^{40}K are calculated by gamma spectrometry, after establishment of the secular equilibrium, in the various samples of building materials using the following ratios of energies:

- ^{214}Pb (295 keV and 352 keV) and ^{214}Bi (609 keV, 1120 keV and 1764 keV) for ^{226}Ra;
- ^{228}Ac (911 keV and 969 keV) and ^{212}Pb (239 keV) for ^{232}Th;
- ^{40}K (1461 keV) from the emission intensity line 10.55%.

Figure 1 shows the minimum, the maximum and the average specific activities of ^{226}Ra, ^{232}Th and ^{40}K radionuclides measured in the different types of

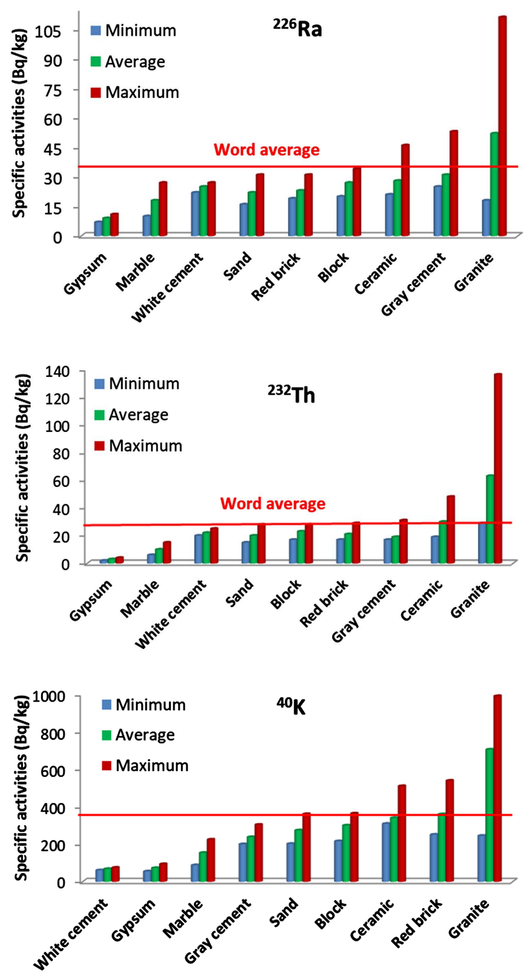

Figure 1. Specific activities of different radionuclides in Moroccan building materials.

building materials. It can be seen that the contribution of the activity of the ^{40}K is much greater than that contributed by the ^{238}U and the ^{232}Th. It should also be noted that the activity of ^{232}Th in each sample is less than that of ^{226}Ra except for the red brick, ceramic and granite samples.

From these values, it results that the low average specific activities are recorded in the gypsum for the radionuclides ^{226}Ra and ^{232}Th, and in the white cement for the ^{40}K with average activities of the order of 9 Bq/kg, 3 Bq/kg and 68 Bq/kg respectively. The highest average specific activities for the ^{226}Ra, ^{232}Th and ^{40}K radionuclides are recorded in the granite and are respectively of the order of 52 Bq/kg, 63 Bq/kg and 705 Bq/kg. All the specific activities of the measured ^{226}Ra, ^{232}Th and ^{40}K are within the permissible limits of 35 Bq/kg, 30 Bq/kg and 370 Bq/kg [4], respectively, with the exception of a few samples of red brick, gray cement, ceramic and granite. Therefore, the choice of materials for building constructions should be monitored and adapted according to the criteria of the limitation of doses.

In **Table 1**, and for comparison with our results, the specific activities of natural radionuclides are grouped together in samples of building materials in Morocco and some other countries. Overall, the specific activities obtained in this study are comparable to those found in other countries, with the exception of a few activities that are remarkably higher than ours.

3.2. Radium Equivalent

Due to the non-uniform distribution of natural radionuclides in building material samples, the radiological index radium equivalent Ra_{eq} is generally represented as the sum of the specific activities of ^{226}Ra, ^{232}Th and ^{40}K based on the assumption that 10 Bq/Kg of ^{226}Ra, 7 Bq/kg of ^{232}Th and 130 Bq/kg of ^{40}K would produce the same dose rate of gamma radiation. This is the most widely used index for radiological risk assessment. It is calculated using the following equation [5] [28]:

$$Ra_{eq} = A_{226\text{Ra}} + 1.43 A_{232\text{Th}} + 0.077 A_{40\text{K}} \quad (1)$$

where $A_{226\text{Ra}}$, $A_{232\text{Th}}$ and $A_{40\text{K}}$ are the specific activities in (Bq/kg) of ^{226}Ra, ^{232}Th and ^{40}K in the samples analyzed.

In **Table 2**, the mean values of the radium equivalent Ra_{eq} varying from 19 to 196 Bq/kg, which are still below the permissible limit of 370 Bq/kg [5], are grouped together for the samples analyzed. We note that the lowest value is found in the gypsum, while the highest is in the granite.

From these results, we can consider that these building materials do not present a significant radiological hazard to the population and can be used in various construction activities. However, it should be noted that the Ra_{eq} values vary considerably in the same type of building materials and may in some cases exceed the permissible limit. This is the case of granite where the maximum value of the equivalent radium Ra_{eq} is of the order of 382 Bq/kg. The use of the latter in construction activities must be moderate.

Table 1. Comparison between the specific activities of building materials in a few countries.

Samples	Country	Specific activities (Bq/kg)			References
		^{226}Ra	^{232}Th	^{40}K	
Gray Cement	European Union	45	31	216	[14]
	China	21.7 ± 1.92	22 ± 0.89	181 ± 3.75	[15]
	Turkey	39.9 ± 18.0	26.4 ± 9.8	316.5 ± 88.1	[16]
	South Korea	34.5 ± 1.7	19.4 ± 1.5	241 ± 6.7	[17]
	Morocco	31 ± 5	19 ± 3	238 ± 29	Present Work
White Cement	Egypt	17.45 ± 2.33	8.44 ± 1.49	4.09 ± 4.72	[18]
	Turkey	32.8 ± 5.1	16.3 ± 7.6	99.2 ± 31.8	[16]
	Qatar	18.9 ± 0.5	4.9 ± 0.5	62.9 ± 22.6	[19]
	Serbia	18 ± 3	12 ± 5	55 ± 37	[20]
	Iraq	49.577 ± 0.865	16.74 ± 2.28	32.6 ± 4.31	[21]
	Morocco	25 ± 4	22 ± 3	68 ± 8	Present Work
Gypsum	Saudi Arabia	33.28 ± 4.7	47.2 ± 2.8	88 ± 4.4	[22]
	Italy	6 ± 5	2 ± 2	32 ± 43	[23]
	Iran	8.1 ± 0.1	2.2 ± 0.1	116 ± 11	[24]
	Morocco	9 ± 1	3 ± 1	73 ± 9	Present Work
Red brick	Iran	37.0 ± 1.5	12.2 ± 0.7	851 ± 15	[24]
	Albania	33.4 ± 6.4	42.2 ± 7.6	644.1 ± 64.2	[25]
	Egypt	23.06 ± 2.60	23.11 ± 2.99	447.84 ± 10.16	[18]
	Morocco	23 ± 4	21 ± 3	360 ± 41	Present Work
Block	Egypt	288.5 ± 17.49	77.77 ± 15.61	909.5 ± 59.73	[18]
	Iran	20.7 ± 1.1	3.0 ± 0.4	436 ± 14	[24]
	Morocco	27 ± 3	23 ± 3	300 ± 37	Present Work
Ceramic	Egypt	51.12 ± 2.74	40.52 ± 2.54	682.6 ± 10.13	[18]
	Turkey	33.1 ± 2.5	49.5 ± 3.3	459.1 ± 51.3	[26]
	Syria	65.878 ± 1.0	28.16 ± 3.0	401 ± 14.67	[21]
	Morocco	28 ± 5	30 ± 5	340 ± 42	Present Work
Marble	Saudi Arabia	12.7 ± 3.4	13.2 ± 1.4	64 ± 3	[22]
	Algeria	23 ± 2	18 ± 2	310 ± 3	[27]
	Morocco	18 ± 2	10 ± 1	154 ± 19	Present Work
Granite	Saudi Arabia	23 ± 1.4	30.0 ± 0.4	340 ± 6.7	[22]
	Turkey	67.5 ± 47.6	77.4 ± 53.0	915.3 ± 361.2	[16]
	Morocco	52 ± 6	63 ± 8	705 ± 84	Present Work
Sand	Turkey	38.8 ± 10.0	29.5 ± 11.3	471.4 ± 101.2	[26]
	Qatar	13.2 ± 0.3	3.34 ± 0.05	225.5 ± 6.1	[19]
	Pakistan	21.5 ± 0.5	31.9 ± 0.5	519.6 ± 6.0	[28]
	Morocco	22 ± 3	20 ± 3	274 ± 47	Present Work

Table 2. Average values of radium equivalent, hazard indices, absorbed dose rate, annual effective dose and the excess lifetime cancer risk in the samples of building materials analyzed.

Samples	Ra_{eq} (Bq/kg)	H_{in}	H_{ex}	$\dot{D}$ (nGy/h)	$\dot{E}_{in}$ (mSv/y)	$\dot{E}_{ex}$ (mSv/y)	$\dot{E}_{tot}$ (mSv/y)	ELCR ($\times10^{-3}$)
Graycement	77 ± 7	0.29 ± 0.05	0.21 ± 0.04	36 ± 2	0.18 ± 0.04	0.04 ± 0.01	0.18 ± 0.04	0.77 ± 0.06
Gypsum	19 ± 2	0.08 ± 0.02	0.05 ± 0.02	9 ± 1	0.04 ± 0.01	0.01 ± 0.01	0.04 ± 0.01	0.19 ± 0.01
Whitecement	62 ± 4	0.23 ± 0.04	0.17 ± 0.03	28 ± 1	0.14 ± 0.03	0.03 ± 0.01	0.14 ± 0.03	0.60 ± 0.05
Red brick	82 ± 12	0.28 ± 0.04	0.22 ± 0.04	39 ± 4	0.19 ± 0.04	0.05 ± 0.01	0.19 ± 0.04	0.83 ± 0.07
Block	82 ± 11	0.30 ± 0.05	0.22 ± 0.04	39 ± 3	0.19 ± 0.04	0.05 ± 0.01	0.19 ± 0.04	0.83 ± 0.07
Ceramic	97 ± 14	0.34 ± 0.05	0.26 ± 0.05	45 ± 5	0.22 ± 0.05	0.06 ± 0.02	0.22 ± 0.05	0.97 ± 0.09
Marble	45 ± 4	0.17 ± 0.03	0.12 ± 0.02	21 ± 1	0.10 ± 0.03	0.03 ± 0.01	0.10 ± 0.03	0.45 ± 0.04
Granite	196 ± 17	0.67 ± 0.06	0.53 ± 0.05	91 ± 7	0.45 ± 0.08	0.11 ± 0.03	0.45 ± 0.08	1.96 ± 0.10
Sand	72 ± 8	0.26 ± 0.04	0.20 ± 0.04	34 ± 3	0.17 ± 0.04	0.04 ± 0.01	0.17 ± 0.04	0.73 ± 0.07

3.3. Internal and External Hazard Indices

The calculation of the total activity of radionuclides in building materials alone does not make it possible to assess the radiological risks of gamma radiation. Other risk indices are also taken into account and are defined by a model taking into account the maximum activity of Ra_{eq} (370 Bq/kg). The external hazard index H_{ex} is defined by the following equation [5] [28]:

$$H_{ex} = \frac{A_{226\text{Ra}}}{370} + \frac{A_{232\text{Th}}}{259} + \frac{A_{40\text{K}}}{4810} \tag{2}$$

In addition to this external hazard, the respiratory organs are threatened because of the decay of ^{226}Ra into ^{222}Rn and its descendants. To account for this threat, the maximum permissible activity for ^{226}Ra is therefore reduced by half (185 Bq/kg). This internal hazard H_{in} is quantified by the following relation [5] [28]:

$$H_{in} = \frac{A_{226\text{Ra}}}{185} + \frac{A_{232\text{Th}}}{259} + \frac{A_{40\text{K}}}{4810} \tag{3}$$

Table 2 gives the internal and external hazard indices of the samples of the building materials studied. The values of the internal hazard index according to the materials vary between 0.08 and 0.67 while for the external hazard index they are between 0.05 and 0.53. The values are maximum for granite and minimum for gypsum. None of these values exceeds the unit, the maximum value of the internal (H_{in}) and external (H_{ex}) hazard indices allowed.

3.4. Absorbed Dose Rate and Annual Effective Dose

The absorbed dose rate $\dot{D}$ (nGy/h) due to the specific activity of natural radionuclides from building materials in air at 1 m height is defined by the following equation [5]:

$$\dot{D}(\text{nGy/h}) = 0.462 A_{226\text{Ra}} + 0.604 A_{232\text{Th}} + 0.0417 A_{40\text{K}} \tag{4}$$

Table 2 summarizes the results of the absorbed dose rates in air for the analyzed building materials. We note that the highest value is attributed to granite (91 nGy/h) while the lowest value is gypsum (9 nGy/h). These values of absorbed dose rates are below the permissible limit (55 nGy/h) [5] with the exception of the granite sample.

To estimate the annual effective dose received by the population, we take into account the coefficient of conversion of dose rate absorbed in air in effective dose (0.7 Sv/Gy) and external occupancy factor (0.2) [5]. The annual effective doses are determined as follows [5]:

$$\dot{E}_{ex}\left(\text{mSv/y}\right)=\dot{D}\left(\text{nGy/h}\right)\times 8760\left(\text{h}\right)\times 0.2\times 0.7\left(\text{Sv/Gy}\right)10^{-6} \tag{5}$$

$$\dot{E}_{in}\left(\text{mSv/y}\right)=\dot{D}\left(\text{nGy/h}\right)\times 8760\left(\text{h}\right)\times 0.8\times 0.7\left(\text{Sv/Gy}\right)10^{-6} \tag{6}$$

The results of the annual external ($\dot{E}_{ex}$), internal ($\dot{E}_{in}$) and total ($\dot{E}_{tot}$) effective doses for the samples of building materials studied are given in Table 2. It is found that the total value for each sample is less than the annual effective dose limit set at 1 mSv/y [5]. Therefore, we consider that these building materials do not present a radiological risk to the population and can be used in the construction of buildings.

3.5. Excess Lifetime Cancer Risk

The Excess Lifetime Cancer Risk (ELCR) treats the probability of developing cancer during the life of a human being at a certain level of exposure. The ELCR is calculated using the following equation [29]:

$$\text{ELCR}=\dot{E}_{tot}\times \text{DL}\times \text{RF} \tag{7}$$

Or:

$\dot{E}_{tot}$ is the total annual effective dose (μSv/year);

DL (Duration of Life) is the average life span of a human being (70 years);

RF is the Risk Factor fatal by cancer (Sv^{-1}). For stochastic effects, the International Commission on Radiological Protection (ICRP) estimates the value of this factor to be 0.05 for the public [30].

In Table 2, ELCR values range from 0.19×10^{-3} to 1.96×10^{-3} where the lowest value is found in the gypsum, while the highest is in the granite. The ELCR value at the granite sample far exceeds the permissible limit of 0.29×10^{-3} [29]. As a result, the risk of cancer increases with increasing exposure to these materials.

3.6. Volume Activities and Radon Exhalation Rates

After calculating the density of traces per unit area and per unit time in the LR115, the volume activities of the radon A_V^{Rn} are calculated using the detection efficiency equal to 0.0258 (traces·cm^{-2}·j^{-1})/(Bq·m^{-3}) [31]. The exhalation rate in terms of area (E_S in Bq·m^{-2}·h^{-1}) and mass (E_M in Bq·kg^{-1}·h^{-1}) of ^{222}Rn are determined by the following equation [32] [33]:

$$E_S = \frac{A_V^{Rn} V \lambda_{Rn}}{S_e \left[t + \left(\frac{1}{\lambda_{Rn}} \right) \left(e^{-\lambda_{Rn} t} - 1 \right) \right]} \tag{8}$$

$$E_M = \frac{A_V^{Rn} V \lambda_{Rn}}{M \left[t + \left(\frac{1}{\lambda_{Rn}} \right) \left(e^{-\lambda_{Rn} t} - 1 \right) \right]} \tag{9}$$

With A_V^{Rn} is the volume activity of radon (Bq·m^{-3}·h); V is the volume of the enclosure (m^3); λ_{Rn} is the ^{222}Rn decay constant (h^{-1}); S_e is the area of the sample (m^2); M is the mass of the sample in kg and t is the exposure time (h).

We present in **Table 3** the average values of the volumetric activity and exhalation rate in terms of area and mass of radon measured in the samples of the building materials analyzed. These values vary respectively from (72 to 350 Bq/m^3), (56 to 273 mBq·m^{-2}·h^{-1}) and (3 to 15 mBq·kg^{-1}·h^{-1}) where the lowest values are identified in the gypsum, while the highest values are in the granite. All volumic activity values for radon are in the range of 100 to 300 Bq/m^3 recommended by ICRP [34] with the exception of some samples of gray cement (191 to 366 Bq/m^3), ceramic (159 to 322 Bq/m^3) and granite (132 to 610 Bq/m^3).

In **Table 4**, for comparison with our results, the volumetric activities and exhalation rates in terms of area and mass of radon in building materials samples in Morocco and some other countries. Overall, the obtained results in this study are comparable to those found in other countries, with the exception of a few values that are remarkably higher than ours.

A positive correlation is found between the specific activities of ^{226}Ra on the one hand, it is determined by high resolution gamma spectrometry and the exhalation rates of ^{222}Rn calculated with the alpha dosimetry based on the use of LR115 on the other hand. This correlation is illustrated in **Figure 2** with a correlation coefficient in the order of 0.96.

Table 3. Volume activity and exhalation rate of radon in different samples of Moroccan building materials.

Samples		A_V^{Rn} (Bq/m^3)		E_S (mBq·m^{-2}·h^{-1})		E_M (mBq·kg^{-1}·h^{-1})	
Type	Nr.	Range	Average	Range	Average	Range	Average
Gray cement	7	191 - 366	248 ± 26	149 - 286	194 ± 21	8 - 15	10 ± 2
Gypsum	5	54 - 92	72 ± 7	42 - 72	56 ± 4	2 - 4	3 ± 1
White cement	5	184 - 198	191 ± 19	144 - 155	149 ± 15	7 - 8	7 ± 1
Red brick	5	130 - 192	159 ± 16	101 - 150	124 ± 13	5 - 8	7 ± 1
Block	5	140 - 211	176 ± 19	109 - 165	137 ± 19	6 - 9	7 ± 1
Ceramic	6	159 - 322	226 ± 22	124 - 251	176 ± 18	7 - 13	10 ± 2
Marble	5	69 - 220	151 ± 16	54 - 172	118 ± 12	3 - 9	6 ± 1
Granite	5	132 - 610	350 ± 34	103 - 476	273 ± 26	5 - 25	15 ± 3
Sand	7	140 - 275	190 ± 20	109 - 215	148 ± 16	6 - 11	8 ± 1

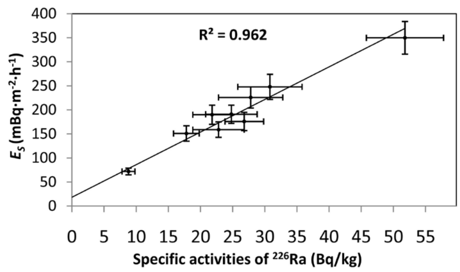

Figure 2. Correlation between the specific activities of ^{226}Ra and the exhalation rate of ^{222}Rnin building materials samples.

Table 4. Comparison between the Radon volume activities and the exhalation rates of radon in building materials in a few countries.

Samples	Country	A_V^{Rn} (Bq/m^3)	E_S (mBq·m^{-2}·h^{-1})	E_M (mBq·Kg^{-1}·h^{-1})	References
Gray cement	India	307	244	11.2	[35]
	Jordan	177	90	6	[36]
	Morocco	248	194	10	Present Work
Cement White	Palestine	102	63	6.4	[37]
	India	365	288	13.3	[35]
	Morocco	191	149	7	Present Work
Gypsum	Saudi Arabia	157.5	145.7	4.6	[38]
	Algeria	42	36	-	[39]
	Morocco	72	56	3	Present Work
Brick red	Algeria	166	101	-	[39]
	Morocco	159	124	7	Present Work
Block	India	235	241	-	[40]
	Jordan	160	82	6	[36]
	Morocco	176	137	7	Present Work
Ceramic	Algeria	75	65	-	[39]
	Palestine	132	75	3.2	[37]
	Morocco	226	176	10	Present Work
Marble	Algeria	56	48	-	[39]
	Libya	264.6	212.7	9.8	[41]
	Saudi Arabia	76.4	72.3	-	[38]
	Morocco	151	118	6	Present Work
Granite	Palestine	246	146	7.2	[37]
	Morocco	350	273	15	Present Work
Sand	Palestine	84	48	2.4	[37]
	Jordan	267	149	14	[36]
	Morocco	190	148	8	Present Work

4. Conclusion

In this present work, we used gamma spectrometry to determine natural radioactivity in 50 samples of building materials commonly used in Morocco. The specific activities of the ^{226}Ra, ^{232}Th and ^{40}K radionuclides measured in these samples vary from 9 to 52 Bq/kg, from 3 to 63 Bq/kg and from 68 to 705 Bq/kg respectively. These activities of the studied samples are within the permissible limits with the exception of a few samples of red brick, gray cement, ceramic and granite. To evaluate the radiological impact of these building materials on the population, the environment and through these specific activities, we calculated several radiological risk indices, namely radium equivalent (Ra_{eq}), internal (H_{in}) and external (H_{ex}) hazard indices, the absorbed dose rate ($\dot{D}$), the total annual effective dose ($\dot{E}_{tot}$), the excess lifetime cancer risk (ELCR), the volume activities (A_V^{Rn}) and the exhalation rate in terms of area (E_S) and mass (E_M). It follows that the values of these indices vary from 19 to 196 Bq/kg, 0.07 to 0.67, 0.05 to 0.53, 9 to 91 nGy/h, 0.05 to 0.56 mSv/y, 0.19×10^{-3} to 1.96×10^{-3}, 72 to 305 Bq/m^3, 56 to 273 mBq·m^{-2}·h^{-1} and 3 to 15 mBq·kg^{-1}·h^{-1} respectively. The lowest values are identified for gypsum, while the highest are attributed to granite. All of the obtained results of these indices respect the permissible limits except for the Ra_{eq} in some granite samples, the ELCR index in all samples except gypsum and the radon volumic activity in some gray cement samples, ceramic and granite. Consequently, the different types of building materials analyzed in this work do not present any significant health risks to the public and can be used in various construction activities with the exception of a few samples of red brick, gray cement, ceramic and granite. The choice of the use of red brick, gray cement and ceramic should be monitored and adapted according to the criteria of the limitation of the doses whereas the use of the granite must be moderate in order to limit over time the health risk which increases with the duration of exposure of humans to these building materials.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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