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Evaluation of natural radioactivity levels and potential radiological hazards of common building materials utilized in Mediterranean region, Turkey

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Abstract

Radiometric measurement of building materials is very important to assess the internal and external exposure caused by the ionizing radiation emitted from terrestrial radionuclides in building materials. The activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in fifty-eight samples of fifteen different structural and covering building materials commonly used in Osmaniye province located in the Mediterranean region of Turkey were measured by using gamma-ray spectroscopy. The activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K varied from 2.5 ± 0.1 (marble) to 145.7 ± 4.4 (clay brick), 1.3 ± 0.1 (marble) to 154.3 ± 4.1 (marble) and 8.6 ± 0.2 (sand) to 1044.1 ± 70.3 (granite), respectively. Radiological parameters (activity concentration index, alpha index, indoor absorbed gamma dose rate and the corresponding annual effective dose rate, and excess lifetime cancer risk) were estimated to evaluate the health hazards associated with these building materials. Since the estimated values of these parameters are within the recommended safety limits or criteria values, the use of the studied building materials in the construction of dwellings can be considered to be safe for the residents of the region.

Keywords: Building materials; Natural radioactivity; External and internal index; Activity Annual effective dose; Excess lifetime cancer risk

Introduction

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Human exposure to ionizing radiation emitted from natural radioactive sources (cosmic and terrestrial radionuclides) is an ongoing and unavoidable fact of life on earth (UNSCEAR 2008). In the UNSCEAR report, the value of worldwide average annual exposure (external and internal) to natural radiation sources was estimated as 2.4 mSv (UNSCEAR 2008). The external exposure (indoor and outdoor) results from gamma-rays from terrestrial or primordial radionuclides such as radioactive potassium ($^{40}$K) and the radioactive series of uranium ($^{238}$U) and thorium ($^{232}$Th). The concentrations of these radionuclides existing in all environmental media (soil, rock, food, water, building materials, etc.) may vary depending on the geological and geochemical structure of the region (UNSCEAR 2008). The average annual external exposure was assessed as 0.48 mSv, of which 0.41 mSv is caused by indoor exposure (UNSCEAR 2008). The internal exposures come from the intake of terrestrial radionuclides by inhalation and ingestion (UNSCEAR 2008). The major contribution to the effective dose from inhalation is due to radon ($^{222}$Rn, half-life=3.83 d), which is the decay product of radium ($^{226}$Ra) in the $^{238}$U series, and its short half-life decay products such as polonium ($^{218,214}$Po), lead ($^{214}$Pb), and bismuth ($^{214}$Bi) (Turhan et al. 2018). The average annual inhalation exposure was assessed as 1.26 mSv, of which 1.15 mSv is due to $^{222}$Rn and 0.1 mSv to thoron ($^{220}$Rn, half-life=55.6 s) (UNSCEAR 2008). Epidemiological surveys carried out in Europe, North America, and China have revealed strong evidence related to increased risk of lung cancer with high levels of radon exposure in dwellings (WHO 2009; Das 2021).

Building materials generally originated from the earth’s crust (rocks and soil) can be divided into three categories: structural materials (cement, concrete, mortar, clay brick, pumice brick, etc.), covering materials used for insulation and ornamental purposes (marble, granite, andesite, tuff, gypsum plaster, etc.) and additive raw materials (blast furnace slag, fly ash, bauxite, phosphogypsum, etc.) obtained as a result of some industrial activities (Turhan et al. 2018). Building materials produced for permanent use used in the construction of
dwellings, schools, and commercial buildings where we spend most of our time (approximately 80% lifetime), are one of the main sources of indoor external and internal exposures (Turhan et al. 2007; Joel et al. 2018). However, the radiation dose received from natural radionuclides in building materials depends on some conditions such as place and type of dwellings, ventilation habits, etc. Also, the activity concentrations of natural radionuclides in building materials vary depending on the geological and geochemical structure of the region where the materials are obtained (UNSCEAR 2008). Therefore, determination of natural radioactivity levels of building materials is very important in the evaluation of radiological hazards arising from indoor external and internal exposures to individuals and preparation standards and national guidelines of these materials in the light of international recommendations (Aykamış et al. 2013; Ravisankar et al. 2016). Recently, due to the increasing social anxiety, many studies on the measurement of natural radioactivity of different building materials and the assessment of the associated radiological risks on human health were published in the literature (Kumara et al. 2018; Al-Hubail and Al-Azmi 2018; Otoo et al. 2018; Leonardi et al. 2018; De With et al. 2018; Abdullahi et al. 2019; Al-Sewaidan 2019; Nuccetelli et al. 2020; La Verde et al. 2020; Orosun et al. 2020; Ghias et al. 2021). Up to now, several studies related to the determination of the activity concentrations of $^{232}$Th, $^{226}$Ra, and $^{40}$K in some building materials used in Turkey and assessment of the radiological health hazards associated with these materials (Erees et al. 2006; Turhan et al. 2008; Turhan 2009; Mavi and Akkurt 2010; Turhan 2010; Turhan et al. 2011; Turhan and Varinlioğlu 2012; Baykara et al. 2012; Solak et al. 2014; Hatungimana et al. 2020). However, there is no detailed study related to the determination of the activity levels of terrestrial radionuclides in building materials utilized in Osmaniye province located in the Mediterranean region of Turkey and evaluation of radiological hazards associated with the utilization of these building materials.
The aim of this study is to obtain reference data related to the radioactivity level of building materials utilized in the construction of homes in Osmaniye province and evaluate their radiological consequence when used as building materials. In this study, the activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in fifty-eight samples of fifteen different structural and covering and other building materials using gamma-ray spectrometry with an HPGe detector. The potential health hazards caused by the utilization of these materials were evaluated by estimating radiological parameters (external and internal, indoor absorbed gamma dose rate and the corresponding annual effective dose rate, and excess lifetime cancer risks). The obtained results were compared with the criterion values and/or recommended limits.

**Materials and method**

**Sample collection and preparation**

For this study, a total of fifty-eight building material samples given in Table 1 were purchased from commercial markets and manufacturers in Osmaniye province. Some of these materials are also widely used in other provinces in the Mediterranean region. Approximately 0.5 kg of each sample was brought to the sample preparation laboratory and coded. Then, the samples, except cement, sand, gypsum, grouting, and ceramic glue samples, were crushed and ground into a fine powder to have the same geometry as the reference materials used in detector efficiency calibration. Before radiometric measurement, all the crushed samples were passed through a sieve of 1 mm pore size and dried at 110 °C for 15 -24 h to remove moisture content. Then each sample was transferred into a cylindrical polystyrene sample container with a volume of 118 mL, weighed, and hermetically sealed. Before counting, the sealed samples were kept for at least one month to obtain secular equilibrium between $^{226}$Ra and its decay products.

**Gamma-ray spectrometry**
Radiometric measurements of the building materials were conducted by using a high-resolution gamma-ray spectrometry system with a coaxial p-type shielded HPGe detector (GEM50P4-83) at the Central Research Laboratory of Kastamonu University, Turkey. Details of the system are given in the study performed by Sultan et al. (2020). The detector has a relative efficiency of 50%, resolution of 1.9 keV at a full-width half maximum (FWHM) for 1332.5 keV gamma-ray photopeak $^{60}$Co and peak to Compton ratio of 66:1. The efficiency calibration of the system, which depends on parameters such as detector sample distance, sample geometry, is determined using the equation given below (Solak et al. 2014):

$$\varepsilon (E_\gamma) = \frac{C_{Net}}{I_\gamma \cdot t_C \cdot A} \cdot f_C \cdot f_G \cdot f_D$$  \hspace{1cm} (1)

where $C_{Net}$ is the net counts of gamma-ray photopeak of interest, $A$ is the activity of the reference material (in Bq), $I_\gamma$ is the emission probability of the gamma-ray of interest, $t_C$ is the counting time in seconds, $f_C$ is the coincidence-summing correction factor, $f_G$ is the geometry correction factor and $f_D$ is the decay correction factor. In this study, RGU-1 (U-ore; 400 ± 2 µg g^{-1}), RGTh-1 (Th-ore; 800 ± 16 µg g^{-1}) and RGK-1 (K$_2$SO$_4$; 44.8 ± 0.3% K) reference materials purchased from IAEA were used for efficiency calibration of the gamma-ray spectrometer to eliminate the influence of coincidence summation and self-absorption effects of the emitting gamma-ray photons (Stoulos et al. 2003; Sultan et al. 2020). First, these reference materials were transferred to the sample containers to be used for measurement and weighed. The containers with RGU-1 and RGTh-1 were then sealed to prevent the escape of radon and thoron gases and kept for at least one month for secular radioactive equilibrium. Each reference container placed on the top of the detector was counted for 5,000-10,000 seconds. The efficiency values obtained using the above formula for gamma-ray photopeaks in the range of 0.2 to 2.6 MeV were fit to the following function (Kurnaz et al. 2020):

$$y(\varepsilon_\gamma) = \frac{1}{a + b \cdot x(E_\gamma)}$$  \hspace{1cm} (2)
where $E_\gamma$ is the energy of the gamma-ray photopeak and the $a$, $b$ and $c$ constants are equal to 4.64, 0.0973 and 0.899, respectively.

**Radiometric measurement**

Each sample of building material studied was placed on the detector and counted for 40,000 – 86,000 seconds to obtain good counting statistics. Background spectrum taken under the same conditions was subtracted from the sample spectra to get net counts for the sample.

GammaVision gamma-ray spectroscopy software was used for spectrum analysis such as peak searching, peak evaluation, nuclide identification, determination of uncertainty of peaks, etc. The activity concentration of $^{226}$Ra was determined using the weighted average of the gamma-ray lines emitted from the progenies of $^{226}$Ra (351.9 keV from $^{214}$Pb and 609.3 and 1764.5 keV from $^{214}$Bi). The activity concentration of $^{232}$Th was determined using the weighted average of the gamma-ray lines of 911.2 keV from $^{228}$Ac and 583.2 keV from $^{208}$Tl. The activity concentration of $^{40}$K was measured directly by its gamma-ray line at 1460.8 keV (Kurnaz et al. 2020). The minimum detectable activity ($MDA$) based on Currie’s derivation, at the 95% confidence, is determined as follows:

$$MDA(Bq \text{ kg}^{-1}) = \frac{2.71 + 4.66\sqrt{B}}{\varepsilon(E_\gamma) \cdot I_\gamma \cdot t_c \cdot M}$$

(3)

where $B$ is the area of the background continuum under the gamma-ray line of interest, $\varepsilon(E_\gamma)$ is the efficiency calculated by Eq. (1) for the interested gamma-ray lines, and $M$ is the mass of the sample (in kg). The values of $MDA$ calculated for $^{226}$Ra, $^{232}$Th and $^{40}$K varied from 0.3 and 0.6 Bq kg$^{-1}$, 0.4 to 0.7 Bq kg$^{-1}$ and 5.2 to 7.1 Bq kg$^{-1}$, respectively.

**Evaluation of radiological hazards**

Radiological parameters such as activity concentration index (external), alpha index (internal) indoor absorbed gamma dose rate caused by the external exposure and the corresponding
annual effective dose rate, and excess lifetime cancer risk were estimated to evaluate the potential radiological hazards to human health associated with these building materials. Preventive actions may be required for building materials with high annual effective dose levels caused by external exposure due to gamma radiation emitted the radionuclides in building materials where technologically enhanced naturally occurring radioactive materials are used, such as fly ash, blast furnace slag, bauxite, phosphogypsum. Therefore the activity concentration index based on the dose criterion was established by European Commission (EC 1999) as a screening tool for identifying building materials that may be exempted or subject to restrictions. The standard equation for the estimation of the activity concentration index ($I$) is given below (EC 1999):

$$I = \left( \frac{A_{Ra}}{300 \text{ Bq kg}^{-1}} + \frac{A_{Th}}{200 \text{ Bq kg}^{-1}} + \frac{A_{K}}{3000 \text{ Bq kg}^{-1}} \right)$$  \hspace{1cm} (4)

where $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the activity concentration of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in terms of Bq kg$^{-1}$, respectively. For structural materials such as cement, concrete, bricks when $I \leq 1$, the annual effective dose $\leq 1 \text{ mSv y}^{-1}$ and while $I \leq 0.5$ the annual effective $\leq 0.3 \text{ mSv y}^{-1}$ (EC 1999). For covering and other materials limited use, when $I \leq 6$, the annual effective dose $\leq 1 \text{ mSv y}^{-1}$ and while $I \leq 2$ the annual effective $\leq 0.3 \text{ mSv y}^{-1}$ (EC 1999).

The alpha index ($I_{\alpha}$) or internal health index, which is related to the assessment of excess $\alpha$-radiation due to the inhalation of $^{222}\text{Rn}$ escaping from building materials, was calculated with the formula given below (Solak et al. 2014):

$$I_{\alpha} = \frac{A_{Ra}}{200 \text{ Bq kg}^{-1}}$$  \hspace{1cm} (5)

If the activity concentration of $^{226}\text{Ra}$ in any building material exceeds a value of 200 Bq kg$^{-1}$, the $^{222}\text{Rn}$ exhalation may lead to indoor $^{222}\text{Rn}$ concentrations exceeding the recommended level of 200 Bq m$^{-3}$. Therefore, the value of $I_{\alpha}$ must be less than or equal to unity.
Indoor absorbed gamma dose rate ($D_R$ in terms of nGy h$^{-1}$) due to gamma-ray radiations emitted from natural radionuclides ($^{226}$Ra, $^{232}$Th, and $^{40}$K) in the building materials was estimated using the formula given by European Commission Report (EC 1999):

For the structural building materials:

$$D_R = 0.92 \cdot A_{Ra} + 1.10 \cdot A_{Th} + 0.08 \cdot A_K$$  \hspace{1cm} (6)

For the covering building materials:

$$D_R = 0.12 \cdot A_{Ra} + 0.14 \cdot A_{Th} + 0.0096 \cdot A_K$$  \hspace{1cm} (7)

The corresponding annual effective dose rate ($E_R$ in terms of mSv y$^{-1}$) was estimated using the following formula (UNSCEAR 2000):

$$E_R = D_R \cdot C_F \cdot OF \cdot T \cdot 10^{-6}$$  \hspace{1cm} (8)

where $D_R$ is the indoor absorbed gamma dose rate given in Eqs. (6) and (7), $C_F$ is dose conversion factor (0.7 Sv Gy$^{-1}$), $OF$ is the indoor occupancy (0.8) and $T$ is 8766 h y$^{-1}$. 

Excess lifetime cancer risk ($ELCR$), which gives the lifetime probability of cancer development as a result of exposure to ionizing radiation, was estimated using the following formula (Solak et al. 2014):

$$ELCR = E_R \cdot AL \cdot F_R$$  \hspace{1cm} (9)

where $E_R$ is the indoor annual effective dose rate given in Eq. (8), $AL$ is the average life (70 y) and $F_R$ is the fatal risk factor (0.057 Sv$^{-1}$) (ICRP 1990).

**Results and discussion**

Table 2 presents the average and range (minimum-maximum) values of activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K measured in the fifteen popularly used building materials in the study area. Fig. 1 shows the frequency distributions (histograms) of the activity concentrations of these radionuclides. A comparison of the average activity concentrations of these radionuclides in the building material samples with Earth’s crust average values is given in Fig. 2. Table 3 compares the average activity concentration of these...
radionuclides measured in the studied some building material samples with the results of similar studies reported in other countries.

It can be seen from Table 2 that the activity concentrations of radionuclides measured in the building materials show a distribution that is directly related to the geology of their origin. The activity concentrations of $^{226}$Ra varied from $2.5 \pm 0.1$ (in MARB sample) to $145.7 \pm 4.4$ (CBRICK sample) Bq kg$^{-1}$. The activity concentrations of $^{232}$Th varied from $1.3 \pm 0.1$ (IMAT sample) to $154.3 \pm 4.1$ (MARB sample) Bq kg$^{-1}$. The activity concentrations of $^{40}$K varied from $8.6 \pm 0.4$ (SND sample) to $1044.1 \pm 70.3$ (GRNT sample) Bq kg$^{-1}$. As can be seen from Fig. 1, the frequency distributions of the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K measured in the studied building materials exhibit a log-normal distribution. Approximately 50%, 85% and 80% of the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K are in the range of 3 to 35 Bq kg$^{-1}$, 1 to 45 Bq kg$^{-1}$ and 9 to 415 Bq kg$^{-1}$, respectively. From Fig. 2, the average activity concentration of $^{226}$Ra measured in the building material samples, except for SND, AGG, MARB and RTIL samples, is higher than the Earth’s crust (worldwide) average value of 32 Bq kg$^{-1}$ (UNSCEAR, 2008). The average activity concentration of $^{232}$Th measured in the building material samples, except for CEM, MARB and GRNT samples, is lower than the Earth’s crust average value of 45 Bq kg$^{-1}$ (UNSCEAR 2008). The average activity concentration of $^{40}$K measured in the building material samples, except for GRNT sample, is lower than the Earth’s crust average value of 412 Bq kg$^{-1}$ (UNSCEAR 2008). It can be seen from Table 3 that the average concentrations of $^{226}$Ra in the CEM, CBRICK, GYP, CONC, and MARB samples are higher than those obtained for some other countries, except for CONC utilized in European Union (EU) and MARB utilized in Greece, while the average concentrations of $^{226}$Ra in the SND and GRNT are lower than those obtained for some other countries, except for SND utilized in India (Polur) and GRNT utilized in Serbia and Iran (Semnan). The average concentrations of $^{232}$Th in the CEM and MARB samples are higher
than those obtained for some other countries, except for CEM utilized in Bangladesh while
the average concentrations of $^{232}$Th in the CONC and SAND are lower than those obtained for
some other countries. Also, the average concentrations of $^{232}$Th in the CBRICK, GRNT, and
GYP are comparable to those obtained for some other countries. The average concentrations
of $^{40}$K in the CONC, SND, CBRICK, GRNT, and GYP are lower than those obtained for
some other countries, except for CBRICK utilized in Iran (Semnan), GRNT utilized in Serbia
and Iran (Semnan), and GYP utilized in Egypt.

The average and range values of the activity concentration index (I) and alpha index ($I_\alpha$)
estimated for the studied building materials are given in Table 4. The values of I and $I_\alpha$ varied
from 0.02 to 1.4 (GRNT sample) and 0.01 to 0.7 (CBRICK sample), respectively. All values
of I estimated for the structural materials don’t exceed the recommended maximum or
criterion limit of unity corresponding to an annual effective dose rate of 1 mSv y$^{-1}$ while all
values of I estimated for the covering and other materials with restricted use are lower than
the exemption level of 2 corresponding to an annual effective dose rate of 0.3 mSv y$^{-1}$. All
values of $I_\alpha$ are lower than the recommended limit of unity corresponding to $^{222}$Rn activity
concentration of 200 Bq m$^{-3}$.

The average and range values of the indoor absorbed gamma dose rate ($D_R$) and the
corresponding annual effective dose rate ($E_R$), and excess lifetime cancer risk (ELCR)
estimated for the structural and covering building materials are given in Table 5. The values
of $D_R$ and $E_R$ varied from 1 (MARB sample) to 261 (CBRICK sample) nGy h$^{-1}$ and 0.003 to
1.3 mSv y$^{-1}$, respectively. The average values of $D_R$ estimated for CONC, SND, MARB,
GRN, and CTILE are below the world average indoor absorbed gamma dose rate of 84 nGy
h$^{-1}$ (UNCCERA, 2000). The average values of $D_R$ estimated for CEM, CBRICK and PBRIC
are higher than %45-61 higher than the world average value. All values of $E_R$ estimated for
the covering building materials are lower than the world average of 0.41 mSv y$^{-1}$ (UNSCEAR
Furthermore, these values meet the exemption for the annual effective dose criterion of 0.3 mSv y\(^{-1}\) recommended by the EU (EC 1999). The average values of \(E_R\) estimated for the structural building materials are higher than the world average of 0.41 mSv y\(^{-1}\) except for CONC samples. Conversely, all average values meet the annual effective dose criterion of 1 mSv y\(^{-1}\) recommended by EU (EC 1999). The average values of ELCR varied from \(2.3 \times 10^{-4}\) to \(2.3 \times 10^{-3}\). All average values of ELCR estimated for the structural and covering building materials, except for MARB and CTILE are above the world average of \(2.9 \times 10^{-4}\) due to the annual effective dose rate caused by external exposure outdoor (UNSCEAR 2000). Whereas the average ELCR values estimated for CEM, CBRICK, and PBRICK are higher than the world average of \(1.4 \times 10^{-3}\) due to the annual effective dose from indoor external exposure (UNSCEAR 2000).

Conclusions

Determination of the activity concentration levels of the natural radionuclides contained in the building materials utilized in the construction of dwellings, schools, and commercial buildings is very important to evaluate the radiological risks associated with the utilization of these materials. The activity concentrations of \(^{226}\text{Ra}, ^{232}\text{Th},\) and \(^{40}\text{K}\) together with the radiological parameters (activity concentration and alpha index, indoor absorbed gamma dose rate and the corresponding annual effective dose rate, and excess lifetime cancer risk) for the popularly utilized 58 building materials (6 structural and 9 covering and other materials) in the Mediterranean region of Turkey, especially Osmaniye province was investigated using the gamma-ray spectroscopy. The activity concentration results of these terrestrial radionuclides reveal that there are significant differences in the measured values of building material samples originating from different areas. This fact is important in choosing suitable materials for utilization in buildings in the regions. It is concluded that all values of the activity concentration and alpha index estimated for the studied building materials are lower than the
criterion of unity. Also, all average values of the annual effective dose rate are below the effective dose rate criterion of 1 mSv y\(^{-1}\) recommended by EU. Consequently, this study reveals that the studied building material samples are within the recommended safety limit and do not pose any significant source of radiation risks. The data obtained in this study is significant in two respects: Firstly, it can create awareness for the local community using these materials regarding the radioactivity that building materials may contain. Secondly, this data is evaluated to be prepared standards and/or regulations regarding the use and management of building materials utilized in Turkey.

**Author contribution**

M. Karataşlı collected the building samples and prepared the samples for the radioactivity measurements. A. Kurnaz and Ş. Turhan performed the laboratory measurements and analyzed the spectra and done the spectra evaluations and the data analysis including the statistical analysis. Ş. Turhan was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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**Competing interests**

The authors declare no competing interests.

**Availability of data and materials**

All data generated or analyzed during this study are included in this published article anyway datasets are available from the corresponding author on reasonable request.

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FIGURE CAPTIONS

Fig. 1  Frequency distributions of the activity concentrations of radionuclides in the studied building materials

Fig. 2  Comparison of the average values of radionuclides measured in the studied building materials with those in the Earth's crust
TABLE CAPTIONS

Table 1  Building materials of different types utilized in Osmaniye province

Table 2  The activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K measured in the studied building material samples

Table 3  Comparison of radioactivity concentrations measured in this study with those in building materials utilized in other countries

Table 4  The values of activity concentration index and alpha index

Table 5  The values of the indoor absorbed gamma dose rate, annual effective dose, and excess lifetime cancer risk
Fig. 1
| Type                                           | Building material | Sample ID | N  |
|------------------------------------------------|-------------------|-----------|----|
| Structural materials used in bulk amounts      |                   |           |    |
| Cement                                         | CEM               |           | 5  |
| Concrete                                       | CONC              |           | 3  |
| Clay brick                                     | CBRCK             |           | 4  |
| Pumice brick                                   | PBRCK             |           | 3  |
| Sand                                           | SND               |           | 5  |
| Aggregate                                      | AGG               |           | 4  |
| Covering and other materials with restricted   |                   |           |    |
| Marble                                         | MARB              |           | 5  |
| Granite                                        | GRNT              |           | 3  |
| Ceramic tile                                   | CTIL              |           | 5  |
| Roofing tile                                   | RTIL              |           | 3  |
| Gypsum                                         | GYP               |           | 5  |
| Limestone                                      | LSTN              |           | 2  |
| Insulating material                            | IMAT              |           | 3  |
| Grouting                                       | GROU              |           | 3  |
| Ceramic glue                                   | CGLUE             |           | 5  |

Table 1
| Sample ID | Activity concentration (Bq kg\(^{-1}\)) | 226Ra | 232Th | 40K  |
|-----------|----------------------------------------|-------|-------|------|
| CEM       | Average 63.7                           | 63.7  | 46.2  | 306.2|
|           | Range 11.8 ± 0.4–91.4 ± 2.7            | 11.8  | 12.1  | 135.5|
| CONC      | Average 46.4                           | 46.4  | 19.0  | 115.0|
|           | Range 13.4 ± 0.3–65.7 ± 1.8            | 13.4  | 12.3  | 48.1  |
| CBRIK     | Average 63.5                           | 63.5  | 30.8  | 372.3|
|           | Range 18.8 ± 0.5–45.7 ± 4.4            | 18.8  | 4.6   | 53.5  |
| PBRIK     | Average 67.6                           | 67.6  | 44.0  | 298.7|
|           | Range 42.7 ± 1.1–95.4 ± 2.8            | 42.7  | 41.0  | 110.6 |
| CONC      | Average 12.3                           | 12.3  | 4.9   | 90.0  |
|           | Range 8.6 ± 0.2–20.2 ± 0.5             | 8.6   | 1.8   | 8.6   |
| AGG       | Average 8.7                            | 8.7   | 6.3   | 123.7 |
|           | Range 7.4 ± 0.2–9.5 ± 0.3              | 7.4   | 6.2   | 118.2 |
| MARB      | Average 30.3                           | 30.3  | 57.9  | 296.7 |
|           | Range 2.5 ± 0.1–89.1 ± 2.3             | 2.5   | 1.3   | 12.7  |
| GRNT      | Average 45.4                           | 45.4  | 82.3  | 931.6 |
|           | Range 13.4 ± 0.4–103.0 ± 2.8           | 13.4  | 46.5  | 784.0 |
| CTILE     | Average 43.5                           | 43.5  | 37.9  | 310.9 |
|           | Range 9.6 ± 0.3–102.6 ± 2.7            | 9.6   | 8.9   | 41.9  |
| RTILE     | Average 27.0                           | 27.0  | 32.6  | 346.6 |
|           | Range 18.9 ± 0.4–36.6 ± 0.9            | 18.9  | 22.9  | 65.6  |
| GYP       | Average 44.5                           | 44.5  | 11.9  | 101.5 |
|           | Range 26.5 ± 0.8–53.4 ± 1.6            | 26.5  | 5.6   | 53.5  |
| LSTN      | Average 44.2                           | 44.2  | 7.2   | 78.9  |
|           | Range 38.9 ± 1.2–49.4 ± 1.5            | 38.9  | 5.1   | 61.2  |
| IMAT      | Average 52.6                           | 52.6  | 7.1   | 118.0 |
|           | Range 17.7 ± 0.5–97.8 ± 2.9            | 17.7  | 1.3   | 66.0  |
| GROU      | Average 37.1                           | 37.1  | 15.5  | 94.0  |
|           | Range 15.3 ± 0.4–53.2 ± 1.6            | 15.3  | 9.1   | 41.4  |
| CGLUE     | Average 60.2                           | 60.2  | 18.1  | 247.8 |
|           | Range 37.2 ± 1.1–97.3 ± 2.9            | 37.2  | 6.3   | 95.8  |

Table 2
| Building material | Country | Activity concentration (Bq kg⁻¹) | Reference |
|-------------------|---------|---------------------------------|-----------|
|                   |         | $^{226}$Ra | $^{232}$Th | $^{40}$K |
| Cement            | Nigeria | 21 | 16 | 147 | Aladeniyi et al. 2021 |
|                   | Iran (Semnan) | 31 | 15 | 231 | Imani et al. 2021 |
|                   | India (Polur) | 37 | 34 | 188 | Ravisankar et al. 2016 |
|                   | Egypt | 45 | 10 | 51 | Shoeib and Thabayneh 2014 |
|                   | European Union | 45 | 31 | 216 | Trevisi et al. 2012 |
|                   | Serbia | 37 | 15 | 43 | Pantelić et al. 2015 |
|                   | Malaysia | 29 | 31 | 205 | Abdullahi et al. 2019 |
|                   | Bangladesh | 61 | 65 | 952 | Asaduzzaman et al. 2015 |
|                   | Turkey (Osmaniye) | 64 | 46 | 306 | This study |
| Concrete          | Nigeria | 23 | 60 | 536 | Aladeniyi et al. 2021 |
|                   | China (Beijing) | 16 | 51 | 605 | Tuo et al. 2020 |
|                   | Serbia | 17 | 21 | 253 | Kuzmanović et al. 2020 |
|                   | European Union | 60 | 35 | 392 | Trevisi et al. 2012 |
|                   | Turkey (Osmaniye) | 46 | 19 | 115 | This study |
| Sand              | Nigeria | 18 | 59 | 236 | Aladeniyi et al. 2021 |
|                   | Iran (Semnan) | 24 | 22 | 362 | Imani et al. 2021 |
|                   | India (Polur) | 11 | 130 | 297 | Ravisankar et al. 2016 |
|                   | Egypt | 17 | 13 | 119 | Shoeib and Thabayneh 2014 |
|                   | Serbia | 26 | 30 | 210 | Pantelić et al. 2015 |
|                   | Malaysia | 43 | 45 | 451 | Abdullahi et al. 2019 |
|                   | Bangladesh | 54 | 77 | 982 | Asaduzzaman et al. 2015 |
|                   | Turkey (Osmaniye) | 12 | 5 | 90 | This study |
| Clay brick        | Nigeria | 40 | 62 | 1045 | Aladeniyi et al. 2021 |
|                   | Iran (Semnan) | 31 | 28 | 338 | Imani et al. 2021 |
|                   | China (Beijing) | 14 | 39 | 678 | Tuo et al. 2020 |
|                   | Serbia | 45 | 49 | 646 | Kuzmanović et al. 2020 |
|                   | India (Polur) | 5 | 23 | 374 | Ravisankar et al. 2016 |
|                   | Egypt | 23 | 23 | 448 | Shoeib and Thabayneh 2014 |
|                   | Czech | 45 | 47 | 611 | UNSCEAR, 2008 |
|                   | Turkey (Osmaniye) | 64 | 31 | 372 | This study |
| Marble            | Iran (Semnan) | 7 | 7 | 917 | Imani et al. 2021 |
|                   | China(Taiwan) | 16 | 22 | 133 | UNSCEAR 2008 |
|                   | Germany | 24 | 5 | 90 | UNSCEAR 2008 |
|                   | Greece | 81 | 34 | 483 | UNSCEAR 2008 |
|                   | Pakistan | 16 | 20 | 248 | UNSCEAR 2008 |
|                   | Turkey (Osmaniye) | 30 | 58 | 297 | This study |
| Granite           | Nigeria | 74 | 100 | 1098 | Aladeniyi et al. 2021 |
|                   | Iran (Semnan) | 38 | 47 | 917 | Imani et al. 2021 |
|                   | China (Beijing) | 356 | 318 | 1637 | Tuo et al. 2020 |
|                   | Serbia | 200 | 77 | 1280 | Kuzmanović et al. 2020 |
|                   | Germany | 100 | 120 | 1000 | UNSCEAR 2008 |
|                   | Italy | 89 | 94 | 1126 | UNSCEAR 2008 |
|                   | Spain | 86 | 45 | 1028 | UNSCEAR 2008 |
|                   | Serbia | 38 | 43 | 660 | Pantelić et al. 2015 |
|                   | Turkey (Osmaniye) | 45 | 82 | 932 | This study |
| Gypsum            | Iran (Semnan) | 12 | 14 | 116 | Imani et al. 2021 |
|                   | Egypt | 8 | 8 | 85 | Shoeib and Thabayneh 2014 |
|                   | Czech | 12 | 10 | 187 | UNSCEAR 2008 |
|                   | Italy | 8 | 3 | 160 | UNSCEAR 2008 |
|                   | Romania | 41 | 40 | 199 | UNSCEAR 2008 |
|                   | European Union | 15 | 9 | 91 | Trevisi et al. 2012 |
|                   | Turkey (Osmaniye) | 45 | 12 | 102 | This study |

Table 3
| Sample ID | I Average | I Range   | I₀ Average | I₀ Range   |
|-----------|-----------|-----------|------------|------------|
| CEM       | 0.5       | 0.3–0.7   | 0.3        | 0.1–0.5    |
| CONC      | 0.3       | 0.2–0.4   | 0.2        | 0.1–0.3    |
| CBRICK    | 0.5       | 0.2–1.0   | 0.3        | 0.1–0.7    |
| PBRICK    | 0.6       | 0.5–0.7   | 0.3        | 0.2–0.5    |
| SND       | 0.10      | 0.06–0.12 | 0.06       | 0.04–0.10  |
| AGG       | 0.102     | 0.096–0.108 | 0.043    | 0.037–0.048 |
| MARB      | 0.49      | 0.02–1.35 | 0.15       | 0.01–0.45  |
| GRNT      | 0.9       | 0.6–1.4   | 0.2        | 0.1–0.5    |
| CTIL      | 0.4       | 0.1–0.9   | 0.2        | 0.1–0.5    |
| RTIL      | 0.37      | 0.32–0.45 | 0.14       | 0.09–0.18  |
| GYP       | 0.24      | 0.16–0.33 | 0.22       | 0.13–0.27  |
| LSTN      | 0.21      | 0.18–0.24 | 0.22       | 0.19–0.25  |
| IMAT      | 0.25      | 0.09–0.47 | 0.26       | 0.09–0.47  |
| GROU      | 0.23      | 0.11–0.32 | 0.19       | 0.08–0.27  |
| CGLUE     | 0.37      | 0.19–0.50 | 0.30       | 0.19–0.49  |

Table 4
| Sample ID | DR (nGy h⁻¹) | ER (mSv y⁻¹) | ELCR |
|-----------|---------------|---------------|------|
| CEM       | Average 134   | 0.7           | 2.3 x 10⁻³ |
|           | Range 87–168  | 0.4–0.8       | 1.5 x 10⁻³–2.9 x 10⁻³ |
| CONC      | Average 73    | 0.4           | 1.3 x 10⁻³ |
|           | Range 44–93   | 0.2–0.5       | 7.5 x 10⁻⁴–1.6 x 10⁻³ |
| CBRICK    | Average 122   | 0.6           | 2.1 x 10⁻³ |
|           | Range 45–261  | 0.2–1.3       | 7.7 x 10⁻⁴–4.5 x 10⁻³ |
| PBRICK    | Average 135   | 0.7           | 2.3 x 10⁻³ |
|           | Range 113–163 | 0.6–0.8       | 1.9 x 10⁻³–2.8 x 10⁻³ |
| SND       | Average 24    | 0.12          | 4.1 x 10⁻⁴ |
|           | Range 16–29   | 0.08–0.14     | 2.7 x 10⁻⁴–5.0 x 10⁻⁴ |
| AGG       | Average 25    | 0.12          | 4.3 x 10⁻⁴ |
|           | Range 23–26   | 0.11–0.13     | 4.0 x 10⁻⁴–4.5 x 10⁻⁴ |
| MARB      | Average 15    | 0.07          | 2.5 x 10⁻⁴ |
|           | Range 1–41    | 0.003–0.199   | 1.2 x 10⁻⁵–7.0 x 10⁻⁴ |
| GRNT      | Average 26    | 0.13          | 4.5 x 10⁻⁴ |
|           | Range 16–42   | 0.08–0.21     | 2.8 x 10⁻⁴–7.3 x 10⁻⁴ |
| CTIL      | Average 13    | 0.07          | 2.3 x 10⁻⁴ |
|           | Range 4–29    | 0.02–0.14     | 7.1 x 10⁻⁵–5.0 x 10⁻⁴ |

Table 5
Figures

**Figure 1**

Frequency distributions of the activity concentrations of radionuclides in the studied building materials
Figure 2

Comparison of the average values of radionuclides measured in the studied building materials with those in the Earth's crust