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Characterization of gas concrete materials used in buildings of Turkey

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ABSTRACT

The activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in gas concrete samples collected from different suppliers and some provinces in Turkey were measured using gamma-ray spectrometry. Knowledge of radioactivity in gas concrete used in building materials enables one to assess any possible radiological risks to human health. The mean activity concentrations observed in the gas concrete samples were 82.0, 28.2 and 383.9 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. The radium equivalent activity, external and internal hazard indices as well as terrestrial absorbed dose and annual effective dose rate was calculated. The results indicate that the radium equivalent activity values of gas concrete samples are lower than the limit of 370 Bq kg^{-1}, equivalent to a gamma-dose of 1.5 mSv y^{-1}. Moreover, mass attenuation coefficients were measured in some gas concrete samples. It was found that the mass attenuation coefficients decreased with increasing photon energies. Also, chemical compositions and structural analysis (XRD and SEM) of the gas concrete samples were investigated.

1. Introduction

Humans are exposed to radiological hazards from natural and artificial radiation sources that exist mainly in the earth's crust. A large percentage of this exposure is incurred in our living environment (indoors) because naturally occurring radionuclides, especially members of the uranium and thorium decay chains and ^{40}K, are present in the building materials [1]. High concentrations of natural radionuclides in building materials can result in high dose rates indoors, from both internal and external exposure [2]. Knowledge of the natural level of radioactivity in building materials is important in the assessment of population exposures, as most individuals spend most of the time indoors (~80%) [3–5].

With the increasing use of radioactive isotopes in many fields such as industries, medicine, nuclear weapons, nuclear reactors and agriculture, it becomes necessary to study the different parameters related to the passage of gamma radiation through a material. The mass attenuation coefficient is an important parameter for studying the interaction of radiation with matter that gives us the fraction of energy scattered or absorbed [6]. Such useful information during accident situations is the effective shielding that the houses' walls and ceilings could provide, making it possible to evaluate the contribution of an eventual plume and deposition of radioactive materials to the dose and to estimate how much protection one can get just by being at home. For this purpose, the mass attenuation coefficient and density of building materials are important parameters to perform the necessary calculations [7].

Gas concrete, which is a building material, is included in the light concrete category. It is produced from different mixtures of silica, sand, cement, lime, water, and aluminum cake, which produce gas [8,9]. Gas concrete that is the most important construction material for dwellings and buildings is considered one of the basic industries that play an important role in the national economy of Turkey. According to our knowledge, there is no data in the literature on natural radioactivity levels and mass attenuation coefficients in gas concrete used in building materials.

The main objectives of the current work are (i) to determine natural (^{226}Ra, ^{232}Th, ^{40}K) radioactivity levels and mass attenuation coefficients, (ii) to assess the possible radiological hazards to human health and (iii) to develop the standards and guidelines for use and management of gas concrete used in building materials in Turkey.

2. Materials and methods

2.1. Sampling

Gas concrete is a kind of light concrete material obtained by a chemical process. Its specific weight is five times lower than that of the usual concrete material. In addition, the heat transmittance of gas concrete is reduced fivefold by the air bubbles inside. It is called "autoclaved aerated concrete (aac)" due to the air bubbles arising in the chemical reaction. This extraordinary property of the product

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Fig. 1. The sampling sites in Turkey.

arises from the pores inside and the solid structure of the calcium silicate. Among these properties is the good-quality heat isolation at high or low outside temperature, easy and of practical use, workforce productivity and high energy saving. Currently, there are eight production facilities in Turkey, belonging to five companies, in Istanbul, Izmir, Kırıkkale, Antalya, Gaziantep, Mardin, Tekirdag and Kocaeli. Turkey is one of the top countries in gas concrete production and consumption. Various gas concrete samples were collected from suppliers and nine provinces in Turkey as shown in Fig. 1.

2.2. Structural and chemical analysis

The X-ray diffraction XRD analysis of some gas concrete samples was carried out by using a Rigaku D/Max-IIIC X-ray diffractometer with Cu Kα radiation over the range 15–65° with a scan speed 0.2° min^{-1} at room temperature.

Scanning electron microscopy (SEM) was performed using a JEOL JEM-5510 operating at an accelerating voltage of 15 kV. The samples were sputtered with a thin film of gold to minimize the charging effects.

The gas concrete samples were prepared in the form of pressed pellets for energy-dispersive X-ray fluorescence (EDXRF) analysis (Epsilon 5, PANalytical, Almelo, the Netherlands). Before doing any other handling, the powder was dried for 4 h at 105 °C to evaporate any remaining water. The pellets were pressed with a hydraulic press applying a pressure of 7 tones during 20 s. The resulting pellets have a diameter of 40 mm and a uniform mass of 400 ± 2 mg.

2.3. Radioactivity measurements

The gas concrete samples were crushed and thoroughly dried at room temperature to constant weight and later crushed to pass through a 2 mm mesh sieve to homogenize them. The samples were then fully dried by using ovens at 105 °C for 24 h to ensure that moisture is completely removed. About 100 g of samples were used and sealed in gas tight, radon impermeable, cylindrical polyethylene plastic containers (5.5 cm diameter and 5 cm height) for gamma activity analysis.

Gamma spectrometry measurements were conducted with a coaxial high purity Ge detector (Canberra, GC 1519 model) of 15% relative efficiency and a resolution of 1.9 keV at the 1332 keV gamma of ^{60}Co. The detector was shielded in a 10 cm thick lead well internally lined with 2 mm Cu foils. The detector output was connected to a spectroscopy amplifier (Canberra, Model 2025). The energy calibration and absolute efficiency calibration of the spectrometer were carried out using calibration sources which contained ^{133}Ba, ^{57}Co, ^{22}Na, ^{137}Cs, ^{54}Mn, and ^{60}Co peaks for the energy range between 80 and 1400 keV (calibration sources supplied by the Isotope Products Laboratories) [10].

The spectrum analysis was performed using computer software Genie 2000 obtained from Canberra. A performance test using the certified reference samples (IAEA-375, IAEA, Vienna) of known activities was conducted for checking the efficiency calibration of the system. The specific activities of these samples were in accordance with their certified values within errors not exceeding 10%. The quality assurance of the measurements was carried out by periodical efficiency and energy calibration and repeated sample measurement. The counting time for each sample was selected to be 50,000 s to obtain the gamma-spectrum with good statistics. To determine the background distribution in the environment around the detector, an empty container was counted in the same manner and in the same geometry as the samples. The background spectra were used to correct the net peak area of gamma rays of the measured isotopes.

The gamma-ray transitions of energies 351.9 keV (^{214}Pb) and 609.3 keV (^{214}Bi) were used to determine the activity concentration of the ^{226}Ra series. The gamma-ray lines at 911.1 keV (^{228}Ac) and 583.1 keV (^{208}Tl) were used to determine the activity concentration of the ^{232}Th series. The activity concentrations of ^{40}K were measured directly through the gamma line emission at 1460.8 keV.

Table 1
Chemical composition of the gas concrete samples.

Chemical components	Unit	Minimum	Maximum	Mean
MgO	%	<ND	1.39	1.25
Al_2O_3	%	4.39	9.27	6.64
SiO_2	%	40.52	47.95	43.69
SO_3	%	2.34	6.48	4.32
K_2O	%	0.74	2.02	1.55
CaO	%	23.73	31.46	27.66
TiO_2	%	0.13	0.23	0.16
V_2O_5	ppm	130	367	203
Cr_2O_3	ppm	144	367	238
MnO	ppm	123	293	199
Fe_2O_3	%	2.36	3.06	2.72
NiO	ppm	<ND	128	82
CuO	ppm	20	52	32
ZnO	ppm	22	59	37
Rb	ppm	14	37	25
SrO	ppm	488	670	546
ZrO_2	ppm	<ND	347	189
BaO	ppm	127	357	181
La_2O_3	ppm	<ND	44	15
PbO	ppm	5	15	10

ND: not detectable.

The activity concentrations for the natural radionuclides in the measured samples were computed using the following relation;

$$C_s = \frac{N_a}{\varepsilon P t w} \,(\mathrm{Bq\,kg^{-1}}) \quad (1)$$

where N_a is the net counting rate of the gamma ray, ε is the counting efficiency of the used detector, P is the absolute transition of gamma decay, t is the counting time in seconds and w the weight of the dried sample in kg. The minimum detectable activity (MDA) of the present measurement system was calculated as follows [11]:

$$\mathrm{MDA} = \frac{\sigma\sqrt{\mathrm{B}}}{\varepsilon P t w} \quad (2)$$

where MDA is in Bq kg^{-1}, σ is the statistical coverage factor equal to 1.645 (confidence level 95%) and B is the background for the region of interest of a certain radionuclide. The MDA for ^{226}Ra, ^{232}Th and ^{40}K were 3.7, 6.1 and 76.2 Bq kg^{-1}, respectively.

2.4. Mass attenuation measurements

The mass attenuation coefficients were determined by performing transmission experiment in narrow beam geometry. Measurements were carried out by using collimated monoenergetic beam. In a narrow beam geometry with the standard gamma-point sources placed one after the other at a distance of 20 cm from the end cap of the detector, the number of counts reaching the detector with and without the samples under study were recorded for a counting time of 10,000 s. The samples were irradiated by photons emitted from ^{109}Cd, ^{57}Co, ^{133}Ba, ^{54}Mn, ^{137}Cs, ^{60}Co and ^{22}Na radioactive sources in the energy range from 88 to 1332.5 keV. For

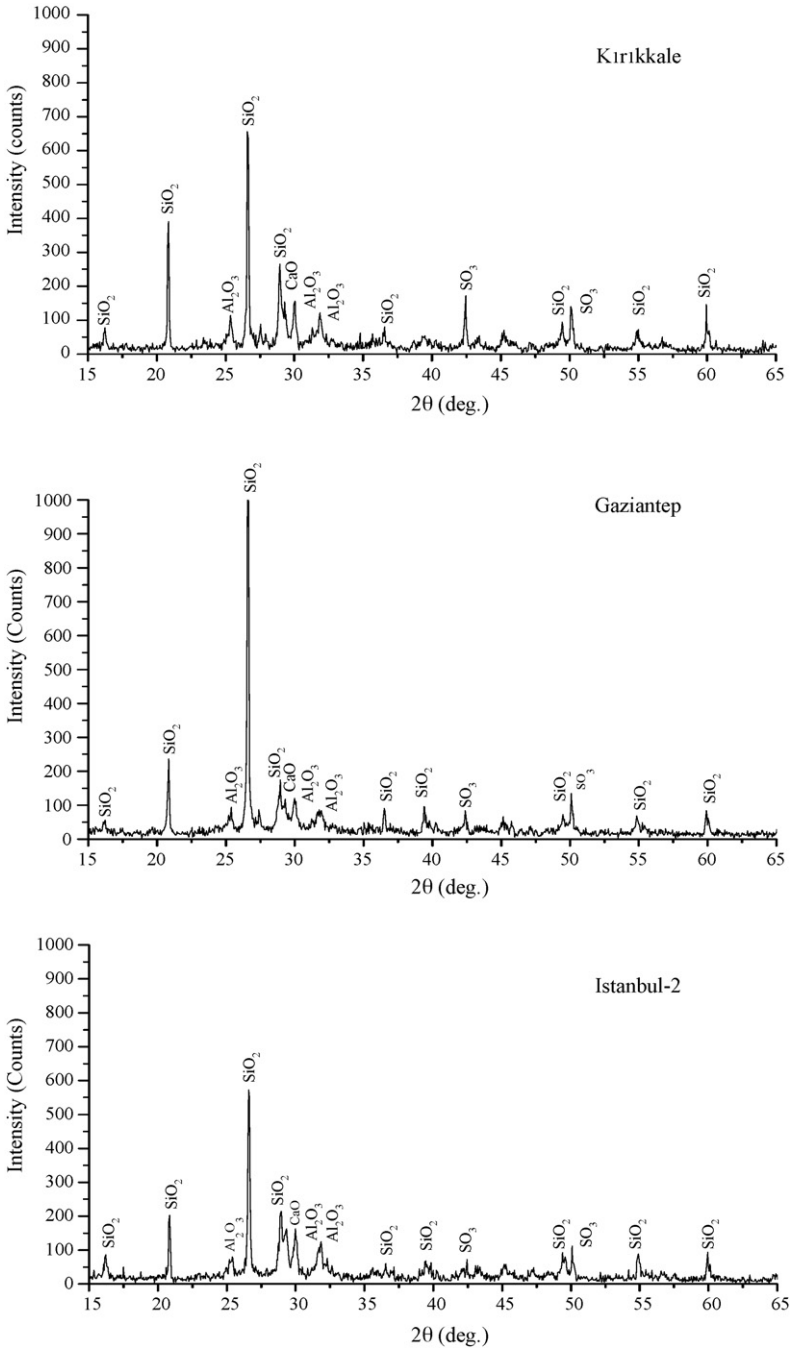

Fig. 2. X-ray diffraction diagram of the some gas concrete samples.

Table 2
Activity concentrations (Bq kg^{-1}) of ^{226}Ra, ^{232}Th and ^{40}K in gas concrete samples.

Samples	^{226}Ra	^{232}Th	^{40}K
Istanbul-1	133.1 ± 9.8	22.5 ± 2.0	178.9 ± 7.2
Istanbul-2	66.2 ± 4.8	43.2 ± 4.3	407.4 ± 16.7
Kocaeli	115.2 ± 9.2	25.1 ± 2.3	251.7 ± 11.3
Yalova	129.8 ± 11.2	34.2 ± 3.1	137.6 ± 5.8
Tekirdag	43.9 ± 2.9	22.7 ± 2.1	474.6 ± 23.7
Edirne	40.5 ± 2.8	19.5 ± 1.9	561.8 ± 25.8
Gümüshane	50.5 ± 3.5	36.1 ± 3.6	467.7 ± 18.7
Trabzon	142.7 ± 11.2	29.5 ± 2.7	523.1 ± 22.1
Gaziantep	46.5 ± 3.6	28.4 ± 2.6	344.2 ± 17.2
Batman	74.2 ± 5.9	22.9 ± 2.1	466.1 ± 20.9
Mardin	84.8 ± 6.9	24.4 ± 2.2	254.9 ± 11.5
Siirt	66.7 ± 3.6	20.6 ± 2.3	474.3 ± 19.9
Sanlıurfa	39.6 ± 2.3	41.1 ± 4.0	500.5 ± 23.0
Ankara	52.7 ± 3.6	15.2 ± 1.4	193.4 ± 8.1
Konya	96.5 ± 8.7	27.1 ± 2.9	606.8 ± 27.3
Kırıkkale	102.2 ± 8.4	25.7 ± 2.6	514.3 ± 22.1
Antalya	71.3 ± 3.9	29.1 ± 3.1	138.2 ± 6.5
Izmir	118.8 ± 10.3	40.9 ± 3.7	414.2 ± 17.8
Range	40.5–142.7	15.2–43.2	137.6–606.8
Mean	82.0	28.2	383.9

each of energy, the measurements for all samples were carried out three times. The measurements were performed by using gamma spectrometry with a high purity Ge detector of 55% relative efficiency and resolution 1.9 keV at the 1332 keV gamma of ^{60}Co (Ortec, GEM55P4 model).

When a material of thickness x is placed in the path of a gamma-radiation, the intensity of the γ-beam is attenuated in matter according to the Beer–Lambert's law,

$$I = I_0 e^{-\mu x} = I_0 e^{-(\mu/\rho)d} \quad (3)$$

where I_0 and I are the unattenuated and attenuated photon intensities, d is the mass per unit area, μ/ρ is the mass attenuation coefficient.

3. Results and discussions

The minimum, maximum and mean values for all chemical compositions of the gas concrete samples are shown in Table 1. It can be shown from the table that they are mainly composed of SiO_2, CaO, Al_2O_3, SO_3 and Fe_2O_3. XRD results of some selected gas concrete samples are shown in Fig. 2. The main peaks shown in Fig. 2 are generally due to SiO_2, Al_2O_3, and CaO. XRD and chemical analysis shows that the results of analysis are compatible with each other. Some SEM photographs were taken to see surface morphology. As shown in photographs in Fig. 3, the surface morphology of all gas concrete samples seems to be the same.

The specific activity concentrations of the natural radionuclides of the ^{226}Ra, ^{232}Th and ^{40}K were determined by using gamma-ray spectroscopy in the gas concrete samples from different suppliers and nine provinces in Turkey, as shown in Table 2. The uncertainties for each measurement in gas concrete samples were calculated from the systematic and random error of the measurement. The activity levels for ^{226}Ra, ^{232}Th and ^{40}K in gas concrete samples were found to range from 40.5 ± 2.8 to 142.7 ± 11.2 Bq kg^{-1}, 15.2 ± 1.4 to 43.2 ± 4.3 Bq kg^{-1} and 137.6 ± 5.8 to 606.8 ± 27.3 Bq kg^{-1} with a mean value of 82.0, 28.2 and 383.9 Bq kg^{-1}, respectively.

A comparison of measured value of ^{226}Ra, ^{232}Th and ^{40}K for all sampling sites is shown in Fig. 4. While the highest mean activity concentration of ^{226}Ra was determined in Trabzon, the province of Ankara showed the lowest mean concentration of ^{232}Th. The activity concentrations of radionuclide ^{40}K is found to be minimum in Yalova (137.6 Bq kg^{-1}) and maximum in Konya (606.8 Bq kg^{-1}).

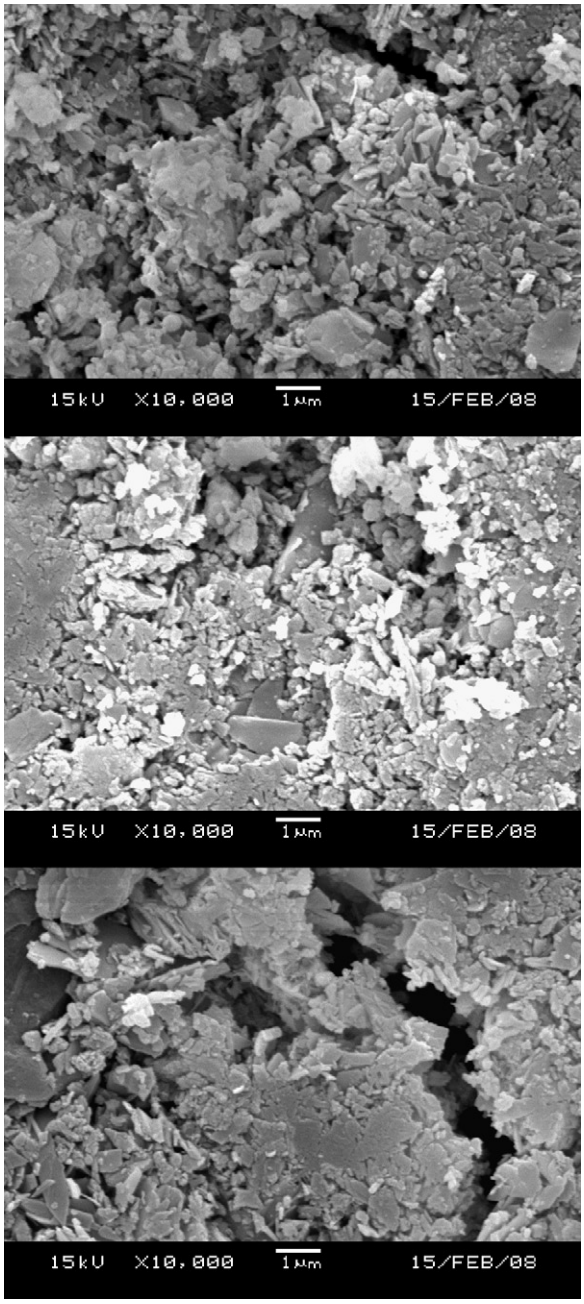

Fig. 3. SEM micrograph of the particles of some gas concrete samples.

The measured mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in gas concrete samples were compared with light weight concrete samples from different countries of the world in Table 3. As shown in the table, ^{226}Ra activity concentration was higher than the concentrations for the literature. For ^{232}Th activity concentra-

Table 3
Comparison of the measured mean activity concentrations (Bq kg^{-1}) with the literature.

	^{226}Ra	^{232}Th	^{40}K	References
Hong Kong	37.8	47.3	141.2	[12]
Norway	51.8	55.5	810.3	[13]
Poland	11.0	16.0	418.0	[14]
Israel	66.1	58.3	1149.0	[5]
Turkey	82.0	28.2	383.9	Present study

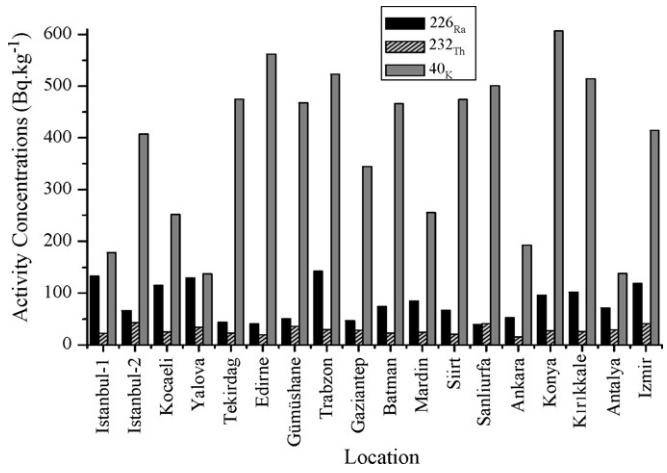

Fig. 4. Comparisons of measured value of ^{226}Ra, ^{232}Th and ^{40}K each province sampling.

tions, the observed value was lower than for Hong Kong, Norway and Israel but higher than for Poland. In the case of ^{40}K, the activity concentrations for Norway, Poland and Israel were higher than that found in Turkish gas concrete samples.

The distribution of ^{226}Ra, ^{232}Th and ^{40}K in gas concrete materials is not uniform. Uniformity with respect to exposure to radiation has been defined in terms of radium equivalent activity (Ra_{eq}) in Bq kg^{-1} to compare the specific activity of materials containing different amounts of ^{226}Ra, ^{232}Th and ^{40}K [15]. The radium equivalent activity is calculated from the following equation [16]:

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (4)$$

where C_{Ra}, C_{Th} and C_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively. The computed values for gas concrete samples, as presented in Table 4, varied from 89.3 to 225.2 Bq kg^{-1}. Ra_{eq} values of the measured samples are lower than the limit value of 370 Bq kg^{-1} recommended by the Organization for Economic Cooperation and Development (OECD) [17].

Radiation hazards due to natural radionuclides of ^{226}Ra, ^{232}Th and ^{40}K may be external depending upon the location of outdoor (outside a dwelling) on the ground [18]. This hazard is defined in terms of external or outdoor radiation hazard index and denoted by H_{ex}, and can be calculated by the following equation [16]:

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (5)$$

where C_{Ra}, C_{Th}, C_K, are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively. The value of this index must be less than unity in order to keep the radiation hazard to be insignificant; i.e. the radiation exposure due to the radioactivity from a construction material is limited to 1.5 mSv y^{-1}. The maximum value of H_{ex} equaling unity corresponds to the upper limit of Ra_{eq} (370 Bq kg^{-1}). The values of H_{ex} calculated from the measured activity concentration of ^{226}Ra, ^{232}Th and ^{40}K are presented in Table 4; they varied in the range between 0.24 and 0.61 and are less than the critical value of unity.

In addition to the external hazard, radon and its short-lived products are also hazardous to the respiratory organs. The inter-

Table 4
Values of hazard indices for gas concrete samples.

Samples	Ra_{eq} (Bq kg^{-1})	D (nGy h^{-1})	AED (mSv y^{-1})	H_{ex}	H_{in}
Istanbul-1	179.1	82.5	0.40	0.48	0.84
Istanbul-2	159.3	73.7	0.36	0.43	0.61
Kocaeli	170.5	78.9	0.39	0.46	0.77
Yalova	189.3	86.4	0.42	0.51	0.86
Tekirdag	112.9	53.8	0.26	0.30	0.42
Edirne	111.6	53.9	0.26	0.30	0.41
Gümüshane	138.1	64.6	0.32	0.37	0.51
Trabzon	225.2	105.6	0.52	0.61	0.99
Gaziantep	113.6	52.9	0.26	0.31	0.43
Batman	142.8	67.5	0.33	0.39	0.59
Mardin	139.3	64.5	0.32	0.38	0.61
Siirt	132.7	63.0	0.31	0.36	0.54
Sanliurfa	136.9	63.9	0.31	0.37	0.48
Ankara	89.3	41.6	0.20	0.24	0.38
Konya	181.9	86.3	0.42	0.49	0.75
Kırıkkale	178.6	84.2	0.41	0.48	0.76
Antalya	123.6	56.3	0.28	0.33	0.53
Izmir	209.2	96.9	0.47	0.57	0.89
Range	89.3–225.2	41.6–105.6	0.20–0.52	0.24–0.61	0.38–0.99
Mean	151.9	70.9	0.35	0.41	0.63

Table 5
Measured values of mass attenuation coefficients (cm^2 g^{-1}) in gas concrete samples.

Energy (keV)	Kırıkkale	Antalya	Tekirdag	Gaziantep	Mardin	Istanbul-2
88.0	0.200 ± 0.009	0.209 ± 0.008	0.215 ± 0.007	0.198 ± 0.007	0.210 ± 0.008	0.210 ± 0.006
122.1	0.188 ± 0.008	0.187 ± 0.007	0.197 ± 0.006	0.180 ± 0.007	0.183 ± 0.005	0.197 ± 0.006
136.5	0.176 ± 0.008	0.166 ± 0.007	0.183 ± 0.006	0.168 ± 0.007	0.173 ± 0.006	0.182 ± 0.007
276.4	0.142 ± 0.007	0.125 ± 0.007	0.143 ± 0.006	0.140 ± 0.005	0.140 ± 0.007	0.145 ± 0.008
302.8	0.121 ± 0.006	0.111 ± 0.006	0.132 ± 0.006	0.117 ± 0.006	0.119 ± 0.006	0.131 ± 0.007
356.0	0.110 ± 0.005	0.098 ± 0.005	0.115 ± 0.006	0.107 ± 0.006	0.108 ± 0.006	0.114 ± 0.005
383.8	0.104 ± 0.005	0.088 ± 0.005	0.109 ± 0.005	0.099 ± 0.003	0.098 ± 0.005	0.111 ± 0.005
661.6	0.068 ± 0.004	0.053 ± 0.003	0.068 ± 0.004	0.055 ± 0.003	0.066 ± 0.003	0.070 ± 0.004
834.8	0.060 ± 0.003	0.045 ± 0.002	0.061 ± 0.003	0.051 ± 0.003	0.055 ± 0.003	0.063 ± 0.003
1173.2	0.055 ± 0.003	0.045 ± 0.002	0.047 ± 0.002	0.045 ± 0.002	0.050 ± 0.003	0.054 ± 0.003
1274.5	0.048 ± 0.002	0.044 ± 0.002	0.045 ± 0.002	0.043 ± 0.002	0.045 ± 0.002	0.048 ± 0.002
1332.5	0.045 ± 0.002	0.043 ± 0.002	0.045 ± 0.002	0.040 ± 0.002	0.044 ± 0.002	0.046 ± 0.002

Table 6
Half thicknesses $X_{1/2}$ (cm) in gas concrete samples.

Energy (keV)	Kırıkkale $\rho = 0.88\,g\,cm^{-3}$	Antalya $\rho = 0.69\,g\,cm^{-3}$	Tekirdag $\rho = 0.89\,g\,cm^{-3}$	Gaziantep $\rho = 0.67\,g\,cm^{-3}$	Mardin $\rho = 0.85\,g\,cm^{-3}$	Istanbul-2 $\rho = 0.88\,g\,cm^{-3}$
88.0	3.96 ± 0.18	4.82 ± 0.18	3.61 ± 0.12	5.19 ± 0.18	3.88 ± 0.15	3.74 ± 0.11
122.1	4.21 ± 0.18	5.39 ± 0.20	3.94 ± 0.12	5.71 ± 0.22	4.46 ± 0.12	3.99 ± 0.12
136.5	4.49 ± 0.20	6.07 ± 0.25	4.24 ± 0.14	6.12 ± 0.26	4.71 ± 0.16	4.32 ± 0.16
276.4	5.57 ± 0.27	8.06 ± 0.45	5.43 ± 0.23	7.34 ± 0.26	5.82 ± 0.29	5.42 ± 0.30
302.8	6.54 ± 0.33	9.07 ± 0.49	5.88 ± 0.26	8.79 ± 0.45	6.85 ± 0.34	6.00 ± 0.32
356.0	7.19 ± 0.32	10.28 ± 0.52	6.75 ± 0.35	9.61 ± 0.54	7.55 ± 0.42	6.89 ± 0.30
383.8	7.61 ± 0.37	11.45 ± 0.65	7.12 ± 0.33	10.39 ± 0.31	8.32 ± 0.42	7.08 ± 0.32
661.6	11.63 ± 0.69	19.01 ± 1.08	11.41 ± 0.67	18.69 ± 1.03	12.35 ± 0.56	11.22 ± 0.64
834.8	13.18 ± 0.66	22.38 ± 0.99	12.72 ± 0.62	20.16 ± 1,19	14.82 ± 0.82	12.47 ± 0.60
1173.2	14.38 ± 0.79	22.38 ± 0.99	16.51 ± 0.71	22.85 ± 1,01	16.31 ± 0.98	14.55 ± 0.81
1274.5	16.48 ± 0.69	22.89 ± 1.03	17.25 ± 0.76	23.91 ± 1,12	18.12 ± 0.80	16.37 ± 0.69
1332.5	17.58 ± 0.77	23.42 ± 1.10	17.25 ± 0.76	25.71 ± 1,29	18.53 ± 0.83	17.08 ± 0.73

nal exposure to radon and its daughter products is quantified by the internal hazard index (H_{in}) which is given by the equation [16]:

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (6)$$

The computed values of H_{in} of gas concrete samples used in building materials in Turkey are given in Table 4. The values of H_{in} varied in the range from 0.38 to 0.99. For the safe use of a material in the construction of dwellings, H_{in} should be less than the unity. All the calculated values are less than unity.

There is a concern that some of the buildings will cause excessive radiation doses to the total body due to gamma rays emitted by ^{214}Pb and ^{214}Bi progeny of ^{226}Ra and ^{232}Th decay chain and ^{40}K also contributes to the total body radiation dose. The total air-absorbed rates due to the mean specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were calculated by the following formula [19]:

$$D(nGy\,h^{-1}) = 0.462C_{Ra} + 0.604C_{Th} + 0.0417C_K \quad (7)$$

This equation is used for calculating the absorbed dose rate in air at a height of 1.0 m above the ground from the measured radionuclide concentration in environmental materials. The absorbed rates were computed from the measured activities in gas concrete samples (Table 4). The mean absorbed gamma-dose in air was calculated as 70.9 nGy h^{-1} (min. 41.6 nGy h^{-1} in Ankara, and max. 105.6 nGy h^{-1} in Trabzon). The mean contributions of the uranium and thorium decay series, and the non-series nuclide ^{40}K to the absorbed dose in air were 37.9 (53%), 17 (24%) and 16 (23%) nGy h^{-1}, respectively.

To estimate the annual effective dose (AED), one must take into account: (a) the conversion coefficient (0.7 Sv Gy^{-1}) from absorbed dose in air to effective dose and (b) the indoor occupancy factor (~80% for Turkish population) [19]. Therefore, the effective dose rate in unit of mSv y^{-1} was estimated by the following formula:

$$AED(mSv\,y^{-1}) = D(nGy\,h^{-1}) \times 8760\,h\,y^{-1} \times 0.7 \times 0.8 \times 10^{-6} \quad (8)$$

The calculated values of AED range from 0.20 to 0.52 mSv, with a mean value of 0.35 mSv.

The experimental mass attenuation coefficients (μ/ρ) and half thickness of six different gas concrete samples were determined for the twelve energies 88.0, 122.1, 136.5, 276.4, 302.8, 356.0, 383.8, 661.6, 834.8, 1173.2, 1274.5 and 1332.5 keV. The results are listed in Table 5. There are slight differences between the results of mass attenuation coefficients in different gas concrete samples at the same energies. These may be due to the compositional variation and density among the different gas concrete samples. It was found that the mass attenuation coefficients of gas concrete samples decreased with increasing photon energies (Table 5 and Fig. 5). The mass attenuation coefficients of samples attain their maximum values at lower photon energies as Compton and photoelectric cross sections are dominant. In fact this reflects the increase in the cross sections of photon interaction with samples' electrons at low energies. Besides increasing of the mass attenuation coefficient of the same sample

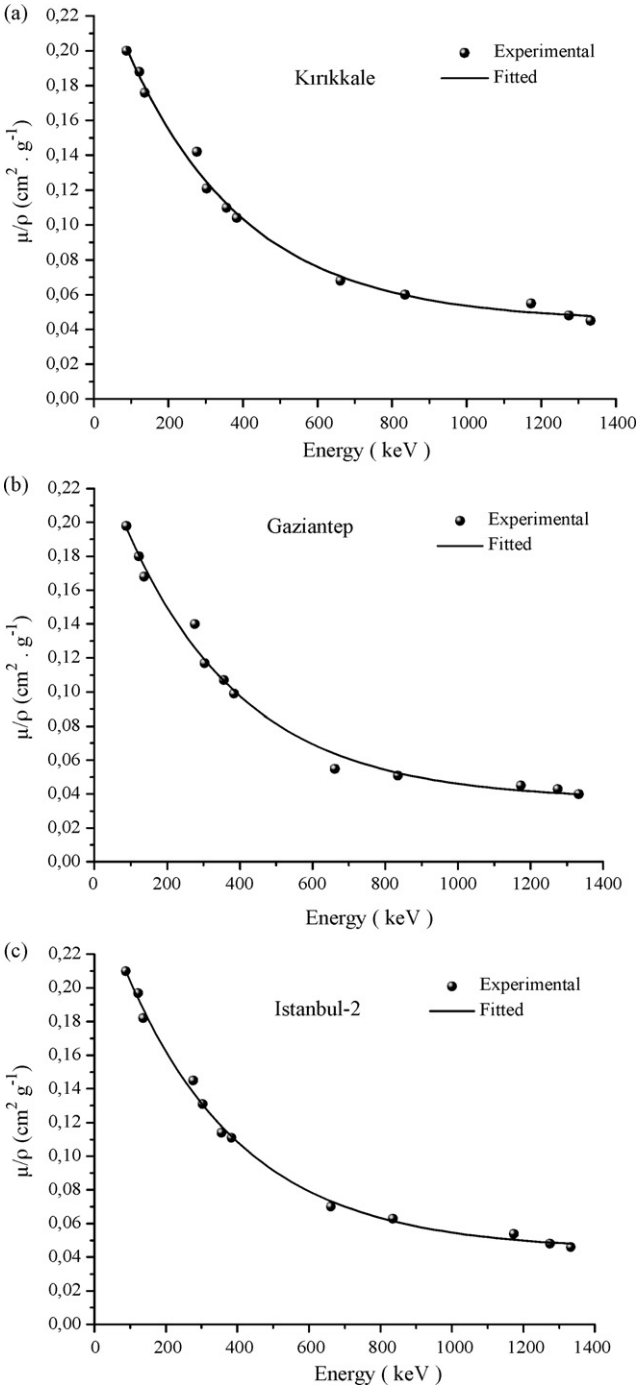

Fig. 5. Mass attenuation coefficients (cm^2 g^{-1}) in gas concrete samples.

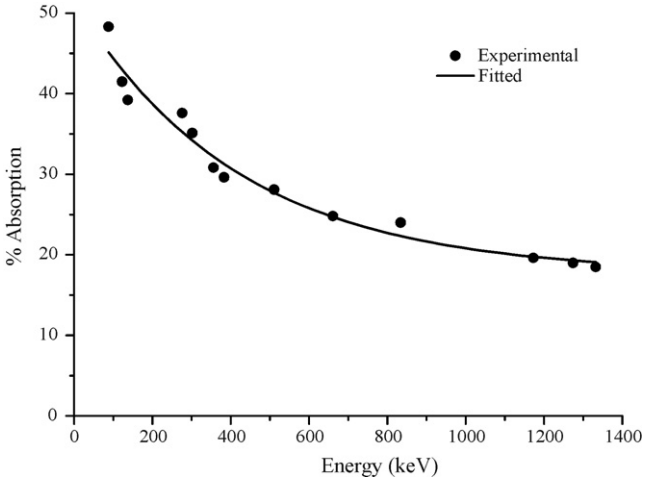

Fig. 6. The gamma-ray absorption rates in typical gas concrete sample at different energies.

at different photon energies, it exhibits little variation at energies above 834.8 keV. The half thicknesses ($X_{1/2}$) of each sample which halved the value of the radiation intensity were calculated by using Eq. (3). It is clearly observed from Table 6 that the half thicknesses of samples increased with increasing photon energy. As should be expected, the density and photon energy are the main parameters that affect the mass attenuation coefficient. For this reason, variations in chemical composition of the materials are significant. Besides determination of mass attenuation coefficients, the attenuation ratio of photons with energies between 88 and 1332.5 keV in a typical gas concrete with 9 cm thickness was determined. As shown in Fig. 6, the gas concrete samples absorb the photon by a ratio of 20–50% in the given energy ranges.

The overall error in the present measurements is estimated to be 3–6%. This error is due to the evaluation of peak areas (≤3%), sample thickness measurements (≈2%), density measurements (≤2%) and counting statistics (≤2%).

4. Conclusions

The radioactivity concentrations of the natural radionuclides of the ^{226}Ra, ^{232}Th and ^{40}K were measured by using the technique of gamma-ray spectroscopy with HPGe detector in gas concrete samples collected from suppliers and some provinces in Turkey. The results may be useful in the assessment of the exposures and the radiation doses due to naturally radioactive element contents in gas concrete. The mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were 82.0, 28.2 and 383.9 Bq kg^{-1}, respectively. Obtained values show that the mean radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), internal hazard index (H_{in}), the indoor absorbed dose rate (D) and annual effective dose rate (AED) in gas concrete samples are 151.9 Bq kg^{-1}, 0.41 nGy h^{-1}, 0.63 nGy h^{-1}, 70.9 nGy h^{-1} and 0.35 mSv y^{-1}, respectively. Also, mass attenuation coefficients were measured in some gas concrete samples. It can be concluded that the mass attenuation coefficients depend on the energy and the material density. To the best of our knowledge, this is the first detailed study of radiological characterization in gas concrete used in building materials in the literature. The results of the present study will be a valuable database for future estimations of the impact of radioactive pollution.

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References

[1] J.A. Ademola, I.P. Farai, Gamma activity and radiation dose in concrete building blocks used for construction of dwellings in Jos, Nigeria, Radiat. Prot. Dosimetry 121 (2006) 395–398.
[2] N.P. Petropoulos, M.J. Anagnostakis, S.E. Simopoulos, Photon attenuation, natural radioactivity content and radon exhalation rate of building materials, J. Environ. Radioact. 61 (2002) 257–269.
[3] L. Zikovsky, G. Kennedy, Radioactivity of building materials available in Canada, Health Phys. 63 (1992) 449–452.
[4] I. Othman, M. Mahrouka, Radionuclide content in some building materials in Syria and their indoor gamma dose rate, Radiat. Prot. Dosimetry 55 (1994) 299–304.
[5] K. Kovler, G. Haquin, V. Manasherov, E. Ne'eman, N. Lavi, Natural radionuclides in building materials available in Israel, Build. Environ. 37 (2002) 531–537.
[6] G.S. Bhandal, K. Singh, Photon attenuation coefficient and effective atomic number study of cements, Appl. Radiat. Isot. 44 (1993) 1231–1243.
[7] I.C.P. Salinas, C.C. Conti, R.T. Lopes, Effective density and mass attenuation coefficient for building material in Brazil, Appl. Radiat. Isot. 64 (2006) 13–18.
[8] E. Oguz, Adsorption of flouride on gas concrete materials, J. Hazard. Mater. 117 (2005) 227–233.
[9] E. Oguz, A. Gürses, N. Canpolat, Removal of phosphate from wastewaters, Cem. Concr. Res. 33 (2003) 1109–1112.
[10] U. Cevik, N. Damla, B. Koz, S. Kaya, Radiological characterization around Afsin-Elbistan coal-fired power plant in Turkey, Energy Fuel 22 (2008) 428–432.
[11] L.A. Currie, Limits for qualitative detection and quantitative determination, Anal. Chem. 40 (1968) 586–593.
[12] E. Stranden, Radioactivity of building materials and the gamma radiation in dwellings, Phys. Med. Biol. 24 (1979) 921–930.
[13] K.N. Yu, Z.J. Cheung, T. Cheung, T.T.K. Cheung, T.Y. Lo, Light weight concrete: ^{226}Ra, ^{232}Th, ^{40}K contents and dose reduction assessment, Appl. Radiat. Isot. 53 (2000) 975–980.
[14] M. Zalewski, M. Tomczak, J. Kapata, Radioactivity of building materials available in Northeastern Poland, Pol. J. Environ. Stud. 10 (2001) 183–980.
[15] N.K. Ahmed, Measurement of natural radioactivity in building materials in Qena city, Upper Egypt, J. Environ. Radioact. 83 (2005) 91–99.
[16] J. Beretka, P.J. Mathew, Natural radioactivity of Australian building materials, industrial wastes and by-products, Health Phys. 48 (1985) 87–95.
[17] Organization for Economic Cooperation and Development (OECD), Exposure to radiation from the natural radioactivity in building materials, Report by a Group of Experts of the OECD Nuclear Energy Agency, 1979.
[18] I. Fatima, J.H. Zaidi, M. Arif, M. Daud, S.A. Ahmad, S.N.A. Tahir, Measurement of natural radioactivity and dose rate assessment of terrestrial gamma radiation in the soil of southern Punjab, Pakistan, Radiat. Prot. Dosimetry 128 (2008) 206–212.
[19] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Sources and effects of ionizing radiation, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, United Nations, New York, 2000.