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RESEARCH ARTICLE

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

Şeref Turhan[1] · Asli Kurnaz[1] · Muhammet Karataşlı[2]

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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 Gamma-ray spectrometry · Radiation exposure · Effective dose · Cancer risk · Osmaniye

Introduction

Human exposure to ionizing radiation emitted from natural radioactive sources (cosmic and terrestrial radionuclides) is an ongoing and unavoidable fact of life on the 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, which is the decay product of radium in the uranium series, and its short half-life decay products. 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 (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; Lubin et al. 1995; Darby et al. 1995; Tirmarche et al. 2012; Axelsson et al. 2015).

Building materials generally originated from the earth's crust (rocks and soil) can be divided into three categories:

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✉ Asli Kurnaz
kurnazasli56@gmail.com; akurnaz@kastamonu.edu.tr

[1] Department of Physics, Faculty of Science and Letters, Kastomunu University, 37150 Kastamonu, Turkey

[2] Department of Electronics and Communication, Faculty of Engineering and Architecture, Beykent University, Sarıyer, İstanbul, Turkey

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). However, the radiation dose received from natural radionuclides in building materials depends on some conditions such as place and type of dwellings and ventilation habits. 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, the 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 (Sas et al. 2017; 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; Kocsis 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; Damla et al. 2009; Turhan 2009; Mavi and Akkurt 2010; Turhan 2010; Turhan et al. 2011; Turhan and Varinlioğlu 2012; Baykara et al. 2012; Tufan and Dişçi 2013; Solak et al. 2014; Yapıcı et al. 2017; Hatungimana et al. 2020; Parmaksız 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. Cement, concrete, clay brick, pumice brick, and ceramic tiles are produced according to Turkish Standards TS EN 197-1, TS EN 206, TS EN 777-1, TS 406, and TS EN 14411, respectively. Trade names of the building materials collected for this study were not given due to commercial concerns. About 70% 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 samples weighing between 0.09 and 0.21 kg were transferred into cylindrical polystyrene sample containers each with a volume of 118 mL and hermetically sealed. Before counting, the sealed samples were kept for at least 1 month to obtain secular equilibrium between ^{226}Ra and its decay products.

Radiometric measurement

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). 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 and sample geometry, is determined using the equation given below (Solak et al. 2014):

$$\varepsilon\left(\mathrm{E}_{\gamma}\right)=\frac{C_{\mathrm{Net}}}{I_{\gamma}\cdot t_{C}\cdot A}\cdot f_{C}\cdot f_{G}\cdot f_{D} \tag{1}$$

where C_{Net} is the net counts of gamma-ray photopeak of interest, A is the activity of the reference material (in Bq), I_{γ} is the emission probability of the gamma-ray of interest; t_C is the counting time in seconds, f_C is the coincidence-summing

Table 1 Building materials of different types utilized in Osmaniye province

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 restriction	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

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_2SO_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). 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):

$$y(\varepsilon_\gamma) = \frac{1}{a + b \cdot x(E)^c} \tag{2}$$

where E_γ 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.

Each sample of building material studied was placed on the detector and counted for 40,000–86,000 s 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. 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:

$$\text{MDA}\left(\text{Bq kg}^{-1}\right) = \frac{2.71 + 4.66\sqrt{B}}{\varepsilon\left(E_\gamma\right) \cdot I_\gamma \cdot t_C \cdot M} \tag{3}$$

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 to 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, and 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):

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

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

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

$$I_\alpha = \frac{A_{Ra}}{200\ \mathrm{Bq\ kg^{-1}}} \quad (5)$$

If the activity concentration of ^{226}Ra in any building material exceeds a value of 200 Bq kg^{-1}, the ^{222}Rn exhalation may lead to indoor ^{222}Rn concentrations exceeding the recommended level of 200 Bq m^{-3}. Therefore, the value of I_α 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):

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

Sample ID		Activity concentration (Bq kg^{-1})		
		^{226}Ra	^{232}Th	^{40}K
CEM	Average	63.7	46.2	306.2
	Range	11.8 ± 0.4–91.4 ± 2.7	12.1 ± 0.3–112.3 ± 3.1	135.5 ± 7.2–423.7 ± 23.8
CONC	Average	46.4	19.0	115.0
	Range	13.4 ± 0.3–65.7 ± 1.8	12.3 ± 0.3–29.3 ±0.6	48.1 ± 2.4–222.6 ± 13.5
CBRICK	Average	63.5	30.8	372.3
	Range	18.8 ± 0.5–45.7 ± 4.4	4.6 ± 0.1–55.2 ± 1.5	53.5 ± 2.4–821.9 ± 60.1
PBRIK	Average	67.6	44.0	298.7
	Range	42.7 ± 1.1–95.4 ± 2.8	41.0 ± 1.3–46.8 ± 1.4	110.6 ± 5.4–493.6 ± 36.8
SND	Average	12.3	4.9	90.0
	Range	8.6 ± 0.2–20.2 ± 0.5	1.8 ± 0.1–7.7 ± 0.2	8.6 ± 0.4–157.7 ± 7.1
AGG	Average	8.7	6.3	123.7
	Range	7.4 ± 0.2–9.5 ± 0.3	6.2 ± 0.2–6.5 ± 0.2	118.2 ± 5.2–134.3 ± 6.7
MARB	Average	30.3	57.9	296.7
	Range	2.5 ± 0.1–89.1 ± 2.3	1.3 ± 0.1–154.3 ± 4.1	12.7 ± 0.7–857.3 ± 62.4
GRNT	Average	45.4	82.3	931.6
	Range	13.4 ± 0.4–103.0 ± 2.8	46.5 ± 1.4–141.9 ± 3.7	784.0 ± 42.5–1044.1 ± 70.3
CTILE	Average	43.5	37.9	310.9
	Range	9.6 ± 0.3–102.6 ± 2.7	8.9 ± 0.2–77.0 ± 2.0	41.9 ± 3.9–641.7 ± 50.6
RTILE	Average	27.0	32.6	346.6
	Range	18.9 ± 0.4–36.6 ± 0.9	22.9 ± 0.5–39.2 ± 1.1	65.6 ± 3.5–505.6 ± 30.2
GYP	Average	44.5	11.9	101.5
	Range	26.5 ± 0.8–53.4 ± 1.6	5.6 ± 0.2–26.2 ± 0.8	53.5 ± 2.8–128.9 ± 7.9
LSTN	Average	44.2	7.2	78.9
	Range	38.9 ± 1.2–49.4 ± 1.5	5.1 ± 0.1–9.3 ± 0.3	61.2 ± 3.7–96.5 ± 5.6
IMAT	Average	52.6	7.1	118.0
	Range	17.7 ± 0.5–97.8 ± 2.9	1.3 ± 0.1–16.8 ± 0.5	66.0 ± 3.4–183.0 ± 9.7
GROU	Average	37.1	15.5	94.0
	Range	15.3 ± 0.4–53.2 ± 1.6	9.1 ± 0.2–20.7 ± 0.6	41.4 ± 2.1–168.6 ± 9.5
CGLUE	Average	60.2	18.1	247.8
	Range	37.2 ± 1.1–97.3 ± 2.9	6.3 ± 0.2–25.8 ± 0.7	95.8 ± 7.1–709.9 ± 40.2

For the structural building materials:

$$D_R = 0.92 \cdot A_{Ra} + 1.10 \cdot A_{Th} + 0.08 \cdot A_K \tag{6}$$

For the covering building materials:

$$D_R = 0.12 \cdot A_{Ra} + 0.14 \cdot A_{Th} + 0.0096 \cdot A_K \tag{7}$$

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

$$E_R = D_R \cdot C_F \cdot OF \cdot T \cdot 10^{-6} \tag{8}$$

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):

$$\mathrm{ELCR} = E_R \cdot AL \cdot F_R \tag{9}$$

where E_R is the indoor annual effective dose rate given in Eq. (8), AL is the average life (70 years), 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. In this study, it was assumed that ^{228}Ra and ^{228}Th were in secular equilibrium with the parent nuclide ^{232}Th, which is common in these sorts of mineral samples (Shahrokhi and Kovács 2021). Fig. 1 shows the frequency distributions (histograms) of the activity concentrations of these radionuclides. A comparison of the average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K 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 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 ± 0.1 (in MARB sample) to 145.7 ± 4.4 (CBRICK sample) Bq kg^{-1}. The activity concentrations of ^{232}Th varied from 1.3 ± 0.1 (IMAT sample) to 154.3 ± 4.1 (MARB sample) Bq kg^{-1}. The activity concentrations of ^{40}K varied from 8.6 ± 0.4

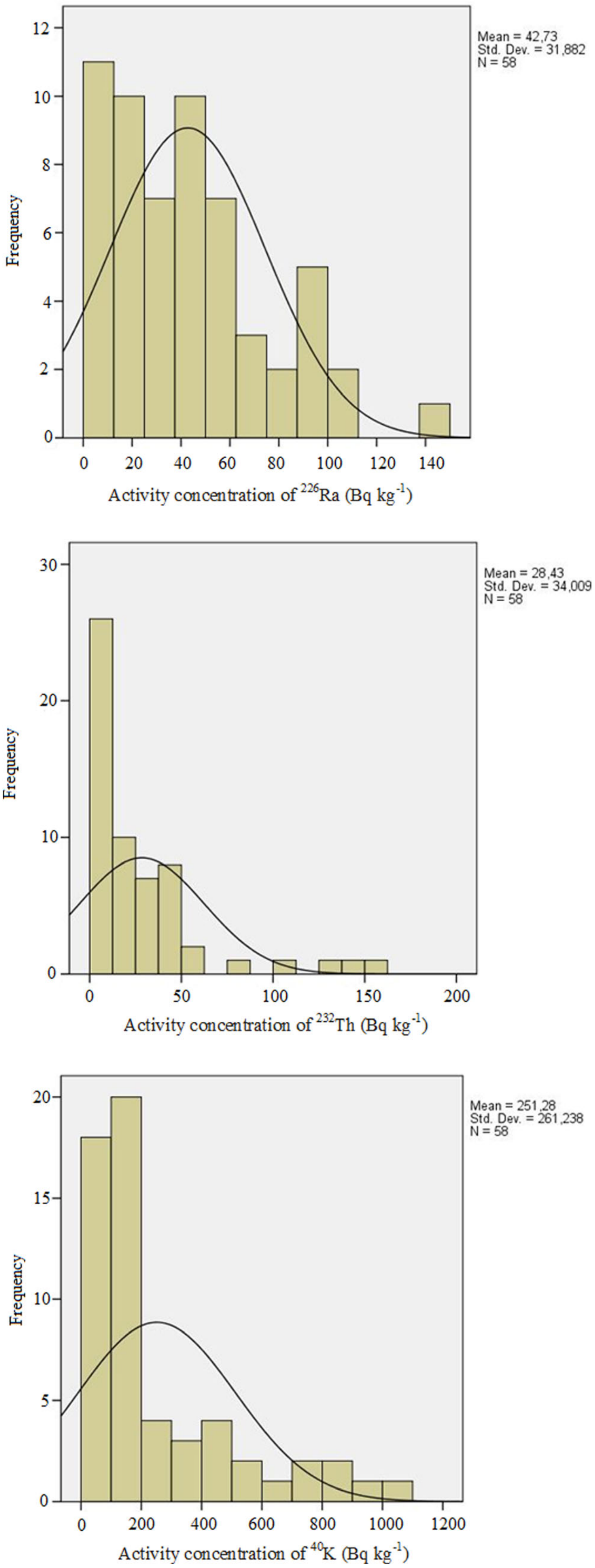

Fig. 1 Frequency distributions of the activity concentrations of radionuclides in the studied building materials

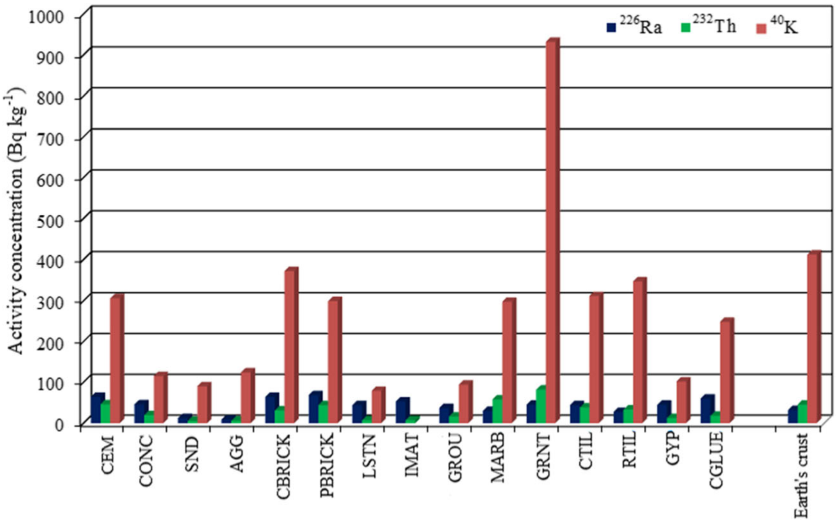

Fig. 2 Comparison of the average values of radionuclides measured in the studied building materials with those in the Earth's crust

(SND sample) to 1044.1 ± 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 the 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, expect 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 and Iran (Mahallat).

The average and range values of the activity concentration index (I) and alpha index (I_α) estimated for the studied building materials are given in Table 4. The values of I and I_α 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 do not 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_α 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 2000). Furthermore, these values meet the exemption for the annual effective dose criterion of 0.3 mSv y^{-1} recommended by the EU (EC 1999).

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

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
	Iran (Mahallat)	34	25	229	Shahrokhi et al. 2020
	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
	Iran (Mahallat)	32	32	289	Shahrokhi et al. 2020
	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
	Iran (Mahallat)	35	28	402	Shahrokhi et al. 2020
	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
	Iran (Mahallat)	27	21	92	Shahrokhi et al. 2020
	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 4 The values of activity concentration index and alpha index

Sample ID	I		I_α	
	Average	Range	Average	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

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 the EU (EC 1999). The average values of ELCR varied from 2.3 × 10^{-4} to 2.3 × 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 × 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 × 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}Ra, ^{232}Th, and ^{40}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, were 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

Table 5 The values of the indoor absorbed gamma dose rate, annual effective dose, and excess lifetime cancer risk

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

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 the 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.

Data availability 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.

Declarations

Ethics approval All analyses were based on previous published studies; thus, no ethical approval consent is required.

Consent to participate Not applicable.

Consent for publication All authors have checked the manuscript and have agreed to the publication on ESPR.

Competing interests The authors declare no competing interests.

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