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Experimental and Simulated Effective Dose for Some Building Materials in France

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ABSTRACT

The specific radioactivity of several building materials used in France, which is considered a direct exposure to radiation, has been assessed by γ-ray spectrometry. Corrected for coincidence summing and self-absorption effects, the values for ^{226}Ra, ^{232}Th and ^{40}K were in the ranges 4 - 56, 3 - 72 and 9 - 1136 Bq·kg^{-1}, respectively. The samples were found to have radium-equivalent activities between 5 and 245 Bq·kg^{-1}. Values of 0.02 - 0.67 for the external and 0.03 - 0.82 for the internal hazard indexes were estimated. The calculated absorbed dose in air agrees closely with MCNPX simulations. The conversion of absorbed dose to annual effective dose gave values between 0.03 - 1.09 mSv·y^{-1}. All these values are below action limits recommended by the International Commission on Radiological Protection. The materials examined would not contribute a significant radiation exposure for an occupant and thus are acceptable for construction.

Keywords: Building Materials; Hazard Indexes; Radium-Equivalent; Absorbed Dose; Annual Effective Dose; MCNPX

1. Introduction

Knowing the natural radioactivity originating from building materials allows assessing radiological hazards to human health [1,2]. These materials usually contain radionuclides from both the uranium and thorium decay series, so the radiation exposure arises mainly from ^{226}Ra, ^{232}Th and ^{40}K [3,4]. One distinguishes an external hazard caused by exposure to radiations, while an internal hazard is the consequence of inhalation of ^{222}Rn and its decay products [5].

Some studies have reported measurement of radioactivity in concrete, gypsum, brick and sand [6-9]. In the present work, the estimation of ^{226}Ra, ^{232}Th and ^{40}K radioactivity has been carried out by HPGe γ-ray spectrometry. The building materials studies were samples offered by a large supplier in Strasbourg. For an accurate estimation of the absorbed dose (KERMA), coincidence summing and self-absorption corrections [10,11] have been taken into consideration.

From the specific radioactivity of the three above-mentioned radioelements, the radium equivalent, the external hazard, the internal hazard, the absorbed dose and the annual effective dose were evaluated. The results are discussed according to criteria proposed by the UNISCEAR [5] and the European Commission [2]. MCNPX was used to evaluate the absorbed doses in air. Comparison of the simulated values with those calculated using a proposed room model [5] permits validating this latter.

2. Sample Preparation and Measurements

The samples were collected, crushed, dried and homogenized, and then were conditioned in cylindrical SG50 containers. When the equilibrium between ^{226}Ra and its daughters was reached (3 - 4 weeks), the radioactivity was measured for ^{226}Ra (186 keV), ^{232}Th via ^{228}Ac (911 and 969 keV) and ^{40}K (1460 keV).

The natural radioactivity was measured using a planar BE detector model 3830 and associated electronics supplied by Canberra [12] with a detector resolution of 1.97 keV at 1332 keV and 0.65 keV at 122 keV. The efficiency calibration of the spectrometer was performed with a standard containing ^{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), having the same dimensions and in the same conditions of measurement as the samples.

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3. Results and Discussion

The specific radioactivities of ^{226}Ra, ^{232}Th and ^{40}K in the samples before and after correction for coincidence summing and self-absorption are reported in **Figure 1** (note that the corrections do not always increase an activity).

The radioactivity ranges between 4 - 56, 3 - 72 and 9 - 1136 Bq·kg^{-1} for the ^{226}Ra, ^{232}Th and ^{40}K, respectively. The lowest activity found was in the gypsum; the highest activity arose from red brick. Similar values have been reported in numerous other countries [8,13].

3.1. Radium-Equivalent

The distribution of ^{226}Ra, ^{232}Th and ^{40}K activities in the samples is non-uniform and that is why the radium-equivalent Ra_{eq} has been defined to evaluate one of the hazards of the building materials. Ra_{eq} is calculated using the following formula [3,4,6].

$$\mathrm{Ra}_{\mathrm{eq}} = A_c(\mathrm{Ra}) + 1.43 \times A_c(\mathrm{Th}) + 0.077 \times A_c(\mathrm{K}) \quad (1)$$

where A_c(Ra), A_c(Th) and A_c(K) are the activities in Bq·kg^{-1} of ^{226}Ra, ^{232}Th and ^{40}K, respectively, found in **Table 1**. This equation originated from the fact that activities of 370, 259 and 4810 Bq·kg^{-1} of these radionuclides give the same γ-ray dose equivalent.

All the values in **Table 1** are lower than the maximum admissible value 370 Bq·kg^{-1} recommended by UNSCEAR [5].

3.2. External Index (H_{ex})

H_{ex} is a radiation hazard index used to assess the indoor radiation dose rate resulting from the direct exposure to

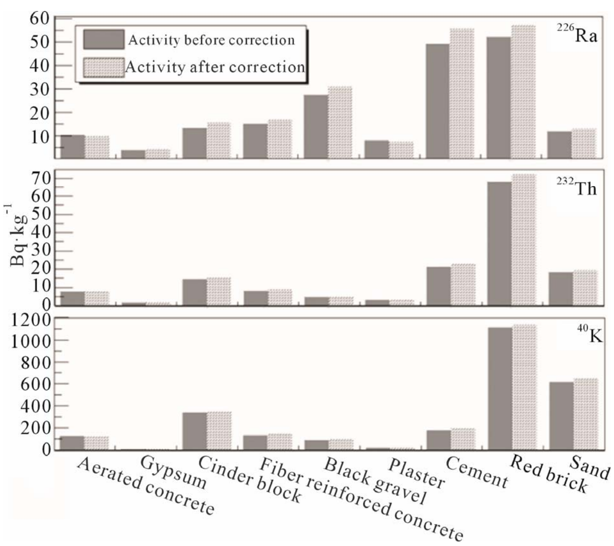

Figure 1. Specific natural radioactivity of the nine building materials without and with corrections for coincidence summing and self-absorption.

Table 1. Comparison of activities and radium-equivalents in some building materials used in France.

		Activity (Bq·kg^{-1})			
Sample	ρ (g·cm^{-3})	A_c (Ra)	A_c (Th)	A_c (K)	Ra_{eq}
Gypsum	1.16	4.3 ± 1.1	<1.62	9.4 ± 5.6	5 ± 1
Cinder-block	1.87	15 ± 2	16 ± 2	354 ± 59	66 ± 5
Fiber reinforced concrete	1.74	17 ± 2	9 ± 2	148 ± 80	40 ± 3
Darkgravel	1.91	31 ± 3	5 ± 1	96 ± 14	46 ± 4
Plaster	0.89	8 ± 1	3 ± 1	22 ± 8	14 ± 2
Cement	1.67	55 ± 6	23 ± 2	197 ± 25	103 ± 7
Red brick	1.63	57 ± 8	72 ± 8	1136 ± 140	246 ± 17
Sand	1.78	13 ± 2	19 ± 2	649 ± 80	90 ± 8
Aerated concrete	0.90	10 ± 2	7 ± 1	128 ± 17	30 ± 3

γ-rays. To be within the norm, H_{ex} must be less than or equal to 1. Von Krieger [14] proposed a model, where he considers a room with infinite wall, ceiling and floor thicknesses, without doors and windows, to calculate H_{ex}. The equation is given by:

$$H_{ex} = \frac{A_c(\mathrm{Ra})}{370} + \frac{A_c(\mathrm{Th})}{259} + \frac{A_c(\mathrm{K})}{4810} \le 1 \quad (2)$$

3.3. Internal Index (H_{in})

H_{in} deals with ^{222}Rn, a decay product of ^{226}Ra, and its short-lived daughters. The model used to calculate this index is given by [4].

$$H_{in} = \frac{A_c(\mathrm{Ra})}{185} + \frac{A_c(\mathrm{Th})}{259} + \frac{A_c(\mathrm{K})}{4810} \le 1 \quad (3)$$

One sees in **Figure 2** that the external hazard index H_{ex} ranges from 0.02 to 0.66 while the internal hazard index H_{in} is from 0.03 to 0.82. Again the lowest values were found for gypsum and the highest values for red brick. All of these values are acceptable because they are below unity.

3.4. Absorbed Dose and Annual Effective Dose

The absorbed dose $\dot{D}(\mathrm{nGy \cdot y^{-1}})$ is due to γ-rays arising from a building structure. The model consists of a room with internal dimensions of 4 × 5 × 2.8 m^3 enclosed on all sides by 20 cm of material with density 2.350 g·cm^{-3} (concrete) [5]. The relation used to calculate the absorbed dose is given by the European Commission [2] as follows.

$$\dot{D} = 0.92 \times A_c(\mathrm{Ra}) + 1.10 \times A_c(\mathrm{Th}) + 0.08 \times A_c(\mathrm{K}) \quad (4)$$

where 0.92, 1.10 and 0.08 nGy^{-1}·Bq^{-1}·kg are the dose conversion coefficients given by UNSCEAR for ^{238}U, ^{232}Th and ^{40}K. A_c(Ra), A_c(Th) and A_c(K) are the activities of ^{226}Ra, ^{232}Th and ^{40}K. This relation permits calculating the absorbed dose in air at 1 m height.

From **Figure 3**, one observes that the highest absorbed dose comes from red brick with the lowest dose coming from gypsum. The samples studied, with the exception of red brick, do not exceed the annual effective dose limit of 1 mSv·y^{-1} set by the European Commission.

To calculate the effective annual dose $\dot{E}$ (mSv), the conversion factor of 0.7 Sv·Gy^{-1} for an adult has been introduced (other values are adopted for infants and children) to convert the absorbed dose in air to the effective dose. The indoor occupancy factor is taken to be 0.8 and the allowed dose is 1 mSv·y^{-1} [5].

The following relation provides the annual effective dose.

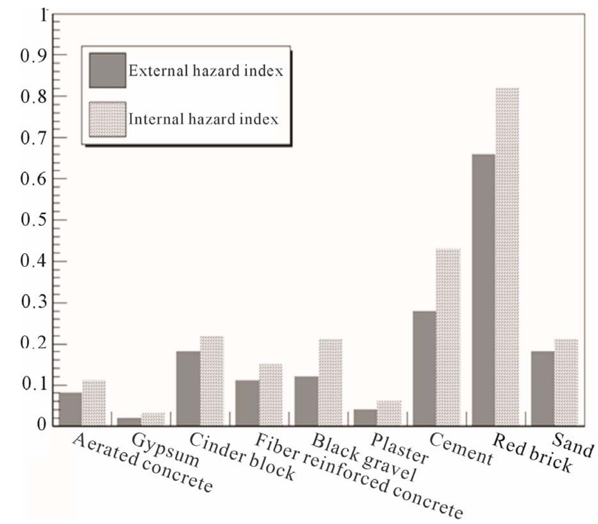

Figure 2. External and internal indexes calculated according to the models of Equations (1) and (2).

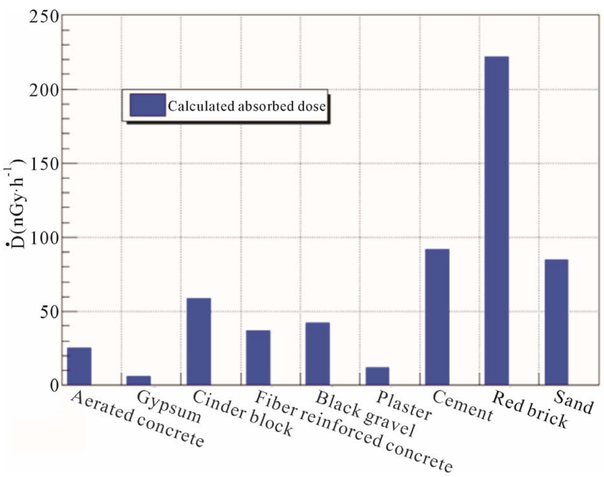

Figure 3. The absorbed dose $\dot{D}$ according to the room model of UNSCEAR.

$$\dot{E}(\mathrm{nSv}) = \dot{D} \times 0.7\left(\mathrm{Sv}\cdot\mathrm{Gy}^{-1}\right) \times 24 \times 365 \times 0.8\left(\mathrm{h}\cdot\mathrm{y}^{-1}\right) \quad (5)$$

These values are plotted in **Figure 4**.

3.5. MCNPX Simulation

Knowing the volume of a room and the apparent density (ρ) of the building materials, we can simulate the radioactivity within the confines of the room and the distribution of the absorbed dose. Simulated results are presented for red brick (ρ = 1.63 g·cm^{-3}) with a radium-equivalent activity of 246 ± 17 Bq·kg^{-1}. This activity corresponds to a γ-ray emission rate for ^{226}Ra and its daughters, which is taken into consideration in the simulation by the WGT card [10].

The dose rate varies as d^{-2} from any point of emission to any other point inside the room. The simulations were performed using a mesh tally as in **Figure 5**, where the dose rate was simulated every 10 cm. At each point, the dose was calculated using the conversion coefficient [1] given in nGy·cm^{-2}. Multiplication of the fluence tally F5 (cm^{-2}) by these coefficients allows obtaining the absorbed dose of γ-ray photons (**Figure 6**).

One sees in **Figure 6** that the absorbed dose distribution is highest near walls. The contributions at intersections produce the highest absorbed dose, which decreases as the center of the room is approached.

3.6. Comparison between Simulations and Measurements

Comparison between the measured and simulated absorbed dose shows good agreement as one can see in **Figure 7** and demonstrates that the room model used to calculate the absorbed dose is valid. The interest of simulations is that one can obtain results for many room dimensions and many materials when the specific radioactivity of the building material is known.

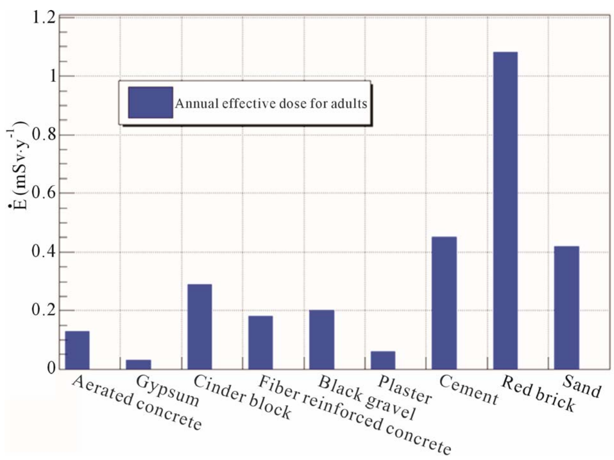

Figure 4. Annual effective dose $\dot{E}$ from the tested construction materials.

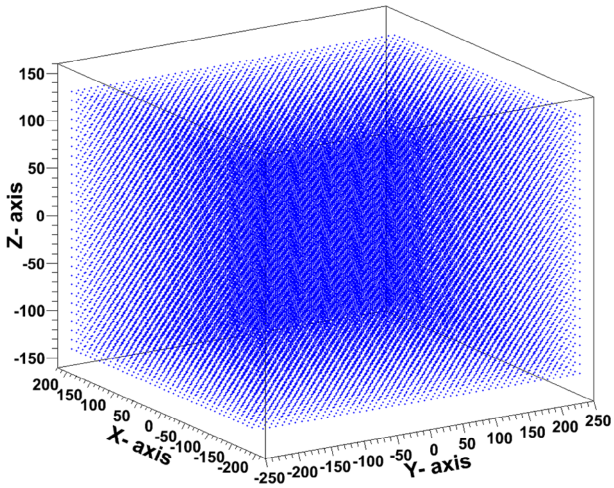

Figure 5. Room dimensions (x, y, z) and the mesh for calculating the dose rate.

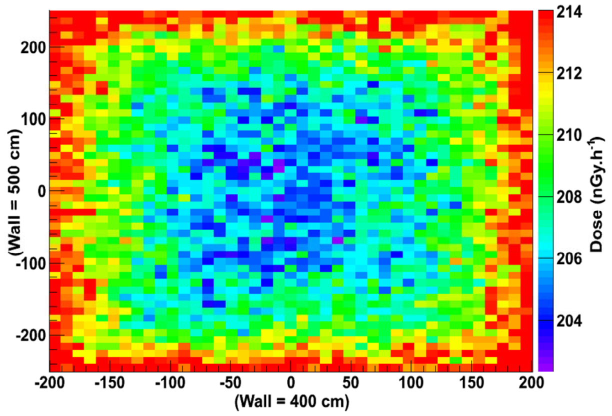

Figure 6. Absorbed dose distribution represented in 2D at 1 m height for a room built of red brick.

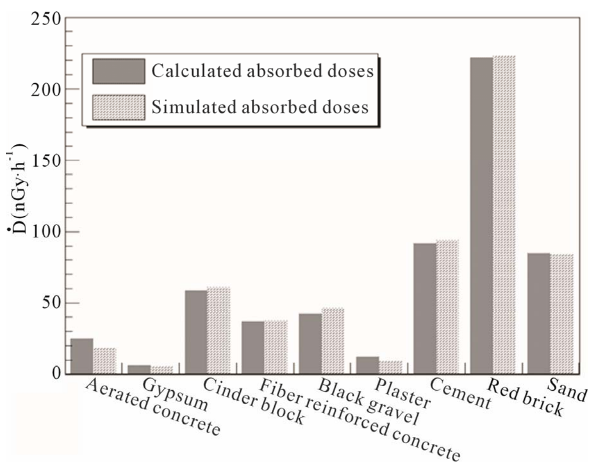

Figure 7. Comparison between the calculated and simulated absorbed doses.

4. Conclusions

The natural radioactivity measured for ^{226}Ra, ^{232}Th and ^{40}K in nine building materials available in France is comparable with values found in other countries except for red brick. The radium-equivalent, the external and internal indexes, the absorbed dose rate in air and the annual effective dose were found to be within acceptable limits. Therefore, the materials do not represent a significant radiological health risk and can be used for dwelling construction.

MCNPX can be used to determine the absorbed dose in air for any dwelling. The radiation hazard due to the natural radioactivity can be estimated for the walls, floor and roof. The simulations take into consideration the attenuation factors and the chemical composition of the building material in the absorbed dose rate calculations for γ-rays. Simulated absorbed dose rates are in good agreement with calculated absorbed doses, which lends confidence to the model used.

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