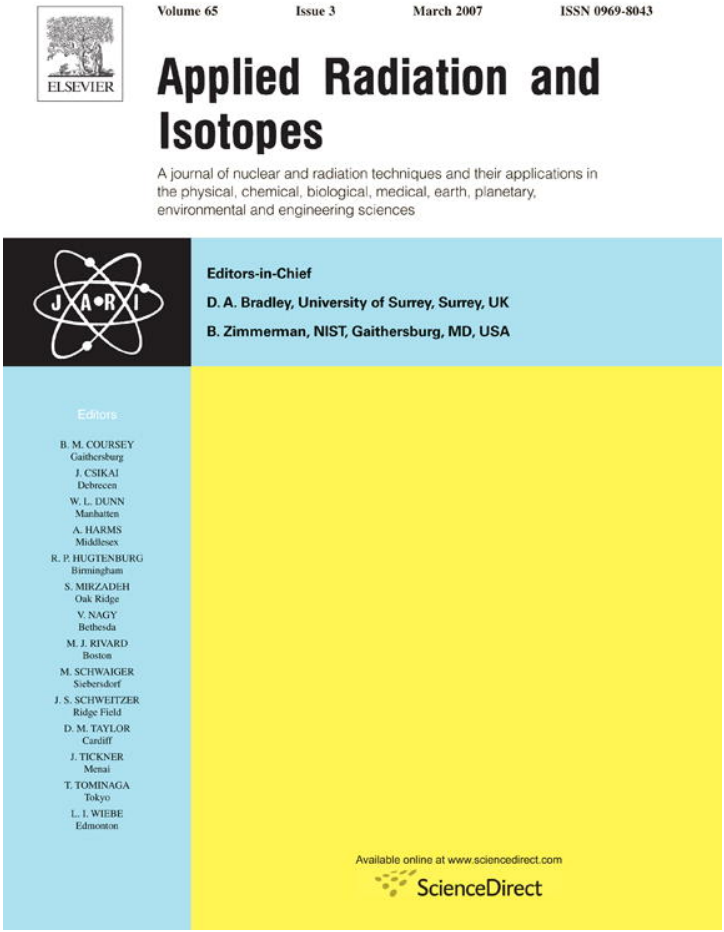
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Natural radioactivity measurement in pumice samples used raw materials in Turkey

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Abstract

The activity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K in different pumice samples have been determined by high-resolution γ-ray spectrometry using a 110% HpGe detector. The radium equivalent activities (Ra_{eq}), external hazard index (H_{ex}), and internal hazard index (H_{in}) associated with the natural radionuclides and representative level index ($I_{\gamma r}$) are calculated to assess the radiation hazard of the natural radioactivity in the pumice samples. The mean values of the measured radioactivity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K for pumice samples from the region of lakes (ROL) are 232.4 ± 8.0, 196.9 ± 7.8, and 1325.8 ± 20.4 Bq kg^{-1} and for pumice samples from Çukurova region (ÇR) 16.3 ± 4.0, 16.1 ± 4.9, and 479.7 ± 170.4 Bq kg^{-1}, respectively. The calculated Ra_{eq} values vary from 435.9 ± 12.5 to 883.6 ± 41.5 Bq kg^{-1} with a mean of 630.9 ± 20.2 Bq kg^{-1} for the ROL samples and from 49.7 ± 3.3 to 101.9 ± 7.2 Bq kg^{-1} with a mean of 76.3 ± 23.7 Bq kg^{-1} for the ÇR samples. For the ROL samples, Ra_{eq} are above the limit of 370 Bq kg^{-1}, equivalent to external γ dose of 1.5 mSv yr^{-1}, recommended for the safe use of construction materials by NEA–OECD, while for the ÇR samples, Ra_{eq} values are lower than the limit.
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Keywords: Radioactivity concentration; Radium equivalent; Health hazard indices; Radium; Thorium; Potassium; γ-ray spectrometer; Pumice

1. Introduction

The most important naturally occurring radionuclides in building and ceramic raws and materials are ^{40}K, ^{238}U with uranium–radium series isotopes and ^{232}Th with thorium series isotopes. These radionuclides are sources of external and internal radiation exposure in dwellings. Therefore, the dweller of houses and office buildings, where they spend about 80% of their time, are exposed to radiation emitted by these radionuclides. γ-radiation originating from ^{238}U and ^{232}Th series isotopes and ^{40}K cause external exposure while the inhalation of ^{222}Rn, ^{220}Rn and their short-lived progeny leads to the internal exposure of the respiratory tract to α particles. Even though these radionuclides are widely distributed, their concentrations have been found to depend on the local geological conditions and as such they vary from place to place (Iqbal et al., 2000; Tennisseen, 1994). In order to assess the radiological hazards to human health, it is important to study the radioactivity levels emitted by these materials. The data obtained from such a study is essential for the development of standards and guidelines for use and management of these materials.

Pumice is a light-colored natural sponge-like material of volcanic origin composed of 60–75% SiO_2, 13–17% Al_2O_3, 1–3% Fe_2O_3, 1–2% CaO, 7–8% Na_2O–K_2O, and low TiO_2 and SO_3 content. Pumice is used in many applications such as in abrasives, cement, concrete, ceramic, and glass industries because of being an inexpensive and widespread geological raw material. Pumice stone is being used in cement and as an aggregate in the production of light-weight concrete. Pumice has also the potential to be used as a ceramic raw material (Kuzugudenli, 2003).

The aim of this study is to measure the natural radioactivity contained in pumice used widely as a raw material and to estimate the radium equivalent activities related to radiological hazard. Therefore, the present study

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presents the results for the measured radioactivities of ^{232}Th, ^{226}Ra, and ^{40}K using γ-ray spectroscopy, the calculated radium equivalent concentrations and values of both internal and external hazard indices of 85 pumice samples used a raw material collected from the Mediterranean region (from 15 different locations in the region of lakes (ROL) and two different locations in Çukurova region (ÇR)) in Turkey.

2. Experimental methods

2.1. Sampling and sample preparation

Eighty-five pumice samples were collected from the Mediterranean region. All the samples were crushed to a fine powder form. The crushed samples were sieved through a 1-mm mesh size to remove the larger size grains and then dried in a temperature-controlled furnace at 110 °C for 10–15 h to remove moisture. These samples were cooled in moisture-free atmospheric medium. The samples were put into cylindrical plastic containers (4 cm diameter, 4 cm height), weighed and hermetically sealed. The sealed samples and the reference materials were stored for more than 30 days before counting so as to allow ^{226}Ra and ^{224}Ra to reach secular equilibrium with their short-lived decay products.

2.2. Radioactivity measurement

The radioactivity measurements were performed with a high-resolution HpGe γ-ray spectrometry system. The system was equipped with a coaxial p-type HpGe detector (GC11021) with an active volume of 451 cm^3 manufactured by Canberra Inc. The HpGe detector has a relative efficiency of 110%, an energy resolution of 2.1 keV at 1332.5 keV of ^{60}Co and of 1.3 keV at 122 keV of ^{57}Co, and a peak-to-Compton ratio of 85:1. For γ-ray shielding, a front opening split-top shield (Canberra Model 767) was used to reduce the background. It features 10 cm lead thickness, which is jacketed by a 9.5-mm steel outer housing. The graded liner comprises 1-mm-thick tin layer and 1.5-mm-thick copper layer to prevent interference by lead X-rays. To minimize scattered radiation from the shield, the detector was centered in it. The detector was interfaced to the digital spectrum analyzer (DSA-1000), which was a full-featured 16 K channel multichannel analyzer on advanced digital signal processing (DSP) techniques . DSA-1000 operates through Genie-2000 γ-spectroscopy software including peak searching, peak evaluation, energy/efficiency calculation mode, nuclide identification, and etc.

The absolute efficiency calibration curves were obtained with the IAEA reference sources of known concentration of ^{238}U (RGU-1), ^{232}Th (RGTh-1), and ^{40}K (RGK-1) contained in the cylindrical plastic container of the same size as the samples. The sample containers were placed on top of the detector for counting. The same geometry was used to determine the peak area of the samples and the references. The counting time for each measurement was varied between 20.000 and 40.000 s so as to obtain good counting statistics. Background measurements were taken for longer periods and were subtracted in order to get net counts for the sample. The concentrations of ^{232}Th, ^{226}Ra, and ^{40}K in the pumice samples were determined using data given in Table 1. The minimum detectable activity (MDA) of the present measurement system was calculated as follows:

$$\mathrm{MDA} = \frac{\mathrm{LLD}}{\varepsilon P t w}, \tag{1}$$

where MDA is in Bq kg^{-1}, ε is the absolute efficiency of the used HpGe detector, P the absolute emission probability of the γ decay, t the measurement time in seconds, w the weight of the dried sample expressed in kg, and LLD the lower limit of detection, as defined below (Currie, 1968)

$$\mathrm{LLD} = 2.706 + 4.653\sigma_{\mathrm{N_B}}, \tag{2}$$

where $\sigma_{\mathrm{N_B}}$ is the standard deviation (SD) of the background in the region of interest and equals square root of the number of counts for the background spectrum. The MDAs for ^{232}Th, ^{226}Ra, and ^{40}K were 0.67, 0.63, and 4.98 Bq kg^{-1}, respectively.

Table 1
Spectroscopic parameters used for the determination of radioactivity concentration

Nuclide to be determined	γ-ray energies (keV)	Absolute emission probability of γ decay (%)[a]	Emitter nuclide
^{232}Th	583.2	30.6	^{208}Tl
	911.2	26.6	^{228}Ac
	969.0	16.2	^{228}Ac
^{226}Ra	351.9	35.1	^{214}Pb
	609.3	44.6	^{214}Bi
	1764.5	15.1	^{214}Bi
^{40}K	1460.8	10.7	^{40}K

[a]Taken from Debertin and Helmer (1988).

3. Results and discussion

The minimum, maximum, and mean activity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K, together with statistical counting uncertainty and SD in the pumice samples are given in Table 2 for each of the 17 locations. The total uncertainty for each measurement is the statistical counting uncertainty (1σ). The mean activity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K were calculated to be 232.4 ± 8.0, 196.9 ± 7.8, and 1325.8 ± 20.4 Bq kg^{-1}, respectively, for the ROL samples and 16.3 ± 4.0, 16.1 ± 4.9, and 479.7 ± 170.4 Bq kg^{-1}, respectively, for the ÇR samples. It is clear that the mean concentration of natural radioactivity in the pumice from the ROL is higher than the mean concentration in the pumice from the ÇR. The

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Table 2
The minimum, maximum and mean activity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K in the pumice samples

Sample code	Number of samples	Activity concentration ± stat. counting uncertainty (Bq kg^{-1})								
		^{232}Th			^{226}Ra			^{40}K		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
I-1	6	218.9±6.2	241.0±6.7	226.3±2.9	191.3±2.8	204.5±3.2	197.7±1.4	1241.5±43.5	1390.0±48.7	1281.5±21.6
I-2	6	217.9±2.2	237.3±5.8	223.9±2.3	173.7±1.3	202.8±2.6	192.2±1.1	1259.5±43.1	1442.1±21.1	1325.6±18.3
I-3	2	230.8±5.6	235.4±5.6	233.1±6.2	197.4±2.6	200.0±2.6	198.7±3.7	1276.2±42.9	1281.0±43.4	1278.6±61.0
I-4	6	219.8±5.5	232.3±5.8	226.4±2.4	182.9±1.0	210.2±2.8	198.4±1.2	1217.8±33.7	1426.9±19.0	1323.9±19.7
I-5	4	262.2±5.9	276.0±6.0	269.6±3.2	217.9±2.2	233.7±2.9	227.0±1.6	1272.7±43.4	1467.0±22.3	1370.6±23.7
I-6	6	160.6±2.7	238.7±2.7	215.9±1.9	121.1±1.6	203.3±3.0	175.1±1.0	1110.5±21.2	1494.4±22.6	1398.9±14.7
I-7	6	275.4±3.9	295.1±1.9	287.5±2.3	234.8±1.2	269.1±3.3	248.7±1.2	1293.3±47.9	1499.8±28.6	1424.3±16.1
I-8	2	212.4±5.3	217.0±2.4	214.7±5.8	166.8±1.3	179.5±2.5	173.2±2.8	1173.5±41.1	1352.5±20.6	1263.0±45.9
I-9	6	221.0±4.7	236.2±3.8	226.8±2.1	179.5±1.2	209.3±1.7	196.7±1.0	1342.5±32.6	1499.2±25.0	1402.0±17.4
I-10	6	174.5±3.0	214.2±3.0	192.1±1.8	131.6±1.7	164.9±2.3	146.7±0.9	1097.6±38.4	1242.6±18.6	1187.8±14.0
I-11	6	183.1±6.3	206.4±4.9	195.8±2.0	156.5±1.7	182.8±2.3	170.2±1.0	1075.7±35.5	1286.7±17.0	1195.2±15.9
I-12	6	222.9±2.0	238.6±5.3	233.0±2.1	180.5±1.8	224.5±2.5	200.7±1.0	1332.5±42.6	1451.0±24.4	1409.7±16.8
I-13	6	179.9±2.7	230.5±1.6	216.0±1.9	151.4±1.6	210.7±2.5	183.8±0.9	1127.1±20.5	1379.0±18.2	1249.4±14.9
I-14	4	219.4±2.1	225.5±3.0	222.1±2.2	171.9±1.6	194.6±2.1	180.6±1.1	1285.0±37.3	1442.4±24.2	1386.6±18.0
I-15	6	271.5±2.8	332.3±7.7	302.2±2.8	211.8±1.0	307.2±3.7	264.4±1.3	1321.9±51.6	1460.7±18.8	1389.4±19.6
Total	78									
Mean±SD			232.4±8.0			196.9±7.8			1325.8±20.4	
C-1	5	11.0±0.5	13.2±1.1	12.3±0.4	8.6±0.6	13.8±0.3	11.2±0.2	300.1±5.5	316.4±8.8	309.3±4.3
C-2	2	19.5±1.1	21.1±1.1	20.3±1.6	18.2±0.7	23.8±0.8	21.0±1.0	647.1±15.1	653.1±14.6	650.1±21.1
Total	7									
Mean±SD			16.3±4.0			16.1±4.9			479.7±170.4	

obtained results indicate that the distribution of natural radionuclides in the pumice samples is not uniform. Therefore, to compare the radioactivity concentrations of the pumice samples containing Th, Ra, and K, a common index is required to obtain the sum of radioactivities. This index is usually called as radium equivalent activity (Beretka and Mathew, 1985):

$$\mathrm{Ra_{eq}} = A_{\mathrm{Ra}} + 1.429A_{\mathrm{Th}} + 0.077A_{\mathrm{K}}, \quad (3)$$

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}. In the definition of $\mathrm{Ra_{eq}}$, it has been assumed that 370 Bq kg^{-1} (10 pCi g^{-1}) of ^{226}Ra, 259 Bq kg^{-1}(7 pCi g^{-1}) of ^{232}Th, and 4810 Bq kg^{-1} (130 pCi g^{-1}) of ^{40}K produce an equal γ-ray dose rate (Krisiuk et al., 1971; Stranden, 1976; Beretka and Mathew, 1985).

The calculated $\mathrm{Ra_{eq}}$ values for the pumice samples are given in Table 3. $\mathrm{Ra_{eq}}$ values vary from 435.9±12.5 to 883.6±41.5 Bq kg^{-1} with a mean of 630.9±20.2 Bq kg^{-1} for the ROL pumice samples and from 49.7±3.3 to 101.9±7.2 Bq kg^{-1} with a mean of 76.3±23.7 Bq kg^{-1} for the ÇR pumice samples. It is observed that the $\mathrm{Ra_{eq}}$ values for the ROL samples are higher than the recommended maximum value 370 Bq kg^{-1} (NEA–OECD, 1979; UNSCEAR, 1982, 1988) while for the ÇR samples, the mean $\mathrm{Ra_{eq}}$ value is lower than the limit.

A conservative model based on infinitely thick walls without windows and doors was proposed by Krieger (1981), Amrani and Tahtat (2001) to limit the radiation exposure due to radioactivity in building materials in Germany to 1.5 mSv y^{-1}. The criterion of this model is called as external hazard index (H_{ex}) and defined as

$$H_{ex} = \frac{A_{\mathrm{Ra}}}{370} + \frac{A_{\mathrm{Th}}}{259} + \frac{A_{\mathrm{K}}}{4810} 1, \quad (4)$$

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}. The value of this index must be less than unity in order to keep the radiation hazard to be negligible; i.e. the radiation exposure due to the radioactivity from building materials is limited to 1.5 mSv y^{-1}. The calculated H_{ex} values range from 1.18 to 2.39, with a mean of 1.71±0.03, which is higher than the limit, for the ROL pumice samples (Fig. 1) and from 0.13 to 0.28, with a mean of 0.18±0.02, which is lower than the limit, for the ÇR pumice samples (Fig. 2).

In addition to the external hazard, radioactive inert gas radon (^{222}Rn), a daughter product of ^{226}Ra and its short-lived secondary products are also hazardous to the respiratory organs. A second criterion formula was suggested by Krieger (1981), Beretka and Matthew (1985); Iqbal et al. (2000) to reduce the acceptable maximum concentration of ^{226}Ra to half the normal limit. The criterion is called as internal hazard index (H_{in}) and defined as

$$H_{in} = \frac{A_{\mathrm{Ra}}}{185} + \frac{A_{\mathrm{Th}}}{259} + \frac{A_{\mathrm{K}}}{4810} 1. \quad (5)$$

For the safe use of materials in the construction of buildings, H_{in} should be less than unity. The calculated

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Table 3
Radium equivalent activities (Ra_{eq}) and representative level index ($I_{\gamma r}$) of the pumice samples

Sample code	Number of samples	$Ra_{eq} \pm$ stat. counting uncertainty (Bq kg^{-1})		$I_{\gamma r}$ (Bq kg^{-1})	
		Range	Mean	Range	Mean
I-1	6	603.6±27.7–655.7±31.0	619.6±13.8	4.320–4.70	4.44
I-2	6	594.3±11.5–638.8±28.3	614.0±11.4	4.285–4.57	4.40
I-3	2	625.7±27.3–634.4±27.3	630.0±38.6	4.478–4.54	4.51
I-4	6	607.8±26.8–645.5±28.5	623.7±12.1	4.358–4.63	4.47
I-5	4	706.2±30.2–729.3±30.6	717.5±16.3	5.029–5.20	5.12
I-6	6	435.9±12.5–644.1±13.6	591.2±8.9	3.153–4.63	4.26
I-7	6	747.7±19.5–784.6±26.5	769.0±11.6	5.346–5.58	5.48
I-8	2	573.2±25.9–580.8±11.8	577.0±28.5	4.103–4.18	4.14
I-9	6	618.0±11.3–642.2±19.2	628.6±10.5	4.439–4.60	4.51
I-10	6	473.7±13.6–553.9±14.0	512.4±8.5	3.427–3.98	3.69
I-11	6	514.7±30.9–564.9±24.2	541.9±9.8	3.692–4.04	3.89
I-12	6	615.0±11.1–675.0±26.3	642.0±10.4	4.429–4.83	4.61
I-13	6	495.2±12.8–631.1±26.6	588.4±9.4	3.560–4.51	4.22
I-14	4	594.8±13.7–612.2±14.4	604.5±10.7	4.285–4.41	4.33
I-15	6	715.1±10.6–883.6±41.5	803.1±14.8	5.122–6.25	5.71
Total	78				
Mean±SD			630.9±20.2		4.52±0.14
C-1	5	49.7±3.3–55.5±2.3	52.6±2.1	0.39–0.42	0.40
C-2	2	98.1±6.9–101.9±7.2	100.0±10.0	0.76–0.79	0.78
Total	7				
Mean±SD			76.3±23.7		0.59±0.19

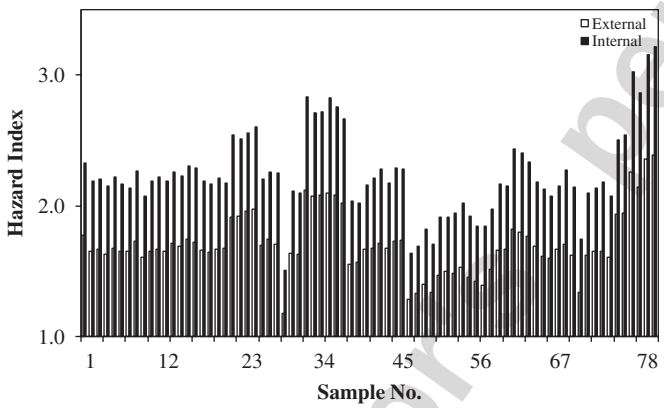


Fig. 1. The calculated values of the health hazard indices (H_{ex} and H_{in}) for the pumice samples collected from the ROL.

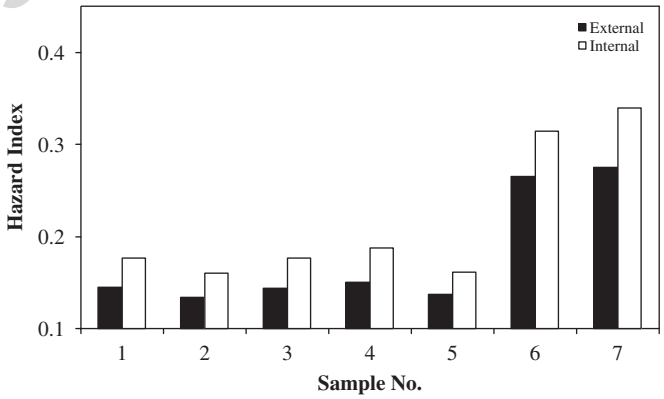


Fig. 2. The calculated values of the health hazard indices (H_{ex} and H_{in}) for the pumice samples collected from the ÇR.

H_{in} values range from 1.51 to 3.22, with a mean of 2.24±0.04, which is higher than the limit, for the ROL pumice samples (Fig. 1) and from 0.16 to 0.34, with a mean of 0.22±0.03, which is lower than the limit, for the ÇR pumice samples (Fig. 2).

Another radiation hazard index, the representative level index ($I_{\gamma r}$) used to estimate the level of γ radiation hazard associated with the natural radionuclides in specific construction materials, is defined as (NEA–OECD, 1979; Alam et al., 1999; Higgy et al., 2000)

$$I_\gamma = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500}, \quad (6)$$

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}. The calculated $I_{\gamma r}$ values for the investigated pumice samples are given Table 3. The $I_{\gamma r}$ values for the ROL and the ÇR pumice samples range from 3.15 to 6.25, with a mean of 4.52±0.14 Bq kg^{-1} and from 0.39 to 0.79, with a mean of 0.59±0.19 Bq kg^{-1}, respectively. It is clear that the ROL pumice samples exceed the upper limit for $I_{\gamma r}$, which is unity, whereas the ÇR samples do not exceed this limit.

4. Conclusion

The activity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K in the pumice samples collected from various localities of the

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Mediterranean region of Turkey have been measured using the γ-ray spectroscopy technique. For each pumice sample, various characterizing quantities such as Ra_{eq}, H_{ex}, H_{in}, and $I_{\gamma r}$ values are calculated. It can be seen that the calculated values for the ÇR pumice samples are all below the limit of γ-radiation dose ($1.5\,mSv\,y^{-1}$). On the other hand, the corresponding values of the pumice samples collected from the ROL are all higher than the acceptable level based on the criterion formulae Eqs. (3)–(6). However, pumice constitutes only a relatively small portion of the materials used for building. Turkish pumice has been primarily used in cement, concrete, brick, and ceramic industries as an aggregate material. Thus, the contributions to the total specific radioactivity of building materials from pumice as an aggregate material become relatively small. It is desirable, however, to select materials of low specific radioactivity for use in building and construction.

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References

Alam, M.N., Miah, M.M.H., Chowdhury, M.I., Kamal, M., Ghose, S., Islam, M.N., Mustafa, M.N., Miah, M.S.R., 1999. Radiation dose estimation from the radioactivity analysis of lime and cement used in Bangladesh. J. Environ. Radioact. 42, 77–85.

Amrani, D., Tahtat, M., 2001. Natural radioactivity in Algerian building materials. Appl. Radiat. Isot. 54, 687–689.

Beretka, J., Matthew, P.J., 1985. Natural radioactivity of Australian building materials, industrial waste, and by-products. Health Phys. 48, 87–95.

Currie, L.A., 1968. Limits for qualitative detection and quantitative determination. Anal. Chem. 40, 586–593.

Debertin, K., Helmer, R.G., 1988. Spectrometry with Semiconductor Detectors. North-Holland, Amesterdam.

Higgy, R.H., El-Tahawy, M.S., Abdel-Fattah, A.T., Al- Akabawy, U.A., 2000. Radionuclide content of building materials and associated γ dose rates in Egyptian dwellings. J. Environ. Radioact. 50, 253–261.

Iqbal, M., Tufail, M., Mirza, M.S., 2000. Measurement of natural radioactivity in marble found in Pakistan using a NaI(Tl) γ-ray spectrometer. J. Environ. Radioact. 51, 255–265.

Krieger, R., 1981. Radioactivity of construction materials. Betonwerk Fertigteil Technol. 47, 468.

Krisiuk, E.M., Tarasov, S.I., Shamov, V.P., Shalak, N.I., Lisa Chenko, E.P., Gomelsky, L.G., 1971. A Study on Radioactivity in Building Materials. Research Institute for Radiation Hygiene, Leningrad.

Kuzugudenli, O.E., 2003. Use of pumice stone as a ceramic raw material. In: The Conference and Exhibition of the European Ceramic Society, Abstract Book.

NEA–OECD, 1979. Exposure to radiation from natural radioactivity in building materials. In: Report by the Group of Experts of the OECD Nuclear Energy Agency (NEA), Paris.

Stranden, E., 1976. Some aspects on radioactivity of building materials. Phys. Norv. 8, 167.

Tennisseen, A.C., 1994. Nature of Earth Materials. Printice-Hall, Englewood Cliffs, NJ, pp. 333–334.

UNSCEAR, 1982. Sources, effects and risks of ionizing radiations. United Nations Scientific Committee on the Effects of Atomic Radiation, New York, UN.

UNSCEAR, 1988. Sources, effects and risks of ionizing radiations. United Nations Scientific Committee on the Effects of Atomic Radiation Report to General Assembly, with Annexes, New York, UN.

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