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Measurement of the natural radioactivity in building materials used in Ankara and assessment of external doses

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Abstract
A total of 183 samples of 20 different commonly used structural and covering building materials were collected from housing and other building construction sites and from suppliers in Ankara to measure the natural radioactivity due to the presence of ^{226}Ra, ^{232}Th and ^{40}K. The measurements were carried out using gamma-ray spectrometry with two HPGe detectors. The specific activities of the different building materials studied varied from 0.5 ± 0.1 to 144.9 ± 4.9 Bq kg^{-1}, 0.6 ± 0.2 to 169.9 ± 6.6 Bq kg^{-1} and 2.0 ± 0.1 to 1792.3 ± 60.8 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. The results show that the lowest mean values of the specific activity of ^{226}Ra, ^{232}Th and ^{40}K are 0.8 ± 0.5, 0.9 ± 0.4 and 4.1 ± 1.4 Bq kg^{-1}, respectively, measured in travertine tile while the highest mean values of the specific activity of the same radionuclides are 78.5 ± 18.1 (ceramic wall tile), 77.4 ± 53.0 (granite tile) and 923.4 ± 161.0 (white brick), respectively. The radium equivalent activity (Ra_{eq}), the gamma-index, the indoor absorbed dose rate and the corresponding annual effective dose were evaluated to assess the potential radiological hazard associated with these building materials. The mean values of the gamma-index and the estimated annual effective dose due to external gamma radiation inside the room for structural building materials ranged from 0.15 to 0.89 and 0.2 to 1.1 mSv, respectively. Applying criteria recently recommended for building materials in the literature, four materials meet the exemption annual dose criterion of 0.3 mSv, five materials meet the annual dose limit of 1 mSv and only one material slightly exceeds this limit. The mean values of the gamma-index for all building materials were lower than the upper limit of 1.

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1. Introduction

All building materials such as concrete, cement, brick, sand, aggregate, marble, granite, limestone, gypsum, etc contain mainly natural radionuclides, including uranium (^{238}U) and thorium (^{232}Th) and their decay products and the radioactive isotope of potassium (^{40}K). In the ^{238}U series, the decay chain segment starting from radium (^{226}Ra) is radiologically the most important and, therefore, reference is often made to ^{226}Ra instead of ^{238}U. The naturally occurring radionuclides in the building materials contribute to radiation exposure, which can be can be divided into external and internal exposure. External exposure is caused by direct gamma radiation while internal exposure is caused by the inhalation of the radioactive inert gas radon (^{222}Rn, a daughter product of ^{226}Ra) and its short-lived secondary decay products. Knowledge of the level of natural radioactivity in building materials is then important to assess the possible radiological hazards to human health and to develop standards and guidelines for the use and management of these materials.

During the last decades, there has been an increasing interest in the study of radioactivity in various building materials [1–19]. However, there are few data available about the specific activity of ^{226}Ra, ^{232}Th and ^{40}K in raw building materials and products in Turkey [20].

The aim of this study is to measure the natural radioactivity in 20 different commonly used building materials in Ankara, Turkey's second largest city (a population of 4319 167) after Istanbul, and to continue the project related to the measurement of the natural radioactivity in Turkish building materials [20]. The results were used to assess the potential radiological hazards associated with these building materials by computing the radium equivalent activity, the gamma-index, the indoor gamma absorbed dose rate and the annual effective dose.

2. Materials and method

2.1. Sample collection and preparation

Samples representing 20 different commonly used structural and covering building materials were collected randomly from sites where housing and other buildings were under construction and from building material suppliers in Ankara for the measurement of the specific radioactivity of ^{226}Ra, ^{232}Th and ^{40}K. Structural building materials (cement, brick, concrete, sand and aggregate) are used in bulk amounts while covering building materials (tiles, limestone, gypsum, natural tiling stones and adhesive) have a restricted use.

The samples were properly catalogued and marked and coded according to the origin and the location of the sampling site. The samples were ground into a fine powder with a particle size less than 1 mm. Some of the samples such as cement and gypsum could be used without any processing because they are already in powdered form. The samples were then dried in a temperature-controlled furnace at 110 °C for 20–24 h to remove moisture. After moisture removal, these samples were cooled in a moisture-free atmosphere. Each sample was then filled into cylindrical plastic containers ($\phi = 5$ cm, $h = 6$ cm), weighed and hermetically sealed. The geometrical dimensions of the samples were kept identical to that of the reference materials (RGU-1, RGTh-1 and RGK-1). The sealed samples and the reference materials were stored for 4 weeks before counting to allow ^{226}Ra and its short-lived decay products to reach secular equilibrium.

2.2. Gamma-ray spectroscopic technique

Two commercially available high-resolution gamma-spectrometry systems with p-type coaxial HPGe detectors manufactured by Canberra Inc. were used to measure the natural radioactivity in the building materials. One of the counting systems was equipped with a HPGe detector with an active volume of 451 cm^3. The detector has a relative efficiency of 110%, an energy resolution of 2.1 keV at 1332.5 keV for ^{60}Co and of 1.3 keV at 122 keV for ^{57}Co, and a peak-to-Compton ratio of 85:1. The other counting system was equipped with an active volume of 57 cm^3. The detector has a relative efficiency of 11.4%, an energy resolution of 1.96 keV at 1332.5 keV for ^{60}Co, and a peak-to-Compton ratio of 42.1:1. The detectors were shielded to reduce the gamma-ray background.

The absolute efficiency calibration of the gamma spectrometry systems was carried out using the radionuclide specific efficiency method in order to reduce the uncertainty in gamma-ray intensities, as well as the influence of coincidence summation and self-absorption effects of the emitting gamma photons [21]. The IAEA reference materials RGU-1 (U ore), RGTh-1 (Th ore) and RGK-1 (K_2SO_4), with densities similar to the samples to be measured after pulverization, were employed for the efficiency calibration of the system. The sample containers were placed on top of the detector for counting. The same geometry was used to determine the peak area of samples and references. On average, the counting time was 8 and 24 h for the 10% and 110% HPGe detectors, respectively. Background measurements were taken under the same conditions of sample measurements and subtracted in order to get net counts for the sample.

The specific activities were averaged from gamma-ray photopeaks at several energies. The gamma-ray lines of 295.2, 351.9 keV from ^{214}Pb and 609.3, 1764.5 keV from ^{214}Bi were used to determine the specific activity of ^{226}Ra. The gamma-ray lines of 338.4, 911.2 keV from ^{228}Ac, 727.3 keV from ^{212}Bi and 583.2 keV from ^{208}Tl were used to determine the specific activity of ^{232}Th. The specific activity of ^{40}K was measured directly by its own gamma-ray line at 1460.8 keV.

3. Results and discussion

3.1. Specific radioactivity

The range (maximum and minimum) and mean of the specific radioactivity values of ^{226}Ra, ^{232}Th and ^{40}K measured in the building materials, together with the statistical uncertainty (1σ) and standard deviation (SD) are shown in table 1 (structural building materials) and table 2 (covering building materials). The mean specific activities are compared in figure 1.

As can be seen from tables 1 and 2, the highest values for the specific activity of ^{226}Ra, ^{232}Th and ^{40}K are 144.9 ± 4.9, 166.9 ± 6.6 and 1792.3 ± 60.8 Bq kg^{-1}, respectively, measured in granite tile while the lowest values of the specific activity of the same radionuclides are 0.5 ± 0.1 (travertine tile), 0.6 ± 0.2 (travertine tile) and 2.0 ± 0.1 Bq kg^{-1} (gypsum), respectively. The mean specific radioactivity in the 20 different building materials studied varies from 0.8 ± 0.5 to 78.5 ± 18.1 Bq kg^{-1}, 0.9 ± 0.4 to 77.4 ± 53.0 Bq kg^{-1} and 4.1 ± 1.4 to 923 ± 161.0 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively.

These mean values are lower than the corresponding world-wide average values which are 40, 40 and 400 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively, except for red brick, white brick, sand, red brick roofing tile, wall and floor ceramic tiles and granite tile [22]. Wall and floor ceramic tiles, commonly used in bathrooms, toilets and kitchens, get their sanitary white appearance from zircon added to the glaze matrix. Zircon pigments are often used in the ceramic industry for glazes due to their high chemical stability and superior resistance to dissolution during firing in glazes.

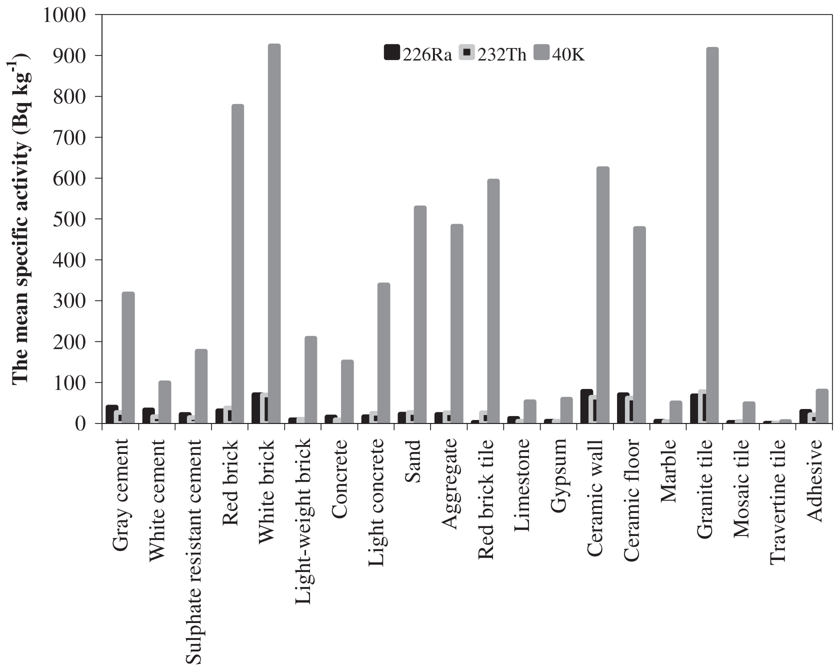

Figure 1. Comparison of the mean specific activities of ^{226}Ra, ^{232}Th and ^{40}K measured in the 20 different types of building materials.

3.2. Radium equivalent activity

The distribution of natural radionuclides in the samples under investigation is not uniform. Therefore, a common radiological index has been introduced to evaluate the actual activity level of ^{226}Ra, ^{232}Th and ^{40}K in the samples and the radiation hazards associated with these radionuclides. This index is usually known as radium equivalent (Ra_{eq}) activity [23]:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_{K} \tag{1}$$

where A_{Ra}, A_{Th} and A_{K} are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bq kg^{-1}. In the definition of Ra_{eq}, it is assumed that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K produce an equal gamma-ray dose rate [24, 25]. The range and mean values of the calculated Ra_{eq} for all the building materials studied are shown in the third and fourth columns of table 3. The calculated Ra_{eq} values range from 2.4 ± 0.2 Bq kg^{-1} (for marble) to 488.8 ± 34.9 Bq kg^{-1} (for granite tile). All of the Ra_{eq} values, except for granite tile, are lower than the criterion limit of 370 Bq kg^{-1} [26]. On the other hand, the mean Ra_{eq} values range from 2.4 ± 0.2 Bq kg^{-1} (for travertine tile) to 244.3 ± 152.3 Bq kg^{-1} (for granite tile) and these values are below the quoted criterion.

3.3. Gamma-index

A number of indices dealing with the assessment of the excess gamma radiation originating from building materials such as external and internal health indices and gamma-concentration indices have been proposed by several investigators [24, 25, 27, 28]. In this study, the gamma-

Table 1. The range and mean values of the specific activities of ^{226}Ra, ^{232}Th and ^{40}K measured in structural building materials.

Material	N		Specific activity (in Bq kg^{-1} ± 1σ)		
			A_{Ra}	A_{Th}	A_K
Grey cement	37	Range	17.8 ± 0.7 to 81.6 ± 3.0	7.8 ± 0.5 to 48.8 ± 1.3	169.1 ± 8.2 to 475.7 ± 10.6
		Mean ± SD	39.9 ± 18.0	26.4 ± 9.8	316.5 ± 88.1
White cement	5	Range	27.5 ± 0.9 to 38.3 ± 1.0	7.5 ± 0.3 to 23.1 ± 0.9	62.4 ± 2.3 to 128.3 ± 2.6
		Mean ± SD	32.8 ± 5.1	16.3 ± 7.6	99.2 ± 31.8
Sulphate resistant cement	7	Range	14.6 ± 0.4 to 33.1 ± 0.7	10.6 ± 0.5 to 17.5 ± 1.0	146.6 ± 10.8 to 230.3 ± 5.1
		Mean ± SD	21.7 ± 6.7	14.0 ± 2.5	176.4 ± 26.5
Red brick	11	Range	24.7 ± 1.1 to 49.0 ± 3.0	26.6 ± 2.1 to 51.2 ± 4.3	587.3 ± 16.0 to 1092.0 ± 26.7
		Mean ± SD	31.2 ± 7.6	37.2 ± 7.8	775.8 ± 149.6
White brick	4	Range	65.8 ± 1.7 to 74.7 ± 3.1	52.8 ± 3.1 to 79.3 ± 2.9	723.0 ± 13.4 to 1079.8 ± 17.7
		Mean ± SD	69.9 ± 4.4	69.6 ± 11.7	923.4 ± 161.0
Lightweight brick	3	Range	4.3 ± 0.3 to 12.9 ± 0.7	6.4 ± 0.7 to 16.6 ± 0.2	148.4 ± 3.5 to 326.0 ± 5.8
		Mean ± SD	8.8 ± 4.3	9.9 ± 5.8	208.3 ± 101.9
Concrete	5	Range	6.6 ± 0.3 to 26.9 ± 1.5	1.3 ± 0.1 to 21.5 ± 1.8	44.8 ± 1.1 to 465.4 ± 9.3
		Mean ± SD	15.7 ± 7.3	8.9 ± 4.3	150.5 ± 28.4
Light concrete (gas concrete)	6	Range	12.3 ± 0.6 to 23.6 ± 1.6	14.1 ± 1.4 to 36.7 ± 1.8	287.9 ± 7.1 to 403.2 ± 6.1
		Mean ± SD	16.5 ± 4.1	24.7 ± 9.6	338.5 ± 55.4
Sand	19	Range	4.8 ± 0.3 to 56.0 ± 1.9	2.2 ± 0.2 to 67.0 ± 3.4	81.6 ± 1.6 to 879.0 ± 24.2
		Mean ± SD	22.9 ± 12.9	26.4 ± 16.2	527.2 ± 129.2
Aggregate	7	Range	16.9 ± 0.6 to 28.3 ± 0.7	14.9 ± 0.8 to 32.3 ± 1.4	404.7 ± 4.9 to 551.6 ± 13.9
		Mean ± SD	21.6 ± 4.2	25.8 ± 6.5	482.2 ± 51.8

index (I_γ) was calculated as proposed by the European Commission (EC 1999) [29]:

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \tag{2}$$

where A_{Ra}, A_{Th} and A_K are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively in Bq kg^{-1}. $I_\gamma \leqslant 1$ corresponds to an annual effective dose less than or equal 1 mSv, while $I_\gamma \leqslant 0.5$ corresponds to an annual effective dose less than or equal 0.3 mSv. The range and mean values of the calculated I_γ are shown in the last two columns of table 3 for all the studied building materials. It is observed in table 3 that the mean values of I_γ are below the criterion of 0.5 corresponding to an annual effective dose 0.3 mSv except for granite and ceramic tiles. The mean values of I_γ for ceramic floor tiles (0.68), ceramic wall tiles (0.78) and granite tiles (0.92) are below the criterion of unity corresponding to an annual effective dose of 1 mSv.

3.4. Estimation of the absorbed gamma dose rate and the annual effective dose

The absorbed dose rate in indoor air (D_R) and the corresponding annual effective dose (H_R), due to gamma-ray emission from the radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in the building material, were evaluated using data and formulae provided by UNSCEAR (2000) and EC (1999) [22, 29, 30]. In the UNSCEAR and European Commission reports, the dose conversion coefficients were calculated for the centre of the standard room. The dimensions of the room are 4 m × 5 m × 2.8 m. The thickness of walls, floor and ceiling and density of the structures are 20 cm and 2350 kg m^{-3} (concrete), respectively. These coefficients correspond to 0.92 nGy h^{-1}

Table 2. The range and mean values of the specific activities of ^{226}Ra, ^{232}Th and ^{40}K measured in covering building materials.

			Specific activity (in Bq kg^{-1} ± 1σ)		
Material	N		A_{Ra}	A_{Th}	A_K
Red brick roofing tile	4	Range	23.1 ± 1.1 to 31.7 ± 2.2	15.0 ± 1.3 to 30.4 ± 2.2	456.8 ± 8.8 to 751.3 ± 13.7
		Mean ± SD	27.5 ± 3.5	25.8 ± 7.3	592.6 ± 137.6
Limestone	7	Range	1.0 ± 0.1 to 26.1 ± 1.3	1.8 ± 0.1 to 8.2 ± 0.7	10.8 ± 0.4 to 130.4 ± 8.6
		Mean ± SD	11.9 ± 9.5	5.4 ± 2.2	52.7 ± 41.2
Gypsum	7	Range	1.2 ± 0.1 to 14.6 ± 0.8	0.8 ± 0.2 to 18.2 ± 1.7	2.0 ± 0.1 to 186.3 ± 9.2
		Mean ± SD	5.2 ± 4.5	5.2 ± 4.9	59.0 ± 41.0
Ceramic wall tile	6	Range	54.2 ± 2.0 to 105.1 ± 5.5	44.8 ± 2.2 to 88.2 ± 6.2	325.7 ± 10.9 to 1043.7 ± 28.3
		Mean ± SD	78.5 ± 18.1	64.3 ± 17.2	623.4 ± 232.9
Ceramic floor tile	5	Range	40.2 ± 2.4 to 96.0 ± 4.5	53.4 ± 4.0 to 68.7 ± 5.0	289.7 ± 9.9 to 579.2 ± 10.7
		Mean ± SD	70.3 ± 23.7	62.1 ± 7.4	476.9 ± 132.3
Marble	22	Range	0.6 ± 0.1 to 27.3 ± 1.3	1.2 ± 0.1 to 11.8 ± 1.0	2.9 ± 0.1 to 366.7 ± 9.3
		Mean ± SD	5.4 ± 4.8	4.9 ± 3.8	49.7 ± 19.0
Granite tile	16	Range	3.1 ± 0.2 to 144.9 ± 4.9	1.2 ± 0.1 to 166.9 ± 6.6	19.7 ± 1.4 to 1792.3 ± 60.8
		Mean ± SD	67.5 ± 47.6	77.4 ± 53.0	915.3 ± 361.2
Mosaic tile	5	Range	0.7 ± 0.1 to 3.8 ± 0.3	3.1 ± 0.3 to 6.6 ± 0.4	3.3 ± 0.1 to 110.8 ± 9.6
		Mean ± SD	2.4 ± 1.2	4.6 ± 1.8	47.8 ± 18.4
Travertine tile	2	Range	0.5 ± 0.1 to 1.1 ± 0.3	0.6 ± 0.2 to 1.1 ± 0.2	3.1 ± 0.1 to 5.1 ± 0.2
		Mean ± SD	0.8 ± 0.5	0.9 ± 0.4	4.1 ± 1.4
Adhesive	5	Range	7.3 ± 0.4 to 69.4 ± 2.7	1.7 ± 0.2 to 56.6 ± 3.3	20.6 ± 0.4 to 816.0 ± 35.5
		Mean ± SD	29.3 ± 24.3	21.2 ± 20.3	79.2 ± 63.6

per Bq kg^{-1} for ^{226}Ra, 1.1 nGy h^{-1} per Bq kg^{-1} for ^{232}Th and 0.080 nGy h^{-1} per Bq kg^{-1} for ^{40}K:

$$D_R\ (\text{nGy h}^{-1}) = 0.92 \times A_{Ra} + 1.1 \times A_{Th} + 0.080 \times A_K \quad (3)$$

where A_{Ra}, A_{Th} and A_K are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively in Bq kg^{-1}.

To estimate the annual effective dose, one has to take into account the conversion factor from absorbed dose in air to effective dose and the indoor occupancy factor. In the recent UNSCEAR (2000) reports, a value of 0.7 Sv Gy^{-1} was used for the conversion factor from absorbed dose in air to effective dose received by adults, and 0.8 for the indoor occupancy factor, implying that 80% of time is spent indoors, on average, around the world. The annual effective dose in units of mSv was estimated using the following formula:

$$H_R = D_R \times 8766\ \text{h} \times 0.8\ (\text{occupancy factor}) \times 0.7\ \text{Sv Gy}^{-1}\ (\text{conversion factor}) \times 10^{-6} \quad (4)$$

where D_R (nGy h^{-1}) is given by equation (3).

The estimated results for D_R and the corresponding H_R are given in table 4. The estimated D_R and H_R values for all the studied structural building materials range from 13.9 to 245.5 nGy h^{-1} and 0.1 to 1.2 mSv, respectively. From the data in table 4, the estimated mean value of D_R for white cement, sulphate resistant cement, lightweight brick, concrete and gas concrete samples is lower than the world average (populated-weighted) indoor absorbed gamma dose rate of 84 nGy h^{-1}. The estimated mean value of D_R for grey cement, sand and aggregate exceeds by 10% the quoted world average value. The highest mean values of D_R are estimated in white brick (221.2 ± 27.5 nGy h^{-1}) and red brick (137.1 ± 26.7 nGy h^{-1}).

Table 3. The range and mean of the calculated radium equivalent (Ra_{eq}) activity and gamma-index (I_γ) values for all building materials.

		Ra_{eq} (in Bq kg^{-1} $\pm 1\sigma$)		I_γ	
Material	N	Range	Mean ± SD	Range	Mean ± SD
Gray cement	37	53.2 ± 4.3 to 169.51 ± 12.6	101.9 ± 31.1	0.2–0.6	0.40 ± 0.06
White cement	5	47.1 ± 7.0 to 80.9 ± 8.0	63.8 ± 14.7	0.2–0.3	0.22 ± 0.05
Sulphate resistant cement	7	45.5 ± 10.8 to 65.0 ± 11.5	55.3 ± 7.4	0.2–0.3	0.20 ± 0.03
Red brick	11	111.0 ± 16.3 to 206.1 ± 27.2	144.0 ± 28.2	0.4–0.8	0.48 ± 0.07
White brick	4	197.7 ± 14.0 to 265.4 ± 20.3	240.4 ± 29.6	0.7–1.0	0.89 ± 0.08
Lightweight brick	3	30.3 ± 3.6 to 48.0 ± 3.8	39.0 ± 8.9	0.1–0.2	0.15 ± 0.03
Concrete	5	16.9 ± 1.4 to 93.4 ± 9.4	40.0 ± 31.4	0.1–0.4	0.15 ± 0.12
Light concrete (gas concrete)	6	55.5 ± 7.3 to 100.7 ± 6.4	77.8 ± 19.3	0.2–0.4	0.28 ± 0.05
Sand	19	14.2 ± 1.4 to 203.3 ± 12.2	101.2 ± 50.6	0.1–0.8	0.42 ± 0.15
Aggregate	7	73.5 ± 5.0 to 116.7 ± 12.5	95.6 ± 14.2	0.3–0.4	0.41 ± 0.07
Red brick roofing tile	4	79.7 ± 7.9 to 128.4 ± 11.6	109.9 ± 21.6	0.3–0.5	0.43 ± 0.06
Limestone	7	1.8 ± 0.4 to 33.5 ± 3.8	20.8 ± 13.2	0.01–0.12	0.07 ± 0.05
Gypsum	7	2.6 ± 0.7 to 55.0 ± 4.9	16.4 ± 10.0	0.01–0.20	0.06 ± 0.02
Ceramic wall tile	6	147.5 ± 5.0 to 311.4 ± 20.2	218.3 ± 56.8	0.5–1.1	0.78 ± 0.16
Ceramic floor tile	5	138.7 ± 10.1 to 237.2 ± 17.0	195.8 ± 41.3	0.5–0.9	0.68 ± 0.08
Marble	22	0.2 ± 0.1 to 53.2 ± 6.4	9.8 ± 3.4	0.001–0.2	0.04 ± 0.01
Granite tile	16	3.2 ± 0.6 to 488.8 ± 34.9	244.3 ± 152.3	0.01–1.8	0.92 ± 0.58
Mosaic tile	5	0.7 ± 0.1 to 20.6 ± 1.9	9.3 ± 8.4	0.002–0.08	0.03 ± 0.02
Travertine tile	2	2.2 ± 0.2 to 2.5 ± 0.3	2.4 ± 0.2	0.008–0009	0.008 ± 0.001
Adhesive	5	11.3 ± 1.3 to 213.0 ± 17.7	79.2 ± 15.3	0.04–0.8	0.29 ± 0.19

Applying dose criteria recently recommended by the EU for building materials, four structural building materials (white cement, sulphate resistant cement, lightweight brick and concrete) meet the exemption for the annual effective dose criterion of 0.3 mSv, five materials (grey cement, red brick, light concrete, sand and aggregate) meet the dose limit of 1 mSv and only one material (white brick) slightly exceeds this limit. In the case of the higher annual effective dose due to some white brick samples the high activity of additives such as pumice is responsible because the specific activity values of ^{226}Ra, ^{232}Th and ^{40}K of the pumice samples are higher than the corresponding world mean values [20].

4. Conclusions

For each sample in this study, the specific activity of ^{226}Ra, ^{232}Th and ^{40}K, the radium equivalent activity, the gamma-index, the absorbed gamma dose rate in indoor air and the corresponding annual effective dose have been determined to assess the radiological hazards from the building materials commonly used in Ankara. The results show that there are considerable variations in the measured values of samples of building material originating from different areas. This fact is important from the point of view of selecting suitable materials for use in building and construction. It is concluded that the calculated mean Ra_{eq} values for all the building materials examined are lower than the recommended maximum level of a radium equivalent of 370 Bq kg^{-1} for raw building materials and products. Also, the calculated mean values of I_γ are below the criterion of unity corresponding to a dose of 1 mSv y^{-1}. It can be seen that the estimated mean annual effective dose for structural building materials is

Table 4. The range and mean values of the estimated indoor absorbed gamma dose rate and the corresponding effective dose rate from structural building materials.

		D_R (nGy h^{-1})		H_R (mSv y^{-1})	
Material	*N*	Range	Mean ± SD	Range	Mean ± SD
Grey cement	37	50.9–150.8	93.2 ± 27.9	0.2–0.7	0.5 ± 0.1
White cement	5	42.8–70.6	56.1 ± 11.9	0.2–0.3	0.3 ± 0.1
Sulphate resistant cement	7	40.5–58.8	49.5 ± 6.8	0.2–0.3	0.24 ± 0.03
Red brick	11	106.6–196.4	137.1 ± 26.7	0.5–1.0	0.7 ± 0.1
White brick	4	182.3–245.5	221.2 ± 27.5	0.9–1.2	1.1 ± 0.1
Lightweight brick	3	28.9–43.0	37.1 ± 7.8	0.1–0.2	0.18 ± 0.04
Concrete	5	15.4–88.9	37.3 ± 30.0	0.1–0.4	0.18 ± 0.15
Light concrete (gas concrete)	6	52.7–91.4	71.8 ± 16.5	0.3–0.4	0.4 ± 0.1
Sand	19	13.9–187.8	96.0 ± 46.6	0.1–0.9	0.5 ± 0.2
Aggregate	7	71.0–109.4	90.2 ± 12.6	0.3–0.5	0.4 ± 0.1

lower than the annual dose limit of 1 mSv except for white brick. Effective doses exceeding the dose criterion should be taken into account in terms of radiation protection according to recommendation 112 issued by the European Union in 1999 [29].

As a conclusion, the present study shows that the building material samples examined, except for white brick, are within the recommended safety limit and do not pose any significant source of radiation hazard.

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