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Natural radioactivity and hazard-level assessment of Portland cements in Turkey

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Abstract The natural radioactivity levels and some radiological parameters of Turkish Portland cements (PC) originated in various regions were determined in this study. The activity concentration of cement samples for ^{226}Ra, ^{232}Th, and ^{40}K were measured using a gamma-ray spectrometer with high purity germanium radiation detector. The PC samples had activity concentrations of 33.0, 16.7, and 239.5 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively. The mean value of radium equivalent value (Ra_{eq}) was found to be 75.4 Bq kg^{-1}. The radium equivalent values in the cement samples were lower than the acceptable level of 370 Bq kg^{-1}. The calculated radiological parameters were found to be below the acceptance levels.

Keywords Natural radioactivity · Radiation hazard · Gamma spectrometry · Cement

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Introduction

Human exposure to environmental radiation comes from a number of naturally occurring and anthropogenic sources. Natural radioactive materials such as uranium, thorium, and ^{40}K can be found everywhere in the world. In addition, humans are exposed to external sources radiations from cosmic and terrestrial radiation. According to United Nations Scientific Committee of the Effects of Atomic Radiation (UNSCEAR), the worldwide average effective dose is 2.42 mSv of which, 0.87 mSv comes from external gamma exposure and 1.55 mSv from internal exposure of inhalation and ingestion dose [1].

The determination of indoor radiation dose for human health is very important and thus, the knowledge of the natural activity level of construction materials such as cement is necessary [2]. The raw materials that are used in cement industry are obtained from soil and rock, which contain diverse amounts of radionuclides of uranium (^{238}U) and thorium (^{232}Th) series, and the radioactive isotope of potassium (^{40}K). In the ^{238}U series, the segment starting from radium (^{226}Ra) is radiological the most important one and, therefore, it is commonly referred to as ^{226}Ra instead of ^{238}U [3]. It is well recognized that some construction materials are naturally more radioactive than others. The natural radioactive materials used in construction even at low level causes an increase external and internal indoor exposure [4]. The external radiation exposure is caused by gamma radiation of the uranium and thorium decay and from ^{40}K. The internal radiation exposure, mainly affecting the respiratory tract, is due to the short-lived daughter products of radon, which are released from materials to the indoor air [5]. People spend about 80% of their life inside houses and workplaces. Therefore, determination of primordial radionuclides (^{226}Ra, ^{232}Th and ^{40}K) and attenuation coefficient in building materials is important in order to protect humans from radiological hazards. Moreover, such knowledge is essential for the development of standards and guidelines for the use of these materials [6, 7].

In this study, the activities of natural radionuclides of ^{226}Ra, ^{232}Th and ^{40}K, and radiological parameters such as radium equivalent activity, absorbed dose rate, gamma and external-internal hazard indices were determined to assess the radiation risk associated with the cement produced in Turkey.

Material and method

Sample collection and preparation

In this study, in order to measure the natural radioactivity levels of Portland cement (PC), CEM I type samples produced in 16 locations were selected representing all geographical regions in Turkey were selected. All PC samples were taken from local markets as 50 kg paper bags. Figure 1 shows the locations of 16 PC sample sources that are produced by Turkish cement plants.

The characteristics of CEM I which include clinker in range of 95–100 and 0–5% minor additive of Gypsum used in buildings are given in TS EN 197-1 [8] standard. This standard is a descriptive standard which includes the composition, properties and eligibility criteria of general cement grades. This standard was revised in Europe in November 2011 and in Turkey in February 2012 [8].

The natural radioactivity levels of cement samples were measured using gamma-ray spectrometry with an HPGe detector. All measurements were duplicated and data sets were given as mean values. All of the cement samples were used without any processing such as crushing, homogenization, and sieving since they were already in a powder form. Of each sample of cement, 1 kg was picked and dried in a temperature-controlled furnace at 110 °C for 20–24 h to completely remove moisture. After drying process, cement samples were cooled in the moisture-free atmosphere and transferred to 250 cm^3 polyethylene beaker. Before counting, the beakers were completely hermetically sealed for 4 weeks to reach the secular equilibrium, where the rate of decay of the radon daughters becomes equal to that of the parent. This step was necessary to ensure that radon gas was confined within the volume and the daughters remained in the sample [3, 9].

Gamma spectrometric measurements

Gamma spectrometric measurements for each sample's activity concentration were conducted with Canberra Inc. manufactured with Extended Range Coaxial high-purity germanium (HPGe) detector placed in Canberra Standard Lead Shield, Canberra DSA1000 digital spectrum analyzer, Genie2000 Basic Spectroscopy Software with Gamma, Interactive Peak Fit and QA/QC options. Properties of the HPGe detector were provided by the manufacturer as Relative efficiency: 50%, Crystal diameter (mm): 69.5, Crystal length (mm): 51.0, End-cap diameter (inch): 3.5, End-cap material: Al.

Energy and efficiency calibrations of the system were performed by using multinuclide gamma standard sources including ^{210}Pb, ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{203}Hg, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{88}Y and ^{60}Co gamma rays (which covers the energy range between 46 and 1836 keV) supplied from Isotope Products Laboratories, Eckert & Ziegler, Berlin, Germany. For self-absorption effects to be taken into account, an epoxy source with 0.4, 1.0 g/cm^3 density, and a

Fig. 1 Locations of sampling points

sand source with 1.7 g/cm^3 density were used. 170 ml polyethylene cylindrical beakers, which were also supplied to Isotope Products Laboratories for reference source filling, were used for measurements. Source to the detector distance was kept at approximately 0.5 cm and true coincidence corrections for the calibration and measurement of radionuclides of interest were performed using Gespecor software.

All sample counts and background counts were taken approximately for 1 day. The specific activity of ^{40}K was measured directly by its own gamma-ray at 1460.8 keV while activities of ^{226}Ra and ^{232}Th were calculated from the weighted mean of their respective daughter products in secular equilibrium in proportion to their errors. The specific activity of ^{226}Ra was calculated using ^{214}Pb (295 and 352 keV) and ^{214}Bi (609 and 1765 keV) while the specific activity of ^{232}Th was calculated using ^{228}Ac (338 and 911 keV) and ^{208}Tl (583 keV).

The minimum detectable activities (MDAs) were calculated using Eq. 1 [10]:

$$\mathrm{MDA} = \frac{2.71 + 4.65\sqrt{B}}{(\varepsilon \times t \times \gamma \times m)} \tag{1}$$

where B is the background counts, ε is the counting efficiency, γ is the gamma emission probability for the gamma of interest, m is the mass of sample and t is the measurement time. The MDA values were estimated to be between 0.7 and 1.8 Bq kg^{-1} for ^{226}Ra, 0.7 and 2.0 Bq kg^{-1} for ^{232}Th and 14.0 and 22.8 Bq kg^{-1} for ^{40}K.

Radium equivalent activity (Ra$_{eq}$)

In order to compare the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in studied cement samples on a combined scale, Radium equivalent activity (Ra$_{eq}$) levels were calculated from Eq. (2):

$$\mathrm{Ra_{eq}} = A_{\mathrm{Ra}} + 1.43A_{\mathrm{Th}} + 0.077A_{\mathrm{K}} \tag{2}$$

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

Criterion formula (CF)

A very useful comparison criterion formula (CF) was suggested by Ravinsankar et al. [11] for limiting the annual radiation dose from building materials. CF is given by Eq. (3):

$$\mathrm{CF} = \frac{A_{\mathrm{Ra}}}{740\ \mathrm{Bq\ kg^{-1}}} + \frac{A_{\mathrm{Th}}}{520\ \mathrm{Bq\ kg^{-1}}} + \frac{A_{\mathrm{K}}}{9620\ \mathrm{Bq\ kg^{-1}}} < 1 \tag{3}$$

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

Representative level index (RLI)

The level of gamma radioactivity associated with different concentrations of certain specific radionuclides can be estimated as a representative level index (RLI) [11, 12] as given by Eq. (4):

$$\mathrm{RLI} = \frac{1}{150}A_{\mathrm{Ra}} + \frac{1}{100}A_{\mathrm{Th}} + \frac{1}{1500}A_{\mathrm{K}} \tag{4}$$

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

Estimation of the absorbed gamma dose rate (D_R) and annual effective dose rate (H_R)

Absorbed gamma dose rate (D_R) in the indoor air, and annual effective dose rate (H_R) related to gamma-ray emission from the radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in the building materials were assessed based on the data and the equations provided by UNSCEAR [1] and the European Commission (EC) [13]. Also, the dose conversion coefficients for the center of a standard room were calculated according to UNSCEAR and EC regulations. The dimensions of the standard room were 4 m × 5 m × 2.8 m. The thickness of the concrete walls, floors, ceiling, and the density of the building were 20 cm and 2350 kg/m^{-3}, respectively. Absorbed gamma dose rate (D_R) was calculated from Eq. (5):

$$D_R\left(\mathrm{nGy\ h^{-1}}\right) = 0.92A_{\mathrm{Ra}} + 1.1A_{\mathrm{Th}} + 0.08A_{\mathrm{K}} \tag{5}$$

where, A_{Ra}, A_{Th}, and A_{K} are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K respectively, in Bq kg^{-1}. According to UNSCEAR [1], taking into account of the external exposure rates from terrestrial gamma radiation, population-weighted average value of worldwide absorbed dose rate in the air was found to be 84.00 nGy h^{-1}. This value was adopted as a reference for comparison of D_R parameter in this study.

Annual effective dose rate (H_R) was calculated from Eq. (6) as adopted from UNSCEAR with Ravisankar et al. coefficients' arrangements [1, 11]:

$$\begin{aligned} H_R\left(\mathrm{mSv\ year^{-1}}\right) &= D_R \times 8766 \times 0.2 \times 0.7 \times 10^{-6} \\ &= D_R \times 0.00123 \end{aligned} \tag{6}$$

where, D_R(nGy h^{-1}) is given by Eq. (5). The worldwide average value of H_R is 0.48 mSv year^{-1} which is adopted from UNSCEAR [1] as a reference value.

Gamma Index (I_γ)

The gamma activity concentration index, I_γ, was defined by the European Commission [13], and Righi and Bruzzi [14] and is given in Eq. (7):

$$I_\gamma = \frac{A_{Ra}}{300\ \mathrm{Bq\ kg^{-1}}} + \frac{A_{Th}}{200\ \mathrm{Bq\ kg^{-1}}} + \frac{A_K}{3000\ \mathrm{Bq\ kg^{-1}}} \quad (7)$$

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

Radiation hazard indices

Radiation hazard indices were measured using the two hazard indices as defined by Beretka and Mathew [15]. The first one was the external radiation hazard, H_{ex}, and the latter was the internal radiation hazard, H_{in}. Those indices are discussed below.

External radiation hazard (H_{ex})

External radiation hazard, H_{ex}, has been adopted as a limit value of unity in order to be non-hazardous. It is given in Eq. (8):

$$H_{ex} = \frac{A_{Ra}}{370\ \mathrm{Bq\ kg^{-1}}} + \frac{A_{Th}}{259\ \mathrm{Bq\ kg^{-1}}} + \frac{A_K}{4810\ \mathrm{Bq\ kg^{-1}}} \quad (8)$$

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

Internal radiation hazard (H_{in})

Internal radiation hazard, H_{in}, is given in Eq. (9). The criterion value is less than or equal to unity [16].

$$H_{in} = \frac{A_{Ra}}{185\ \mathrm{Bq\ kg^{-1}}} + \frac{A_{Th}}{259\ \mathrm{Bq\ kg^{-1}}} + \frac{A_K}{4810\ \mathrm{Bq\ kg^{-1}}} \quad (9)$$

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

Results and discussion

Activity concentration

The measured activity concentration of ^{226}Ra, ^{232}Th and ^{40}K of the studied cement is given in Table 1. The lowest value of ^{226}Ra activity of the analyzed cement samples was measured in sample PC16 (14.30 Bq kg^{-1}), while the highest value for the same radionuclide was measured in PC05 (76.0 Bq kg^{-1}, Table 1). The highest activity value for ^{232}Th was still found in PC05 (34.0 Bq kg^{-1}) and the lowest was 6.70 Bq kg^{-1} in PC11. The lowest value for ^{40}K was 60.0 Bq kg^{-1} measured in PC06, and the highest value was 530.0 Bq kg^{-1} in PC08.

The contents of ^{226}Ra, ^{232}Th and ^{40}K in tested cement samples depends on the raw materials and probably vary considerably in relation to the various geological source and geochemical characteristics. The mean activity concentrations of radionuclide parts in PCs were measured as 33.0, 16.7 and 239.5 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively.

Radium equivalent activity (Ra_{eq})

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K determined in this study for PCs, were also compared with other studies shown in Table 2. In addition to this, the mean activity concentration values of ^{226}Ra, ^{232}Th, and ^{40}K found to be 68, 80, and 45%, respectively, which were lower than the cement samples given in Table 2. On the other hand, the maximum activity concentration values of singular cement samples for of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, were lower than 11, 25, and 5% of cement samples given in Table 2.

Ra_{eq} levels are given in Tables 1 and 2. All studied cement samples were compared with the specification limit of 370 Bq kg^{-1} [12]. Ra_{eq} values of cements in this study were between 36.0 and 144.9 Bq kg^{-1}. The mean value of Ra_{eq} was calculated as 75.4 Bq kg^{-1}. All Ra_{eq} values of measured PC are lower than the criterion limit of 370 Bq kg^{-1}. Ra_{eq} values in Table 2 also shows that even in other PC samples around the world, Ra_{eq} is lower than the criterion limit value. However, mean Ra_{eq} value of cements in this study was 75.4 Bq kg^{-1} which was lower than 74% as shown in Table 2. Meanwhile, the maximum level of Ra_{eq} was 144.9 Bq kg^{-1}, 17% lower compared to other cement samples given in Table 2.

Criterion formula (CF)

CF values of the cement samples were between 0.05 and 0.20 (mean value of CF = 0.10) and all values were considerably lower compared to the recommended maximum value 1.0. Therefore, it can be concluded from CF results that, the annual radiation dose from building materials manufactured using Turkish PC have minimal effect on human health.

Activity concentration comparison

Comparison of natural radioactivity of PCs and data sets of this study for ^{226}Ra, ^{232}Th and ^{40}K is shown in Table 2. Same type comparison was also fulfilled for Radium-equivalent activity (Ra_{eq}) values for the same two sets of data.

Representative level index (RLI)

RLI values of PC samples of the present study were between 0.27 and 1.02. Mean value of RLI was 0.55.

Table 1 Activity concentrations and some of the related parameter values in studied Portland cement (PC) samples of Turkey

Sample ID	Activity concentration ($Bq\ kg^{-1}$ ± relative error)			Ra_{eq} ($Bq\ kg^{-1}$)	Criterion formula (CF)	RLI ($Bq\ kg^{-1}$)	Absorbed dose rate (D_R) ($nGy\ h^{-1}$)	Annual effective dose rate (H_R) ($mSv\ year^{-1}$)
	^{226}Ra	^{232}Th	^{40}K					
PC01	25.0 ± 3.0	20.0 ± 3.2	301 ± 27.1	76.78	0.10	0.57	69.08	0.08
PC02	47.0 ± 5.2	24.0 ± 3.6	271 ± 24.4	102.19	0.14	0.73	91.32	0.11
PC03	26.0 ± 3.1	17.9 ± 2.9	278 ± 25.0	73.00	0.10	0.54	65.85	0.08
PC04	34.0 ± 4.1	28.0 ± 3.9	295 ± 26.6	96.76	0.13	0.70	85.68	0.11
PC05	76.0 ± 8.4	34.0 ± 4.8	264 ± 23.8	144.95	0.20	1.02	128.44	0.16
PC06	27.0 ± 3.2	8.4 ± 1.7	60 ± 9.6	43.63	0.06	0.30	38.88	0.05
PC07	31.0 ± 3.7	21.0 ± 3.2	380 ± 30.4	90.29	0.12	0.67	82.02	0.10
PC08	32.0 ± 3.8	33.0 ± 4.6	530 ± 42.4	120.00	0.16	0.90	108.14	0.13
PC09	25.1 ± 3.0	8.2 ± 1.6	65 ± 9.8	41.83	0.06	0.29	37.31	0.05
PC10	26.0 ± 3.1	8.0 ± 1.6	144 ± 14.4	48.53	0.07	0.35	44.24	0.05
PC11	31.0 ± 3.7	6.7 ± 1.5	85 ± 11.9	47.13	0.06	0.33	42.69	0.05
PC12	28.0 ± 3.4	11.5 ± 2.1	252 ± 22.7	63.85	0.09	0.47	58.57	0.07
PC13	39.0 ± 4.7	9.0 ± 2.1	230 ± 23.0	69.58	0.09	0.50	64.18	0.08
PC14	40.0 ± 4.8	21.0 ± 3.4	324 ± 25.9	94.98	0.13	0.69	85.82	0.11
PC15	27.0 ± 3.2	10.2 ± 1.9	215 ± 19.4	58.14	0.08	0.43	53.26	0.07
PC16	14.3 ± 1.9	7.7 ± 1.2	139 ± 13.9	36.01	0.05	0.27	32.75	0.04
Min	14.3	6.7	60	36.01	0.05	0.27	32.75	0.04
Mean	33.0	16.7	239	75.48	0.10	0.55	68.01	0.08
Max	76.0	34.0	530	144.95	0.20	1.02	128.44	0.16
SD	13.69	9.39	123.24	30.86	0.04	0.22	27.32	0.03
CV	0.41	0.56	0.51	0.41	0.41	0.41	0.40	0.40
Limit				370.00	1.00	1.00	84.00 (world average)	0.48 (world average)

Except for PC05, all of the studied cement samples were lower than limit value of RLI, 1.00. However, RLI level of PC05 was only 1.02, which was very close to the limit. RLI level of PC05 exceed only 2% rate to the limit value 1.0, which was suggested by Alam et al. [49].

Estimation of the absorbed gamma dose rate (D_R) and annual effective dose rate (H_R)

In this study, data set for absorbed gamma dose rates (D_R) in the indoor air for cement samples varied between 32.7 and 128.4 nGy h^{-1}. The mean value of D_R was 68.0 nGy h^{-1}. Apart from 5 samples (PC02, PC04, PC05, PC08, and PC14), all the cement samples had lower values compared to the world average of $D_R = 84.00$ nGy h^{-1}. In addition, the studied cement sample overall mean value of D_R was lower than the world average reference value of 84.00 nGy h^{-1} (Table 1). Annual effective dose rate (H_R) values varied between 0.04 and 0.16 mSv $year^{-1}$ (mean is 0.08 mSv $year^{-1}$) for the studied cements. All the H_R values were considerably lower than the average reference value of the world.

Gamma index (I_γ)

Gamma index values of the studied cement samples are given in Table 3. Their minimum value was 0.13, while the maximum value was 0.51 with a mean of 0.27.

Radiation hazard indices

Two hazard indices, the external radiation hazard, H_{ex}, and the internal radiation hazard, H_{in} were studied.

External radiation hazard (H_{ex})

According to Table 3, the minimum, maximum, and mean values of H_{ex} are 0.10, 0.39, and 0.20, respectively. These values were significantly less than unity, which was adopted as a reference limit value.

Table 2 Comparison of natural radioactivity of Portland cements

Country	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Ra$_{eq}$ (Bq kg^{-1})	References
Algeria	41.0	27.0	422.0	112.1	[17]
Australia	51.8	48.1	114.7	129.4	[15]
Austria	27.0	14.0	210.0	63.2	[18, 19]
Bangladesh	61.0	80.0	1133.0	262.6	[20]
Brazil	61.7	58.5	564.0	188.8	[21]
Cameroon	27.0	15.0	277.0	69.8	[22]
China	51.7	32.0	207.7	113.5	[23]
China	57.0	37.0	173.0	123.2	[24]
China	118.7	36.1	444.0	204.5	[25]
Egypt	35.0	19.0	93.0	69.3	[26]
Egypt	35.6	43.2	82.0	103.7	[27]
Egypt	78.0	33.0	337.0	151.1	[28]
Finland	40.2	19.9	251.0	88.0	[29]
Greece	92.0	31.0	310.0	160.2	[30]
Greece	63.0	24.0	284.0	119.2	[31]
India	37.0	24.0	432.0	104.6	[32]
Iran	31.0	12.0	121.0	57.5	[33]
Ireland	66.0	11.0	130.0	91.7	[34]
Italy	46.0	42.0	316.0	130.4	[35]
Italy	38.0	22.0	218.0	86.2	[36]
Japan	36.0	21.0	139.0	76.7	[37]
Jordan	46.0	12.0	201.0	78.6	[38]
Malaysia	81.4	59.2	203.5	181.7	[39]
Malaysia	34.7	32.9	190.6	96.4	[40]
Netherlands	27.0	19.0	230.0	71.9	[41]
Nigeria	30.2	24.6	251.3	84.7	[42]
Norway	29.6	18.5	259.0	76.0	[43]
Pakistan	37.0	28.0	200.0	92.4	[44]
Pakistan	26.1	28.7	272.9	88.2	[45]
Saudi Arabia	14.3	14.1	161.2	46.9	[46]
Slovakia	9.4	18.3	149.9	47.1	[2]
Slovakia	11.8	18.4	156.5	50.2	[47]
Tunisia	22.0	10.0	176.0	49.9	[48]
Turkey	41.0	26.0	267.0	98.7	[3]
Turkey	52.0	40.0	324.0	134.1	[7]
Min	9.4	10.0	82.0	46.9	
Mean	44.5	28.6	265.8	105.8	
Max	118.7	80.0	1133.0	262.6	
Turkey (present study)					
Min	14.3	6.7	60.0	36.0	
Mean	33.0	16.8	239.6	75.5	
Max	76.0	34.0	530.0	144.9	

Internal radiation hazard (H_{in})

Table 3 shows that the minimum value, maximum value, and mean of H_{in} were 0.14, 0.60, and 0.29, respectively. The limit values were acceptable, since they were less than a unity. Although sample PC05 gave a maximum value of 0.60, which was close to unity, the other values were generally low.

Table 3 Gamma index and radiation hazard values of studies Portland cement (PC) samples

Sample ID	Gamma index (I_γ)	Radiation hazards	
		H_{ex}	H_{in}
PC01	0.28	0.21	0.27
PC02	0.37	0.28	0.40
PC03	0.27	0.20	0.27
PC04	0.35	0.26	0.35
PC05	0.51	0.39	0.60
PC06	0.15	0.12	0.19
PC07	0.34	0.24	0.33
PC08	0.45	0.32	0.41
PC09	0.15	0.11	0.18
PC10	0.17	0.13	0.20
PC11	0.17	0.13	0.21
PC12	0.23	0.17	0.25
PC13	0.25	0.19	0.29
PC14	0.35	0.26	0.36
PC15	0.21	0.16	0.23
PC16	0.13	0.10	0.14
Min	0.13	0.10	0.14
Mean	0.27	0.20	0.29
Max	0.51	0.39	0.60
SD	0.11	0.08	0.11
CV	0.41	0.41	0.39
Limit		1.00	1.00

Conclusions

The activity concentrations of PC samples from different regions of Turkey were measured by gamma-ray spectrometry to determine the exposure of natural radiation and radiological parameters. The mean values of activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 68, 80, and 45% respectively lower in comparison with the other cement samples as given in Table 2. The mean value of Ra_{eq} was found to be 75.4 Bq kg^{-1}. All Ra_{eq} values of the measured PC samples were lower than the criterion limit of 370 Bq kg^{-1}. The mean absorbed gamma dose rates (D_R) for the studied cement samples, was 68.0 nGy h^{-1} and this value was found to be lower than the average literature value of $D_R = 84.00$ nGy h^{-1}.

This study assembles the radioactive data of cement samples from different regions of Turkey and it could be a handy database for future estimations of the impact of radioactive pollution as well as for the improving of the specific requirements for cements in the Turkey eco-labeling process. This work is also useful in maintaining radioactive data within the recommended ranges, especially RLI, D_R, and keeping these parameters within the limits.

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References

1. United National Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Sources and Risks of Ionizing Radiation. Report to the General Assembly with Annexes, New York, USA 2000
2. Estokova A, Palascakova L (2013) Assessment of natural radioactivity levels of cements and cement composites in the Slovak Republic. Int J Environ Res Public Health 10:7165–7179
3. Turhan S (2008) Assessment of the natural radioactivity and radiological hazards in Turkish cement and its raw materials. J Environ Radioact 99:404–414
4. Righi S, Bruzzi L (2006) Natural radioactivity and radon exhalation in building materials used in Italian dwellings. J Environ Radioact 88:158–170
5. Khan K, Khan HM (2001) Natural gamma-emitting radionuclides in Pakistani Portland cement. Appl Radiat Isot 54:861–865
6. El-Taher A, Makhluf S, Nossair A, Abdel Halim AS (2010) Assessment of natural radioactivity levels and radiation hazards due to cement industry. Appl Radiat Isot 68:169–174
7. Damla N, Cevik U, Kobya AI, Celik A, Celik N, van Grieken R (2010) Radiation dose estimation and mass attenuation coefficients of cement samples used in Turkey. J Hazard Mater 176:644–649
8. Engin Y, Tarhan M (2012) TS EN (Turkish Standart European Norm) 197-1:2012 Standardı'ndaki Değişiklikler (in Turkish). Hazır Beton 67–71
9. El-Taher A (2012) Assessment of natural radioactivity levels and radiation hazards for building materials used in Qassim Area, Saudi Arabia. Rom J Phys 57:726–735
10. Currie LA (1968) Limits for qualitative detection and quantitative determination. Anal Chem 40:586–593
11. Ravisankar R, Vanasundari K, Suganya M, Raghu Y, Rajalakshmi A, Chandrasekaran A, Sivakumar S, Chandramohan J, Vijayagopal P, Venkatraman B (2014) Multivariate statistical analysis of radiological data of building materials used in Tiruvannamalai, Tamilnadu, India. Appl Radiat Isot 85:114–127
12. NEA-OECD (1979) Exposure to radiation from natural radioactivity in building materials. Report by NEA group of Experts of the Nuclear Energy Agency OECD, Paris
13. EC (European Commission) (1999) Radiation Protection, 112-radiological protection principles concerning the natural radioactivity of building materials. Directorate-General Environment. Nuclear Safety and Civil Protection
14. Bruzzi Righi S (2006) Natural radioactivity and radon exhalation in building materials used in Italian dwellings. J Environ Radioact 88:158–170
15. Beretka J, Mathew PJ (1985) Natural radioactivity of Australian building materials, industrial wastes and by-product. Health Phys 48:87–95
16. Krieger R (1981) Radioactivity of construction materials. Betonw. Fert Technol 47:468–473
17. Amrani D, Tahtat M (2001) Natural radioactivity in Algerian building materials. Appl Radiat Isot 54:687–689
18. Sorantin P, Steger F (1984) Natural radioactivity of building materials in Austria. Radiat Prot Dosim 7:59–61

19. Trevisi R, Risica S, D'Alessandro M, Paradiso D, Nuccetelli C (2012) Natural radioactivity in building materials in the European Union: a database and an estimate of radiological significance. J Environ Radioact 105:11–20
20. Roy S, Alam MS, Begum M, Alam B (2005) Radioactivity in building materials used in and around Dhaka city. Radiat Prot Dosim 114:527–532
21. Malanca A, Pessina V, Dallara G (1993) Radionuclide content of building materials and gamma-ray dose rates in dwellings of Rio-Grande Do-Norte Brazil. Radiat Prot Dosim 48:199–203
22. Ngachin M, Garavaglia M, Giovani C, Kwato Njock MG, Nourreddine A (2007) Assessment of natural radioactivity and associated radiation hazards in some Cameroonian building materials. Radiat Meas 42:61–67
23. Lu X, Yang G, Ren C (2012) Natural radioactivity and radiological hazards of building materials in Xianyang, China. Radiat Phys Chem 81:780–784
24. Xinwei L (2005) Radioactive analysis of cement and its products collected from Shaanxi, China. Health Phys 88:84–86
25. Lu X, Chao S, Yang F (2014) Determination of natural radioactivity and associated radiation hazard in building materials used in Weinan, China. Radiat Phys Chem 99:62–67
26. El-Bahi SM (2004) Assessment of radioactivity and radon exhalation rate in Egyptian cement. Health Phys 86:517–522
27. El-Taher A (2010) INAA and DNAA for uranium determination in geological samples from Egypt. App Radiat Isot 68:1189–1192
28. El Afifi EM, Hilal MA, Khalifa SM, Aly HF (2006) Evaluation of U, Th, K and emanated radon in some NORM and TENORM samples. Radiat Meas 41:627–633
29. Mustonen R (1984) Natural radioactivity and radon exhalation rate from Finnish building materials. Health Phys 46:1195–1203
30. Stoulos S, Manolopoulou M, Papastefanou C (2003) Assessment of natural radiation exposure and radon exhalation from building materials in Greece. J Environ Radiact 69:225–240
31. Papastefanou C, Stoulos S, Manolopoulou M (2005) The radioactivity of building materials. J Radioanal Nucl Chem 266(3):367–372
32. Kumar V, Ramachandran TV, Prasad R (1999) Natural radioactivity of Indian building materials and by-products. Appl Radiat Isot 51:93–96
33. Fathivand AA, Amidi J (2007) Assessment of natural radioactivity and the associated hazards in Iranian cement. Radiat Prot Dosim 124:145–147
34. Lee EM, Menezes G, Fich EC (2004) Natural radioactivity in building materials in the Republic of Ireland. Health Phys 86:378–383
35. Sciocchetti G, Scacco F, Baldassini PG (1984) Indoor measurement of airborne natural radioactivity in Italy. Radiat Prot Dosim 7:347–351
36. Rizzo S, Brai M, Basile S, Bellia S, Hauser S (2001) Gamma activity and geochemical features of building materials: estimation of gamma dose rate and indoor radon levels in Sicily. Appl Radiat Isot 55:259–265
37. Suzuki A, Iida T, Moriizumi J, Sakuma Y (2000) The effects of different types of concrete on population doses. Radiat Prot Dosim 90:437–443
38. Ahmad MN, Hussein AJA (1997) Natural radioactivity in Jordanian building materials and the associated radiation hazards. J Environ Radioact 39:9–22
39. Chong CS, Ahmed GU (1982) Gamma activity of some building materials in west Malaysia. Health Phys 43:272–273
40. Majid AAB, Ismail AF, Yasir MS, Yahaya R, Bahari I (2013) Radiological dose assessment of naturally occurring radioactive materials in concrete building materials. J Radioanal Nucl Chem 297:277–284
41. Ackers JG, Den Boer JF, De Jong P, Wolschrijn RA (1985) Radioactivity and exhalation rates of building materials in the Netherlands. Sci Total Environ 45:151–156
42. Agbalagba EO, Osakwe ROA, Olarinoye IO (2014) Comparative assessment of natural radionuclide content of cement brands used within Nigeria and some countries in the world. J Geochem Explorat 142:21–28
43. Stranden E (1976) Some aspects on radioactivity of building materials. Phys Norv 8:167–173
44. Rahman SU, Rafique M, Matiullah Jabbar A (2013) Radiological hazards due to naturally occurring radionuclides in the selected building materials used for the construction of dwellings in four districts of the Punjab Province, Pakistan. Radiat Prot Dosim 153:352–360
45. Khan K, Khan HM (2001) Natural gamma-emitting radionuclides in Pakistani Portland cement. Appl Radiat Isot 54:861–865
46. Al Mugren KS, El-Taher A (2016) Risk assessment of some radioactive and elemental content from cement and phosphate fertilizer consumer in Saudi Arabia. J Environ Sci Technol 9(4):323–328
47. Estokova A, Palacakova L (2013) Study of natural radioactivity of slovak cements. Chem Eng Trans 32:1675–1680
48. Hizem N, Fredj AB, Ghedira L (2005) Determination of natural radioactivity in building materials used in Tunisian dwellings by gamma ray spectrometry. Radiat Prot Dosim 114:533–537
49. Alam MN, Chowdhury MI, Kamal M, Ghose S, Islam MN, Mustafa MN, Miah MMH, Ansary MM (1999) The 226Ra,232Th and 40 K activates in beach sand minerals and beach soils of Cox's bazaar, Bangladesh. J Environ Radioact 46:243–250