BUILDING MATERIALS PHOTON ATTENUATION, NATURAL RADIOACTIVITY CONTENT AND RADON EXHALATION RATE

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High concentrations of natural radionuclides in building materials result in high dose rate indoors due to radon and thoron exhalation and the γ-rays emitted from them. Among the natural radionuclides contained in building materials, most attention has been given to $^{226}$Ra due to $^{222}$Rn exhalation and the subsequent internal exposure. In external dose calculations due to building materials it is usually assumed that there exists radioactive equilibrium among the radionuclides of both the uranium and thorium series. In the case of the radionuclides of the uranium series it is assumed that there exists radioactive equilibrium among the long lived radionuclides $^{238}$U, $^{226}$Ra and $^{210}$Pb. The above assumption is seldom checked mainly because of the difficulties in the γ-spectroscopic determination of $^{238}$U and $^{210}$Pb which is possible only by using low-energy photons, where intense self-absorption of the photons inside the sample exists. In this case the count-rate during a γ-spectroscopic analysis is highly affected by the intense self-absorption of the photons. For the determination of radionuclides emitting low-energy photons a method has been developed which needs as input among others the linear attenuation coefficient $\mu$ for the analysed material. This paper presents:

1. Correlations in the form $\mu=f(\rho,\epsilon)$ developed for the estimation of the linear attenuation coefficient $\mu$(cm$^{-1}$) as a function of the material packing density $\rho$(grcm$^{-3}$) and the photon energy $E$(keV) for several materials of environmental importance, such as building materials.

2. Gamma-spectroscopic analysis techniques used for the determination of $^{238}$U, $^{226}$Ra, $^{210}$Pb, $^{232}$Th and $^{40}$K in environmental samples, together with the results obtained from the analysis of building materials used in Greece and industrial by-products used for the production of building materials. Among the techniques reported one is based on the direct determination of $^{226}$Ra and $^{235}$U from the analysis of the multiplet photopeak at ~186keV.

3. Results from radon exhalation measurements of building materials such as cement and fly-ash and building structures conducted in the radon chambers in our Laboratory.

Keywords: Building materials, low-energy photons, self-absorption, linear attenuation coefficient, radioactive disequilibrium, radon exhalation rate.

INTRODUCTION

High concentrations of natural radionuclides in building materials result in high dose rate indoors - internal and external. Internal dose due to radon and thoron exhalation from building materials and external dose mainly due to the γ-rays emitted from the radionuclides. Among the natural radionuclides existing in building materials most attention has been given so far to $^{226}$Ra due to $^{222}$Rn exhalation. External irradiation has not been given much attention yet, as considered of less importance compared to internal irradiation. Thus, remedial actions taken and mitigation techniques developed and applied aim only to the reduction of $^{222}$Rn concentration indoors, and the internal dose due to radon and thoron daughters, without reducing the external dose due to β and γ-rays emitted from the radionuclides existing in building materials and constructions. Moreover, in external dose calculations radioactive equilibrium among the nuclides of the uranium and the thorium series is usually assumed. In the case of the radionuclides of the uranium series it is specifically assumed that there exists radioactive equilibrium among the long lived $^{238}$U, $^{226}$Ra and $^{210}$Pb. The above assumption which is seldom checked, is sometimes not valid, especially when
industrial by-products with radioactive disequilibrium are used in the building materials' industry. Typical such cases of by-products are:

- Fly-ash and bottom ash (slag) from coal burning power plants. Fly-ash is often used in the production of cement, while sometimes it is also used in the production of other building materials such as bricks. In Greece fly-ash from lignite burning power plants is used as an additive to black cement at percentages about 10-15%. Though radioactive equilibrium among the nuclides of the uranium and thorium series in lignite usually exists [Anagnostakis, 1998], disequilibrium is observed after the combustion process among the isotopes of the above series, due to the different physical and chemical properties of the uranium, radium and lead [Coles et al, 1978]. According to [UNSCEAR, 1982] \(^{210}\text{Pb}\) concentration in slag may be as much as 3.9kBqkg\(^{-1}\). Similar values for fly-ash samples from greek lignite burning power plants are reported in this paper.

- Alum shale, used for the production of a kind of light-concrete known as blue concrete [Akerblom, 1995].

- Phosphogypsum, produced from the fertilizer industry, with concentrations reaching 1500Bqkg\(^{-1}\) [UNSCEAR, 1982]. In the products and by-products of the phosphate industry significant disequilibrium is reported among the radionuclides of the uranium series [Roessler et al, 1979].

Besides the disequilibrium in building materials, mainly due to the use of by-products in building materials industry, there exist raw building materials with high probability of radioactive disequilibrium, such as pumice stone, a material of volcanic origin often used especially in the past for insulation purposes and today used in the production of light pumice-stone bricks.

The natural radionuclides concentrations in building materials is quite often determined using high resolution \(\gamma\)-spectroscopic techniques. \(^{226}\text{Ra}\) concentration is usually determined indirectly from its daughters in equilibrium [Simopoulos et al, 1987a]. In the case of radionuclides emitting only low energy photons, such as \(^{234}\text{Th}\) (63.29keV) which is usually in radioactive equilibrium with \(^{238}\text{U}\) and \(^{210}\text{Pb}\) (46.5keV), the count-rate during the \(\gamma\)-spectroscopic analysis is highly affected by the intense self-absorption of the photons inside the sample, especially in large volume samples. The self-absorption, besides the sample's volume and shape, depends on the material, the material packing density inside the sample and the photon energy. For the quantitative determination of radionuclides emitting low-energy photons a method has been recently developed [Anagnostakis et al, 1995a], to take into account for the difference in the self-absorbing properties between the calibration source material and the analysed material. The method needs as input the source-to-detector geometry and the linear attenuation coefficient \(\mu\) (cm\(^{-1}\)) for both the analysed material and the calibration source material, at the respective photon energy. The linear attenuation coefficient \(\mu\) for materials with known composition, such as efficiency calibration sources, may be found in the literature [Hubbell, 1982] or may be calculated [Anagnostakis, 1998]. In the case of building materials and other materials of environmental origin, data for the linear attenuation coefficient \(\mu\) are seldom found in the literature, especially in the low energy region 40-200keV.

**PHOTON LINEAR ATTENUATION COEFFICIENT \(\mu\) OF BUILDING MATERIALS**

For the determination of the linear attenuation coefficient \(\mu\) at photon energy \(E\) for a material with density \(\rho\) (grcm\(^{-3}\)), an experimental technique was applied [Anagnostakis et al, 1994a]. The technique is based on the attenuation of the photons of an open photon beam with energy \(E\) and intensity \(I_0\), impigning samples prepared from the material under study, with various thicknesses \(x_i\).
The determination, by \( \gamma \)-spectroscopic analysis, of the intensity \( I_i \) of the photon beam passing through each sample and the fitting of the experimental data \((x_i, I_i)\) to the transmission formula:
\[
I = I_0 \cdot e^{-\mu x}
\]
(1)
leads to the estimation of the linear attenuation coefficient \( \mu \). The technique was checked using various materials with known values of coefficient \( \mu \), covering a wide range of its values. The total uncertainty associated with the estimation of \( \mu \) was less than 5%. In the frame of this research this technique was applied to:

- Building materials, such as black cement, white cement and sand. Among the building materials used in Greece black cement is one of the most important from the radiological point of view because of its relatively high natural radioactivity content [Louizi et al, 1995] and its extensive use in constructions.
- By-products of industrial processes, such as fly-ash and bottom-ash from lignite-burning power plants, used in Greece in the production of building materials.
- Lignite feeding the power-plants.
- Soil.

For each one of the above materials the linear attenuation coefficient \( \mu \) was determined using several samples with different packing densities, at the photon energies: 45.36keV (\(^{152}\)Eu), 46.63keV (\(^{152}\)Eu), 59.54keV (\(^{241}\)Am), 121.78keV (\(^{152}\)Eu) and 186.25keV (\(^{226}\)Ra), as shown in Figure 1. The above photon energies were selected to satisfactorily cover the energy region 40-200keV, where self-absorption is more intense and several photons of interest are emitted. Material packing densities for each material were selected to cover the whole density range of practical interest. The experimental data \((\mu_i, \rho_i)\) for various materials at the photon energy of 59.54keV are presented in Figure 1 together with their fitted regression lines. The total uncertainty associated with the estimations of values of the linear attenuation coefficient \( \mu \) from the regression lines is less than 10%. Using the confidence interval ellipse method [Konstantaropoulou et al, 1991] it was proved that these regression lines are statistically independent at the significance level \( \alpha = 0.01 \). This conclusion is very important since, for efficiency corrections due to self-absorption of photons, in some cases the assumption is made that, different materials having the same density present the same absorbing properties [Nemeth et al, 1992]. According to the results obtained during this research, the values of coefficient \( \mu \) for some materials of environmental interest such as black cement, may be significantly higher than those for other environmental materials having the same density, such as soil at photon energies lower than ~120keV.

The experimentally obtained data \( \mu_i(E_i, \rho_i) \) for each material were fitted to estimate the parameters of multiparametric correlations in the form:
\[
\ln(100 \cdot \mu) = a \cdot (\ln E)^b \cdot (\ln(100 \cdot \rho))^c
\]
(2)
where:
- \( \mu \): the linear attenuation coefficient (cm\(^{-1}\))
- \( \rho \): the material packing density (grcm\(^{-3}\))
- \( E \): photon energy (keV)
- \( a, b, c \): parameters to be estimated from the fitting for each material.

The parameters of the correlations for soil, fly ash, bottom-ash, lignite and black cement, together with the values of the correlation coefficients \( r \) and those of residual mean square (RMS) are given
in Table 1. The correlations obtained were incorporated into a computer code to predict $\mu$ for the above materials in the energy region 40-200keV. The estimated values for $\mu$ are used as input for the technique developed by the authors, to take into account for the difference in the self-absorbing properties between the calibration source material and the analysed material, thus allowing for the quantitative determination, of radionuclides emitting photons in the above energy region using $\gamma$-spectroscopic techniques.

Extension of this research to other building materials, such as concrete, may produce data for the attenuation of photons useful in dosimetric calculations indoors. Moreover, the correlation developed for soil may provide useful data for dosimetric calculations outdoors due to terrestrial $\gamma$-radiation.

**GAMMA SPECTROSCOPIC ANALYSIS TECHNIQUES AND RESULTS.**

An extensive research for the determination of the natural radionuclides: $^{226}$Ra, $^{232}$Th and $^{40}$K, in lignite, fly-ash and bottom-ash, has been undertaken since 1983 by [Simopoulos et al, 1987a, 1987b]. The research was extended to the determination of the natural radioactivity of building materials used in Greece, as it has been progressively reported by [Louizi et al, 1995].

For the $\gamma$-spectroscopic determination of the natural radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K, two high resolution high efficiency Ge detectors and a LEGe were used. $^{226}$Ra and $^{232}$Th were determined indirectly from their daughters in equilibrium. For this reason the materials under study were hermetically sealed in 282ml plastic cylindrical boxes, which were further covered with a film of epoxy resin, to limit, as far as possible, the escape of any gas from the box. To allow for equilibrium of $^{226}$Ra and $^{232}$Th with their decay products all specimens are analysed at least three weeks after the boxes are sealed. The $^{226}$Ra radioactivity is derived from the weighted mean of the activities of two photopeaks of $^{214}$Pb (295.2, 352.0keV) and of three photopeaks of $^{214}$Bi (609.3, 1120.3, 1764.5keV). In the case of $^{232}$Th two photopeaks of $^{228}$Ac (338.4, 911.1keV) and the photopeaks of $^{212}$Pb (238.6keV) and $^{208}$Tl (583.1keV) are used in the same way. The radioactivity of $^{40}$K is obtained from the single photopeak of this isotope at 1460.75keV. The total uncertainty of the obtained values of the radioactivity of the naturally occurring radionuclides is calculated from the systematic and the random error of the measurements. Further details on the calibrations performed, the $\gamma$-spectroscopic analysis and the quality assurance procedures followed, may be found in [Simopoulos et al, 1987] and [Anagnostakis et al, 1995b].

In the frame of this research a new technique was also introduced for the direct determination of $^{226}$Ra from its photopeak at 186.25keV, which is not often used because of the adjacent $^{235}$U peak at 185.75keV, since these two photopeaks form a multiplet which is not easily analysed. If radioactive equilibrium between $^{238}$U and $^{226}$Ra may be assumed, the contributions of the photons emitted from $^{235}$U and $^{226}$Ra to the above multiplet photopeak may be calculated, and thus it leads the estimation of activities of the two isotopes. In the case that radioactive equilibrium between $^{238}$U and $^{226}$Ra may not be assumed, $^{226}$Ra may be determined only provided that the $^{235}$U activity has been previously determined from other photons that it emits [Gorbatyuk et al, 1973]. The technique developed in this work is only based on the analysis of the photopeak at ~186keV using a high resolution detector, such as a LEGe detector (530eV fwhm at 122keV). In the case that:

- the energy calibration of the LEGe detector system allows for sufficient number of channels per keV (e.g. ~20channels / keV),
- the $\gamma$-spectroscopic analysis software used is sensitive in the analysis of multiplet photopeaks,
the statistics of the multiplet photopeak at ~186keV is good,

the multiplet photopeak at ~186keV may be analysed into its two components, at 185.75 and 186.25keV, allowing for the direct determination of $^{226}$Ra and $^{235}$U respectively. In this case $^{238}$U may be determined indirectly from $^{235}$U, under the assumption of natural isotopic abundance of the uranium isotopes.

During this research, for every sample analysed:

- The $^{226}$Ra activity was determined both indirectly from its decay products assumed in equilibrium and from the 186.25keV photons, when applicable.
- The $^{238}$U activity was determined indirectly from the 63.29keV photons emitted from its decay product $^{234}$Th. When the photopeak at ~186keV was analysed, $^{238}$U was also determined from the 185.72keV photons of $^{235}$U.
- The $^{210}$Pb activity was determined from its 46.54keV photons.

For the $\gamma$-spectroscopic analysis the in-house developed software SPUNAL [Anagnostakis et al, 1994b] was used. SPUNAL is equipped with sensitive algorithms, suitable for the detection and the analysis of close-lying and/or overlapping peaks which may constitute the components of a multiplet, such as the one at ~186keV. In the case of the analysis of a spectrum collected from a LEGe detector, where photons in the energy region 40-200keV are used, efficiency corrections due to self-absorption are automatically performed by the software, based on the technique developed by [Anagnostakis et al, 1995a]. An indicative value for the efficiency correction factor used, to take into account for the difference in the self-absorbing properties between the calibration source material 4M HCl and a sample of black cement with packing density 1.4grcm$^{-3}$, volume 282ml and height 69mm, for 46.54keV photons is ~0.5.

Using the techniques previously described, a series of building materials often used in Greece were analysed for the determination of $^{238}$U, $^{226}$Ra, $^{210}$Pb, $^{235}$U, $^{232}$Th and $^{40}$K. Samples of two by-products of lignite burning: fly-ash and bottom-ash were also analysed. Table 2 presents the results obtained.

**RADON EXHALATION RATE MEASUREMENTS TECHNIQUES AND RESULTS**

The technique applied for the exhalation rate measurements is based on the enclosure of sample under analysis inside one of the two available Radon Chambers (1.8m$^3$ and 8.5m$^3$) for about 20 days, and the monitoring of the growth of radon concentration inside the chamber. Radon concentration inside the chambers is being monitored using several techniques including grab-sampling [Louizi et al, 1994] and portable instruments. Environmental parameters such as temperature and humidity inside the chamber are being monitored and controlled. A least square fitting to the radon growth curve data of the examined sample (Figure 2) is used for the estimation of the radon exhalation rate. The experimental data are fitted to the formula:

$$A = \frac{E}{V} \cdot (1 - e^{-\lambda t}) + A_0 \cdot e^{-\lambda t} \quad (3)$$

where:

- $A$: radon concentration inside the chamber (Bqm$^{-3}$) at time $t$,
E : exhalation rate from the sample in Bq s\(^{-1}\) (parameter estimated from the fitting)
V : radon chamber volume (m\(^3\)),
t : time elapsed since enclosure of sample in the chamber (hrs),
\(\lambda\) : decay constant (hrs\(^{-1}\)), in case of no leakage of radon from the chamber and negligible back-diffusion it should be equal to radioactive decay constant of \(^{222}\)Rn (parameter estimated from the fitting) and
\(A_0\) : initial radon concentration inside the chamber (background) in Bq m\(^{-3}\) (parameter estimated from the fitting).

Table 3 presents typical results of radon exhalation measurements (mBq kg\(^{-1}\) s\(^{-1}\)) of building materials and industrial by-products with the highest \(^{226}\)Ra activities detected in Greece.

Table 4 presents typical results of radon exhalation rate measurements (mBq m\(^{-2}\) s\(^{-1}\)) for typical structural modules used in building constructions in Greece, constructed using raw building materials with the highest \(^{226}\)Ra activity detected.

CONCLUSIONS

From the gamma-spectroscopic analyses of building materials and industrial by-products performed the following conclusions are drawn:

- Among the materials analysed the most important from the radiological point of view is black cement, because of its relatively high natural radioactivity content reaching about 150 Bq kg\(^{-1}\) [Louizi et al., 1995] and its wide use in constructions. It should be noted that in Greece quite often the dominant building material is concrete. The relatively higher natural radioactivity of black cement may be attributed to the use of fly-ash.
- Clay bricks have relatively high \(^{40}\)K activity.
- The pumice stone samples examined present a high variability. Furthermore, in one of the five samples analysed, in which high natural radioactivity was detected, significant disequilibrium among the nuclides of the uranium series was also observed.
- The natural radioactivity of fly-ash samples is relatively high and varies significantly depending on the origin of the lignite feeding the power plant. Significant disequilibrium between \(^{226}\)Ra and \(^{210}\)Pb may exist, due to the high enrichment of fly-ash in \(^{210}\)Pb, depending on the fly-ash sampling location along the emission control system of the power plant, with the ratio of \(^{210}\)Pb/\(^{226}\)Ra reaching the value of 4 [Anagnostakis, 1998]. This should be taken into account when collecting fly-ash from the Power Plant to be used in building materials industry.
- The natural radioactivity of bottom-ash was found to be lower than that of fly-ash. Significant disequilibrium among the nuclides of the uranium series was observed with the ratio \(^{210}\)Pb/\(^{226}\)Ra about 0.4 due to \(^{210}\)Pb depletion in bottom-ash [Anagnostakis, 1998].
- Radioactive disequilibrium between \(^{226}\)Ra and \(^{210}\)Pb was found in a few of the black cement samples, presumably due to the use of fly-ash in cement production.

From the radon exhalation measurements results obtained the conclusion is drawn that radon exhalation rate from building materials and structural modules, depends, further to the \(^{226}\)Ra concentration, on other factors such as the material matrix and structural module construction. From the fly-ash samples analysed the conclusion is drawn that high \(^{226}\)Ra activity in fly-ash does not necessarily implies high radon exhalation rate. The radon exhalation rate from the typical structural
modules studied, was rather low, though the raw materials used had relatively high $^{226}\text{Ra}$ activity. Simple calculations for a typical greek room constructed with high $^{226}\text{Ra}$ activity raw materials, assuming typical living habits in Greece lead to $^{222}\text{Rn}$ concentration indoors of $34\text{Bq m}^{-3}$ [Louizi et al, 1995].

REFERENCES


Table 1: Multiparametric correlations: $\ln(100\cdot\mu)=a\cdot(\ln E)^b\cdot(\ln(100\cdot\rho))^c$ of the linear attenuation coefficient $\mu$ for various materials, where $\mu$ in cm$^{-1}$, $E$ in keV and $\rho$ in grcm$^{-3}$.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample size</th>
<th>Density (grcm$^{-3}$)</th>
<th>Energy (keV)</th>
<th>Correlation coef. (r)</th>
<th>RMS (%)</th>
<th>$a \pm$ std.err (%)</th>
<th>$b \pm$ std.err (%)</th>
<th>$c \pm$ std.err (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black cement</td>
<td>29</td>
<td>1.28-1.64</td>
<td>45-186</td>
<td>0.9944</td>
<td>7.5</td>
<td>6 ±32</td>
<td>-1.6± 2.0</td>
<td>1.1 ±18</td>
</tr>
<tr>
<td>Fly-ash</td>
<td>35</td>
<td>0.72-1.19</td>
<td>45-186</td>
<td>0.9942</td>
<td>7.0</td>
<td>7.5 ±12</td>
<td>-1.7± 2.3</td>
<td>1.1 ±6.1</td>
</tr>
<tr>
<td>Bottom-ash</td>
<td>21</td>
<td>0.74-1.19</td>
<td>45-121</td>
<td>0.9909</td>
<td>7.0</td>
<td>1.4 ±20</td>
<td>-1.4± 4.0</td>
<td>1.9 ±6.3</td>
</tr>
<tr>
<td>Lignite</td>
<td>35</td>
<td>0.72-1.17</td>
<td>45-121</td>
<td>0.9904</td>
<td>5.6</td>
<td>1.0 ±13</td>
<td>-1.1 ±3.2</td>
<td>1.8 ±4.5</td>
</tr>
<tr>
<td>Soil</td>
<td>70</td>
<td>0.54-1.95</td>
<td>45-186</td>
<td>0.9847</td>
<td>10.5</td>
<td>3.0 ±8.6</td>
<td>-1.3 ±2.8</td>
<td>1.3 ±3.5</td>
</tr>
</tbody>
</table>

Table 2: Natural radioactivity of building materials used in Greece.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample Size</th>
<th>$^{238}$U (Min-Max)</th>
<th>$^{226}$Ra (Min-Max)</th>
<th>$^{210}$Pb (Min-Max)</th>
<th>$^{232}$Th (Min-Max)</th>
<th>$^{40}$K (Min-Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Cement</td>
<td>83</td>
<td>up to 173</td>
<td>29-147</td>
<td>up to 183</td>
<td>13-30</td>
<td>172-331</td>
</tr>
<tr>
<td>White Cement</td>
<td>10</td>
<td>---</td>
<td>14-26</td>
<td>---</td>
<td>7-13</td>
<td>5-67</td>
</tr>
<tr>
<td>Clay Bricks</td>
<td>13</td>
<td>---</td>
<td>25-48</td>
<td>---</td>
<td>27-56</td>
<td>476-895</td>
</tr>
<tr>
<td>Sea Sand</td>
<td>6</td>
<td>---</td>
<td>7-13</td>
<td>---</td>
<td>8-16</td>
<td>145-302</td>
</tr>
<tr>
<td>Sand</td>
<td>13</td>
<td>---</td>
<td>1-5</td>
<td>---</td>
<td>up to 3</td>
<td>1-37</td>
</tr>
<tr>
<td>Marble Powder</td>
<td>10</td>
<td>---</td>
<td>up to 1</td>
<td>---</td>
<td>up to 1</td>
<td>up to 25</td>
</tr>
<tr>
<td>Mosaic</td>
<td>7</td>
<td>---</td>
<td>1-4</td>
<td>---</td>
<td>1-3</td>
<td>up to 23</td>
</tr>
<tr>
<td>Gypsum</td>
<td>6</td>
<td>---</td>
<td>6-17</td>
<td>---</td>
<td>up to 10</td>
<td>5-40</td>
</tr>
<tr>
<td>Pumice Stone</td>
<td>5</td>
<td>up to 361</td>
<td>50-874</td>
<td>up to 1003</td>
<td>54-60</td>
<td>1048-1158</td>
</tr>
<tr>
<td>Quicklime</td>
<td>2</td>
<td>---</td>
<td>9-32</td>
<td>---</td>
<td>up to 1</td>
<td>---</td>
</tr>
<tr>
<td>Perlite</td>
<td>1</td>
<td>---</td>
<td>46</td>
<td>---</td>
<td>56</td>
<td>1048</td>
</tr>
<tr>
<td>Wall tiles</td>
<td>1</td>
<td>---</td>
<td>58</td>
<td>---</td>
<td>46</td>
<td>409</td>
</tr>
<tr>
<td>Fly-ash</td>
<td>~350</td>
<td>up to 1443</td>
<td>273-1377</td>
<td>up to 3986</td>
<td>41-65</td>
<td>143-661</td>
</tr>
<tr>
<td>Bottom-ash</td>
<td>~60</td>
<td>up to 715</td>
<td>102-743</td>
<td>up to 290</td>
<td>20-49</td>
<td>111-480</td>
</tr>
</tbody>
</table>
Table 3: Radon exhalation rate from building materials and by-products of industrial processes.

<table>
<thead>
<tr>
<th>Building Material</th>
<th>$^{226}\text{Ra}$ content (Bq kg$^{-1}$)</th>
<th>$^{222}\text{Rn}$ exhalation rate (mBq kg$^{-1}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>142</td>
<td>0.01</td>
</tr>
<tr>
<td>Fly-ash</td>
<td>1000</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 4: Radon exhalation rate from structural modules

<table>
<thead>
<tr>
<th>Structural module</th>
<th>$^{226}\text{Ra}$ concentration of the main building material used (Bq kg$^{-1}$)</th>
<th>Weighted $^{226}\text{Ra}$ concentration (Bq kg$^{-1}$)</th>
<th>Radon exhalation rate (mBq m$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slab</td>
<td>Cement: 147</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>Cement: 147, Fly-ash: 1000*</td>
<td>140</td>
<td>3.6-6.2</td>
</tr>
<tr>
<td>Granite tiles</td>
<td>Granite tiles</td>
<td>----</td>
<td>3</td>
</tr>
<tr>
<td>Brick wall</td>
<td>Clay bricks: 48</td>
<td>29</td>
<td>0.3</td>
</tr>
<tr>
<td>Brick wall</td>
<td>Clay bricks: 33</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>Pumice stone bricks wall</td>
<td>Pumice stone bricks: 48</td>
<td>48</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* Fly-ash was added to enhance $^{226}\text{Ra}$ activity of the sample.
Figure 1: Linear attenuation coefficient $\mu$ of various materials as a function of material density for photon energy 59.54keV.
Figure 2: Radon concentration growth data inside the radon chamber due to radon exhalation from a concrete slab.