ENVIRONMENTAL DOSE ASSESSMENT FOR THE RADIONUCLIDES EMBEDDED IN BUILDING MATERIALS USED IN RESIDENTIAL BUILDINGS

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Abstract. Our environment is constantly emitting radiation from natural radionuclides embedded in earth, soils, living materials and cosmic sources. As we basically live with radiation and this radiation is mainly due to natural occurring radioisotopes, a correct assessment for the radionuclides we enclose in the buildings we live in or deploy our daily activities may raise specific concerns. In this paper we performed a dose and radiation risk assessment of specific major radionuclides present in common building materials. In order to achieve this, two type of residential buildings were analyzed – one flat on second floor of a building so that the soil radon emissions can be ignored and a house built on the ground level, currently being under construction. The estimated annual equivalent dose value for the house is 0.27 mSv/y and for the flat is 0.34 mSv/y. The determined dose levels are both under the maximum values allowed by the national and international regulations.

Key words: natural radionuclide, gamma-ray spectrometry, hazard indexes, dose estimation.

1. INTRODUCTION

The environment we live in constantly emits ionizing radiation generated by NORM (Naturally Occurring Radioactive Materials) incorporated in earth, soil and living matter but also generated from cosmic sources. Because we basically live surrounded by such radiation produced by natural radioactive isotopes, the correct assessment of the radionuclides existing in our residential buildings is a very important task to be fulfilled. In the present paper we made an evaluation of the health risk produced by the major specific radionuclides found in some widely used building materials. According to [1, 2], the contribution of the main radionuclides to the natural total dose is the following: 14% are represented by the natural radioactive

series of $^{232}$Th, 55.8% are represented by the natural radioactive series of $^{235}$U and $^{238}$U and 13.85% are represented by $^{40}$K.

Even since 1999, according to European Technical Guidance Radiation Protection 112, European Union set the index which represents the estimative dose produced by the radionuclides present in building materials [3]. In 2014, the European Commission emitted Basic Safety Standard (BSS) (Fundamental Security Standard) to protect against the radiological hazard resulted by the exposure to ionizing radiation generated from the radionuclides contained by building materials [4].

In this study, two types of residential buildings were chosen: a flat located at the second floor of a block of flats in order to ignore radon emissions from the ground and a house at ground level, which is now under construction. Both buildings are new built and placed near Bucharest. The flat is located in Popesti-Leordeni and the house can be found in Magurele, Ilfov County. Location of the two buildings for which the study was made is shown in Figure 1.

![Fig. 1 – Localization of the flat and of the house for which the study was made.](image)

2. MATERIALS AND METHODS

The concentrations of NORM contained in building materials were determined by using high resolution gamma-ray spectrometry method. In order to create the
proper radioactive matrix of the analyzed samples, a composition analyze of the
samples was previous performed and its major contained elements were identified.
The method used for the elemental composition analyze was X-ray fluorescence
(XRF).

For the elemental composition analyze, the samples were crushed to a maximum
1 cm diameter, then milled by using a Retsch PM 100 type mill. In order to be sure
that no errors will exist in concentrations determinations, the samples were sieved
to a maximum 63 µm granulation. The samples were dried in an oven at temperatures
between 50°C and 60°C. For mass determinations, the drying process was suspended
until the constant mass was reached.

The samples were gravimetrically homogenized and then pressed to pill shape.
The pill shape was obtained by using aluminum foils as a support and a manual
FLUXANA – HD ELECTRONIK VANOEX 25 t type press provided with a mold
designed to obtain 32 mm diameter pills.

The spectrometric system used for the determination of the major elemental
constituents was a Xenemetrix ED-XRF EX-6600 SDD type system containing a
XEG 60 type radiation generator (Pmax = 300 W, HVmax = 60 kV, Imax = 4.9 mA),
a 25 mm² area SSD (Silicon Drift Detector) type detector and an analogical digital
pulse processor (ADDP). The software used for the acquisition and analyze of the
XRF spectra was nEXtvers. 2.0.q.6. In order to obtain an optimal signal for the
measured elements, the system is provided with the following filters: Ti, Fe, W,
Mo, Rh and Sn and with the following targets: Zr, Si, Ti, Fe, Ge, Mo, Sn and Gd.
For the energy calibration and for testing, the system is provided with the following
reference disks: Al, Cu, Mo, Sn, Ti, Al_Cu and Ti_Sn.

The procedure used for the qualitative and quantitative determinations of the
major elemental concentrations was elaborated according to [5] and [6]. Measuring
uncertainties were estimated according to [7, 8, 9]. The following major concentration
elements were found: Na2O, MgO, SiO2, Al2O3, K2O, Fe, CaO, which does not show
significant spectral interferences (for high accuracy measurements).

The measuring conditions used in the evaluation of the major elements
concentrations, Na, Mg, Al, Si, K, Ca, are presented in Table 1 [10]. Here, the
analytical lines, the filters/the targets and the atmospheric condition from the
measuring chamber were presented.

The voltage and current applied to the X-ray generator were adjusted
according to the concentration of the measured element. Acquisition time was set
according to the number of the counts collected for each targeted element. The time
was set in order to collect at least 20000 counts for each of the elements presented
in Table 1.

Using the measuring conditions showed in Table 1, the calibration of the
system for the quantitative determinations was performed. The reference materials
used for the quantitative calibration of the system were: NCS DC 73372 (Lake
deposit) [11], NCS DC 73307 (Stream Sediment) [12] – certified by China National
Analysis Centre for Iron and Steel. In order to verify the accuracy of the method the following reference materials were used: IAEA-SL-1 (Lake Sediment) [13] – certified by International Atomic Energy Agency and TILL-1 [14] (Geochemical Soil) – certified by Natural Resources Canada, CANMET Mining and Mineral Sciences Laboratories.

### Table 1

The spectral lines, the filters/ the targets and the atmospheric condition from the measuring chamber used for elemental composition determinations (Tugulan et al., 2016)

<table>
<thead>
<tr>
<th>Element</th>
<th>Spectral line</th>
<th>Target/Filter</th>
<th>Pressure in the measuring chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>Kα</td>
<td>Si target</td>
<td>Vacuum</td>
</tr>
<tr>
<td>Mg</td>
<td>Kα</td>
<td>Direct irradiation (from the generator)</td>
<td>Vacuum</td>
</tr>
<tr>
<td>Al</td>
<td>Kα</td>
<td>Direct irradiation (from the generator)</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>Si</td>
<td>Kα</td>
<td>Direct irradiation (from the generator)</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>K</td>
<td>Kα</td>
<td>Ti target</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>Ca</td>
<td>Kα</td>
<td>Ti target</td>
<td>Atmospheric pressure</td>
</tr>
</tbody>
</table>

For the radiometric determination, the samples were crushed and then milled. The samples were kept in the mill until a maximum 100 µm granulation was obtained. For the mass determinations, the samples were dried until constant mass was obtained. After the drying was complete the samples were gravimetrically homogenized and then approximately 150 g of each sample was introduced in SARPA GAN type cylindrical containers. In order to achieve secular equilibrium of Rn and its descendants, the filled SARPA GAN containers were sealed and kept for 28 days before starting the measurements. The activity concentrations of the radionuclides from the natural series of $^{232}$Th, $^{238}$U and $^{235}$U and the one of $^{40}$K were determined by using a gamma-ray spectrometry system provided by CANBERRA. The system is made of a REGe type detector characterized by ISOXCALL, an DSA 1000 type multichannel analyzer and a 747 type lead shield. Detector window is made of a 0.6 mm thickness carbon-epoxy composite disk. The relative efficiency of the detector is of 40% and the FWHM is of 1.96 keV for 1332 keV ($^{60}$Co) and 0.89 keV for 122 keV ($^{57}$Co). The software used for data acquisition and spectral analyses was GENIE 2000. For efficiency calibration of the system, sample self-absorption and coincidences summing corrections, LabSOCS software suite was used. The measuring time was set to 90000 s. This time was chosen considering the fact that the measurements were performed for natural occurring radionuclides with activity values close to Minimum Detectable Activity (MDA), which strongly depends to measuring time [15–17].

In order to avoid Rn accumulation inside the lead shield of the detector, the measurements were performed only in the usual week working days, period when laboratory ventilation was on and relatively constant.
In order to perform an as best possible background subtraction, three different background measurements were taken (300000 s each one). This way, the acquisition rates for each energy of interest found in the background existing in the gamma-ray spectrometry laboratory in which the measurements were performed were determined. Background counting rates considered in calculus were the mean values of the three background measurements.

The accuracy of the method used to determine the activity concentrations of the radionuclides found in the studied building material was tested by using the following certified reference materials (by International Atomic Energy Agency): IAEA-RGTh-1 (Thorium Ore) [18], IAEA-384 (Fangataufa Sediment) [19] and IAEA-385 (Irish Sea Sediment) [20].

In Figures 2 and 3, the graphical user interface of LabSOCS software used for composing geometry of the measured samples (efficiency calibration) is showed. In Figure 2, the parameters inserted for geometrical description are presented and in Figure 3 the ones for describing the chemical composition of the samples.

Fig. 2 – LabSOCS – measuring geometry composer.
The natural series of $^{232}$Th was determined by using its following descendants: $^{228}$Ac (using 209.25 keV, 794.95 keV, 911.20 keV and 968.97 keV energies), $^{212}$Pb (using 238.63 keV energy), $^{212}$Bi (using 727.33 keV and 1620.50 keV energies) and $^{208}$Tl (using 583.19 keV and 860.56 keV energies).

The natural series of $^{238}$U was determined by using its following descendents: $^{214}$Pb (using 295.22 keV and 351.93 keV energies), $^{214}$Bi (using 609.31 keV, 768.36 keV, 934.06 keV, 1120.29 keV, 1661.28 keV, 1729.60 keV and 1847.42 keV energies) and $^{210}$Pb (using 46.54 keV energy).

$^{40}$K is a monoenergetic gamma-ray emitter, its 1460.83 keV gamma quanta emission being used for its activity concentration determination.

The nuclear decay data considered in calculus were adopted from [21]. The energetic interferences of the spectral lines presented above were analytically separated by using the method described in [22].

The assessment of the radiological risk induced by the gamma-ray emissions of the natural radioactive series and of $^{40}$K was performed by using the radiological risk index $I_{\gamma}$ (described in [23] and applied in [24–30]). It was determined by using the following Equation:
where \( A_{Ra-226} \), \( A_{Th-232} \) and \( A_{K-40} \) are the activity concentrations [Bq·kg\(^{-1}\)] of the involved radionuclides. The radiological risk induced by the presence of the natural radionuclides is negligible if the results of Equation (1) is less than or equal to 1.

This condition was set starting from the equivalent dose of 1 mS/y, dose limit for population.

Another evaluator which represents the radiological risk produced by the presence of natural radionuclides mixtures (\(^{226}\)Ra, \(^{232}\)Th and \(^{40}\)K) is the equivalent risk index \( Ra_{eq} \). It was described in [31] and applied in [24–30, 32]. The equivalent risk index can be determined by using the following Equation:

\[
Ra_{eq} (Bq/kg) = A_{Ra-226} + 1.43 \cdot A_{Th-232} + 0.077 \cdot A_{K-40}.
\]  

The equivalent risk index for radium recommended in [26] and [31] is \( Ra_{eq} \leq 370 \text{ Bq kg}^{-1} \). This value was obtained starting from an activity concentration of 370 Bq·kg\(^{-1}\) for \(^{226}\)Ra, of 259 Bq·kg\(^{-1}\) for \(^{232}\)Th and of 4810 Bq·kg\(^{-1}\) for \(^{40}\)K.

External risk index (\( H_{ex} \)) is another assessment factor for the gamma-ray produced by the natural radioisotopes. It was proposed by [33] and it can be determined using the following Equation:

\[
H_{ex} = \frac{A_{Ra-226}}{370} + \frac{A_{Th-232}}{259} + \frac{A_{K-40}}{4810}.
\]  

In order to have a negligible risk (starting from the dose limit for population [34]), the result of Equation (3) must be less than or equal to 1.

Because the descendant of \(^{226}\)Ra is \(^{222}\)Rn, which is a radioactive gas emitting corpuscular alpha particles, the internal risk assessment was mandatory. \(^{222}\)Rn has also other radioactive descendants which emit \( \gamma \)-rays but also corpuscular \( \alpha \) and \( \beta \) radiation. Considering the fact that radon is a gas, it can be inhaled, this way affecting the internal organs. The internal risk assessment index induced by radon and its descendants to the internal organs of the human body, (\( H_{in} \)), is calculated using the approach proposed by [32] and applied in [26, 27]:

\[
H_{in} = \frac{A_{Ra-226}}{185} + \frac{A_{Th-232}}{259} + \frac{A_{K-40}}{4810}.
\]  

In order to have a negligible influence of the internal risk assessment index, its value must be must be less than 1.

Using the activity to dose conversion factors presented in [34] (adopted from [35]), the absorbed dose rate value in air (DDA) is determined using the following Equation:

\[
DDA(\text{nGy} \cdot \text{h}^{-1}) = 0.462 \cdot A_{Ra-226} + 0.604 \cdot A_{Th-232} + 0.0417 \cdot A_{K-40}.
\]
where 0.462, 0.604 and 0.0417 are the activity to dose conversion factors presented in [35] for the absorbed dose rate value in air induced by the natural radioactive series of $^{238}$U and $^{232}$Th and also by $^{40}$K. Activity to dose conversion factors are expressed in (nGy $\cdot$ h$^{-1}$) $\cdot$ (Bq $\cdot$ kg$^{-1}$)$^{-1}$. By using Equation (5), the absorbed dose rate value in air depends only of the precision of the determination of isotopes producing it, unlike other dosimetric method found in literature [36–38], affected by higher associated uncertainties.

The effective annual dose (DEEA) was determined according to [34], using the following Equation:

$$\text{DEEA}(\text{mSv} \cdot \text{an}^{-1}) = \text{DDA}(\text{nGy} \cdot \text{h}^{-1}) \cdot 8760 \cdot 0.8 \cdot 0.7 \cdot \text{Sv} \cdot \text{Gy}^{-1} \cdot 10^{-6},$$

(6)

where DDA represents the dose rate determined according to Equation (5), 8760 h is the number of hours in a year, 0.8 is the internal occupancy factor (according to [34]), 0.7 represents the conversion factor from absorbed dose to effective annual dose (DEEA) recommended in [34] and $10^{-6}$ make the conversion of nSv to mSv.

The health risk produced by the natural radioisotopes to the internal organs of the human body (DAEG), according to [26] and [39], is calculated using the following Equation:

$$\text{DAEG}(\text{mSv} \cdot \text{an}^{-1}) = 3.09 \cdot A_{\text{Ra-226}} + 4.18 \cdot A_{\text{Th-232}} + 0.314 \cdot A_{\text{K-40}}$$

(7)

Gamma-ray activity concentration index, $I$, was set by the European Union in Directive 2013/59/Euratom [4] and it is calculated using the following Equation:

$$I = \frac{A_{\text{Ra-226}}}{300} + \frac{A_{\text{Th-232}}}{200} + \frac{A_{\text{K-40}}}{3000},$$

(8)

This index, $I$, is correlated with the external dose produced by the gamma-ray produced by the natural radionuclides embedded at the surface of building materials. A value of index $I \leq 2$ is corresponding to a dose rate of 0.3 mSv·an$^{-1}$ and a value of $I$ index between $2 \leq I \leq 6$ is corresponding to a value of 1 mSv·an$^{-1}$ [3, 4, 40]. The building materials with a value of gamma-ray activity concentration index greater than 6 are concerning and recommended to be avoid, since the annual dose provided by them is higher than the value considered acceptable for population, 1 mSv·an$^{-1}$ [4, 41].

3. RESULTS AND DISCUSSIONS

The LabSOCS software used for the efficiency calibration of the gamma-ray spectrometry system provide two methods to introduce the content of the major elements in the samples which must be measured: a) the elemental content pre-set (examples: “dirt4” for sand and ceramics; “concrete” used for concrete and BCA etc.); b) user available major elemental composition (if the elemental composition
of the sample can be previously determined). In order to determine the activity concentration of building materials with high accuracy, the elemental composition of the measured samples was previously determined by X-rays fluorescence spectrometry.

In Table 2, the major elemental composition of the studied building materials, determined by using X-rays fluorescence spectrometry, is presented.

The accuracy of the high resolution gamma-ray spectrometry method used for activity concentration determinations was previously verified by comparing the results obtained using LabSOCS and GESPECOR with reference materials. The elemental content pre-sets of LabSOCS were used for efficiency calibrations. The obtained results were in a very good agreement [42].

Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>NaO₂ (%)</th>
<th>MgO (%)</th>
<th>SiO₂ (%)</th>
<th>Al₂O₃ (%)</th>
<th>K₂O (%)</th>
<th>Fe (%)</th>
<th>CaO (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Brick Flat</td>
<td>1.08 ± 0.13</td>
<td>1.52 ± 0.18</td>
<td>62.6 ± 5.0</td>
<td>14.9 ± 1.2</td>
<td>2.20 ± 2.2</td>
<td>4.37 ± 0.44</td>
<td>1.15 ± 0.23</td>
</tr>
<tr>
<td>Cement (after maturing) Flat</td>
<td>0.38 ± 0.08</td>
<td>1.90 ± 2.1</td>
<td>15.5 ± 1.5</td>
<td>3.09 ± 0.43</td>
<td>0.71 ± 0.09</td>
<td>0.67 ± 0.09</td>
<td>28.4 ± 2.3</td>
</tr>
<tr>
<td>Ceramic tile Flat</td>
<td>3.80 ± 0.38</td>
<td>0.44 ± 0.12</td>
<td>60.6 ± 4.8</td>
<td>15.2 ± 1.2</td>
<td>0.86 ± 0.10</td>
<td>1.65 ± 0.20</td>
<td>4.11 ± 0.49</td>
</tr>
<tr>
<td>Hone Flat</td>
<td>6.53 ± 0.65</td>
<td>0.16 ± 0.11</td>
<td>61.1 ± 4.8</td>
<td>12.9 ± 1.1</td>
<td>0.59 ± 0.08</td>
<td>1.47 ± 0.18</td>
<td>3.23 ± 0.39</td>
</tr>
<tr>
<td>Sand Flat</td>
<td>2.41 ± 0.25</td>
<td>0.33 ± 0.11</td>
<td>79.0 ± 6.3</td>
<td>6.51 ± 0.78</td>
<td>1.82 ± 1.8</td>
<td>1.09 ± 0.13</td>
<td>0.60 ± 0.15</td>
</tr>
<tr>
<td>Concrete (B250) House</td>
<td>1.39 ± 0.17</td>
<td>0.43 ± 0.12</td>
<td>57.8 ± 4.6</td>
<td>3.78 ± 0.53</td>
<td>1.02 ± 1.22</td>
<td>0.99 ± 0.12</td>
<td>13.0 ± 1.6</td>
</tr>
<tr>
<td>Autoclaved aerated concrete House</td>
<td>1.09 ± 0.13</td>
<td>0.45 ± 0.12</td>
<td>50.7 ± 4.1</td>
<td>3.10 ± 0.43</td>
<td>0.77 ± 0.09</td>
<td>0.71 ± 0.09</td>
<td>18.7 ± 1.9</td>
</tr>
<tr>
<td>Ceramic Brick House</td>
<td>0.94 ± 0.12</td>
<td>2.26 ± 0.23</td>
<td>55.7 ± 4.5</td>
<td>14.2 ± 1.1</td>
<td>2.42 ± 2.4</td>
<td>4.39 ± 0.44</td>
<td>3.46 ± 0.48</td>
</tr>
</tbody>
</table>

In this paper, in order to increase the accuracy of gamma-ray spectrometry measurements as much as possible, the elemental composition of the measured samples determined by XRF was used in LabSOCS samples definition.

In Table 3, the activity concentrations of the natural radionuclides found in the tested building materials, by using LabSOCS efficiency calibration with the consideration of the XRF determined elemental compositions of the samples but also using the pre-set ones are presented.

The standard deviations between the values obtained considering the experimental determined matrix and the ones obtained considering the pre-set matrix were calculated using the following Equation:

$$SD(\%) = \frac{A_{\text{preset}} - A_{\text{exp}}}{A_{\text{exp}}} \times 100$$
where $A_{\text{preset}}$ is the activity concentration measured using the LabSOCS matrix pre-set and $A_{\text{exp}}$ is the activity concentration using LabSOCS and the experimental XRF major elemental composition determination.

Table 3
Activity concentrations of the natural radionuclides found in the tested building materials (by using high resolution gamma-ray spectrometry).

<table>
<thead>
<tr>
<th>Radionuclide/Sample</th>
<th>$^{226}\text{Ra}$ [Bq/kg]</th>
<th>u [Bq/kg]</th>
<th>$^{232}\text{Th}$ [Bq/kg]</th>
<th>u [Bq/kg]</th>
<th>$^{40}\text{K}$ [Bq/kg]</th>
<th>u [Bq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Brick – Flat (1)</td>
<td>71.3</td>
<td>9.9</td>
<td>46.5</td>
<td>6.7</td>
<td>513</td>
<td>60</td>
</tr>
<tr>
<td>Ceramic Brick – Flat (2)</td>
<td>71.7</td>
<td>10.0</td>
<td>46.7</td>
<td>6.7</td>
<td>514</td>
<td>60</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>0.48</td>
<td></td>
<td>0.39</td>
<td></td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Cement (after maturing) – Flat (1)</td>
<td>32.0</td>
<td>4.5</td>
<td>16.8</td>
<td>2.7</td>
<td>214</td>
<td>25</td>
</tr>
<tr>
<td>Cement (after maturing) – Flat (3)</td>
<td>32.1</td>
<td>4.5</td>
<td>16.8</td>
<td>2.7</td>
<td>214</td>
<td>25</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>0.41</td>
<td></td>
<td>0.38</td>
<td></td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Hone – Flat (1)</td>
<td>30.2</td>
<td>4.2</td>
<td>39.7</td>
<td>5.7</td>
<td>223</td>
<td>26</td>
</tr>
<tr>
<td>Hone – Flat (2)</td>
<td>30.4</td>
<td>4.3</td>
<td>39.9</td>
<td>5.7</td>
<td>223</td>
<td>26</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>0.50</td>
<td></td>
<td>0.43</td>
<td></td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Hone – Flat (1)</td>
<td>473</td>
<td>66</td>
<td>54.1</td>
<td>7.7</td>
<td>159</td>
<td>19</td>
</tr>
<tr>
<td>Hone – Flat (2)</td>
<td>475</td>
<td>66</td>
<td>54.3</td>
<td>7.7</td>
<td>159</td>
<td>19</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>0.55</td>
<td></td>
<td>0.42</td>
<td></td>
<td>–0.10</td>
<td></td>
</tr>
<tr>
<td>Sand – Flat (1)</td>
<td>42.7</td>
<td>6.0</td>
<td>8.55</td>
<td>1.51</td>
<td>367</td>
<td>43</td>
</tr>
<tr>
<td>Sand – Flat (2)</td>
<td>41.6</td>
<td>5.8</td>
<td>8.33</td>
<td>1.55</td>
<td>361</td>
<td>42</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>–2.50</td>
<td></td>
<td>–2.38</td>
<td></td>
<td>–1.60</td>
<td></td>
</tr>
<tr>
<td>Concrete (B250) – House (1)</td>
<td>10.2</td>
<td>1.5</td>
<td>8.10</td>
<td>0.99</td>
<td>265</td>
<td>17</td>
</tr>
<tr>
<td>Concrete (B250) – House (3)</td>
<td>10.2</td>
<td>1.5</td>
<td>8.08</td>
<td>1.48</td>
<td>265</td>
<td>31</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>–0.75</td>
<td></td>
<td>–0.22</td>
<td></td>
<td>–0.30</td>
<td></td>
</tr>
<tr>
<td>Autoclaved Aerated Concrete – House (1)</td>
<td>13.2</td>
<td>1.9</td>
<td>10.2</td>
<td>2.2</td>
<td>305</td>
<td>38</td>
</tr>
<tr>
<td>Autoclaved Aerated Concrete – House (3)</td>
<td>13.3</td>
<td>2.6</td>
<td>10.3</td>
<td>2.2</td>
<td>307</td>
<td>38</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>0.47</td>
<td></td>
<td>0.51</td>
<td></td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>Ceramic Brick – House (1)</td>
<td>68.9</td>
<td>9.6</td>
<td>48.3</td>
<td>7.0</td>
<td>748</td>
<td>85</td>
</tr>
<tr>
<td>Ceramic Brick – House (2)</td>
<td>70.7</td>
<td>9.7</td>
<td>48.9</td>
<td>7.1</td>
<td>751</td>
<td>88</td>
</tr>
<tr>
<td>Standard Deviation [%]</td>
<td>2.57</td>
<td></td>
<td>1.33</td>
<td></td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>

(1) Major elemental composition determined by XRF;
(2) LabSOCS "dirt4" pre-set;
(3) LabSOCS "concrete" pre-set.

In Table 4, the radiologic risk index values, the doses and the dose rates produced by the natural isotopes embedded in the building materials used in the studied two residential buildings.

The determined $R_{eq}$ values were placed between 42.3 Bq/kg (Concrete (B250) – House) and 562 Bq/kg (Hone – Flat). The only value found to exceed the radiological risk limit was the one for hone (Flat), 370 Bq/kg.

All $H_{ext}$ values determined for the studied building materials were found to be under radiological risk values, excepting the one for hone – flat. The determined values were placed between 0.11 and 1.52.
The index used for internal radiological risk assessment, $H_{int}$, was determined to be between 0.14 and 2.80. As in the case of $H_{ext}$, $H_{int}$ exceeds the limit only in case of hone – flat.

Table 4
The radiologic risk index values, the doses and the dose rates produced by the natural isotopes embedded in the studied building materials

<table>
<thead>
<tr>
<th>Radionuclide / Sample</th>
<th>$I_{\gamma}$</th>
<th>$R_{Na_{eq}}$ [Bq/kg]</th>
<th>$H_{ext}$</th>
<th>$H_{in}$</th>
<th>$D$ [nGy/h]</th>
<th>DEEA [mSv/y]</th>
<th>DAEG [mSv/y]</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Brick – Flat</td>
<td>1.28</td>
<td>177</td>
<td>0.48</td>
<td>0.67</td>
<td>82.5</td>
<td>0.10</td>
<td>0.58</td>
<td>0.64</td>
</tr>
<tr>
<td>Cement – Flat</td>
<td>0.52</td>
<td>72.4</td>
<td>0.20</td>
<td>0.28</td>
<td>33.8</td>
<td>0.04</td>
<td>0.24</td>
<td>0.26</td>
</tr>
<tr>
<td>Ceramic tile – Flat</td>
<td>0.75</td>
<td>104</td>
<td>0.28</td>
<td>0.36</td>
<td>47.2</td>
<td>0.06</td>
<td>0.33</td>
<td>0.37</td>
</tr>
<tr>
<td>Hone – Flat</td>
<td>3.80</td>
<td>562</td>
<td>1.52</td>
<td>2.80</td>
<td>258</td>
<td>0.32</td>
<td>1.74</td>
<td>1.90</td>
</tr>
<tr>
<td>Sand – Flat</td>
<td>0.61</td>
<td>83.2</td>
<td>0.22</td>
<td>0.34</td>
<td>40.2</td>
<td>0.05</td>
<td>0.28</td>
<td>0.31</td>
</tr>
<tr>
<td>Concrete (B250) – House</td>
<td>0.33</td>
<td>42.3</td>
<td>0.11</td>
<td>0.14</td>
<td>20.7</td>
<td>0.03</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>Autoclaved Aerated Concrete – House</td>
<td>0.39</td>
<td>51.3</td>
<td>0.14</td>
<td>0.17</td>
<td>25.0</td>
<td>0.03</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>Ceramic Brick House</td>
<td>1.44</td>
<td>196</td>
<td>0.53</td>
<td>0.71</td>
<td>92.2</td>
<td>0.11</td>
<td>0.65</td>
<td>0.72</td>
</tr>
<tr>
<td>Weighted mean – Flat</td>
<td><strong>1.07</strong></td>
<td><strong>149</strong></td>
<td><strong>0.40</strong></td>
<td><strong>0.62</strong></td>
<td><strong>69.9</strong></td>
<td><strong>0.34</strong></td>
<td><strong>0.49</strong></td>
<td><strong>0.54</strong></td>
</tr>
<tr>
<td>Weighted mean – House</td>
<td>0.89</td>
<td>115</td>
<td>0.31</td>
<td>0.41</td>
<td><strong>54.4</strong></td>
<td><strong>0.27</strong></td>
<td><strong>0.39</strong></td>
<td><strong>0.43</strong></td>
</tr>
</tbody>
</table>

The dose rates, $D$, produced by the natural radionuclides found in the analysed building materials were found to be placed between 20.7 nGy/h (Concrete (B250) – House) and 258 nGy/h (Hone – Flat).

Annual effective equivalent doses, DEEA, calculated from the activity concentrations of the natural radionuclides embedded in the studied building materials were found to be placed between 0.03 mSv/y (Concrete (B250) and Autoclaved Aerated Concrete – House) and 0.32 mSv/y (Hone – Flat). None of these values exceeds the annual dose limit for population regulated by [41].

The index used for the assessment of the radiological risk induced by the natural radionuclides to the internal organs of the human body (DAEG) was found to have values placed between 0.15 mSv/y (Concrete (B250) – House) and 1.74 mSv/y (Hone – Flat). Only the dose rate produced by the natural radionuclides found in hone (Flat) was found to exceed the limit for population regulated by [41].

The risk index, $I_{\gamma}$, calculated according to European Directive 2013/59/Euratom [4], was found to have values between 0.16 mSv/y (Concrete (B250) – House) and 1.90 mSv/y (Hone – Flat). The only value exceeding the radiological risk limit was the one for hone (Flat).

At the bottom of Table 4, the risk indexes, doses and dose rates caused by the natural radionuclides embedded in the studied building materials were calculated as weighted means, for both the flat and the house. It can be seen that only in the case of $I_{\gamma}$ calculated for the flat the radiological risk is exceed. The annual doses
calculated for both residential buildings were found to be under the regulated limit for population.

4. CONCLUSIONS

The weighted mean values were calculated by taking into account the ratios between the building materials types in the case of each of the two buildings (considering their architectural plans). This way annual equivalent dose values being obtained for both buildings. The value obtained for the house was of 0.27 mSv/y (54.4 nGy/h dose rate) and the one for the flat was of 0.34 mSv/y (69.9 nGy/h dose rate).

The annual effective equivalent dose values for both studied residential buildings were found not exceeding the 1 mSv/y limit regulated by Romanian legislation [41].

REFERENCES


