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Assessment of natural radioactivity and radiation hazard in volcanic tuff stones used as building and decoration materials in the Cappadocia region, Turkey

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ABSTRACT   The concentrations of natural radionuclides in 6 different colors of volcanic tuff stones which are derived from the Cappadocia region in Turkey were determined using gamma-ray spectroscopy with a HPGe detector, and the mineralogical composition and formula of stones were determined by an X-ray powder diffractometer. The average activity concentrations of ^{238}U, ^{232}Th and ^{40}K are 50.7, 58.6 and 717.6 Bq.kg^{-1}, which are higher than the world averages of 35, 30 and 400 Bq.kg^{-1}, respectively. The radium equivalent activities (Ra_{eq}), external hazard index (H_{ex}), and internal hazard (H_{in}) associated with the natural radionuclides, alpha (I_α) and gamma indices (I_γ) were calculated to assess the radiation hazard of the natural radioactivity in the volcanic tuff stones. The average indoor annual effective dose equivalent is 0.1 mSv. All values of the indoor effective dose are lower than the exemption dose value of 0.3 mSv. The calculated radium equivalent activity values vary from 60.31 Bq.kg^{-1} to 281.32 Bq.kg^{-1} with a mean of 189.78 Bq.kg^{-1}. All values of radium equivalent activity are lower than the world average. The average indoor absorbed dose rate (D_{in}) for volcanic tuff stones, calculated to be 21.18 nGy.h^{-1}, is lower than the world average of 84 nGy.h^{-1}.

1. Introduction

Natural radioactivity is widespread in the earth's environment; it exists in soil, plants, water and air. Environmental natural gamma radiation is formed from terrestrial and cosmic sources (Merdanoglu and Altinsoy, 2006). Natural radiation is the largest contributor to the external dose of the world's population (UNSCEAR, 2000) These dose rates vary from one place to another depending upon the concentration of natural radionuclides such as ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K present in the soil (UNSCEAR, 1988).

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Article publié par EDP Sciences

Besides medical exposure and cosmic radiation, building materials containing naturally occurring radionuclides are the main source of exposure as well. Construction raw materials are products which are derived from rock, soil and industrial additives such as the products of phosphoric acid (phosphogypsum) and fly ash produced from power stations. In addition to the naturally occurring radioactivity in the soil and rocks, these building material additives also contain trace amounts of natural radionuclides knowledge of the natural radioactivity in these materials is important for determining the amount of public exposure because people spend most of their time (about 80%) indoors (Al-Sulaiti *et al.*, 2011; Stoulos *et al.*, 2003).

Generally, the specific activities of ^{238}U, ^{232}Th and ^{40}K in the building raw materials and their products mainly depend on geological and geographical conditions as well as the geochemical characteristics of those materials (Turhan, 2008; Baykara *et al.*, 2011).

Internal exposure involves the inhalation of alpha particles emitted from the short-lived decay products of radon (^{222}Rn, the daughter product of ^{226}Ra) and thoron (^{220}Rn, the daughter product of ^{224}Ra).

The most important source of external radiation exposure in buildings is caused by the gamma rays emitted from members of the uranium and thorium decay chains and from ^{40}K occurring naturally in building materials.

The building materials in large buildings made of brick, concrete or stone act as attenuators of gamma rays emitted outdoors; therefore, the indoor absorbed dose depends mainly on the concentration of radioactive substances occurring in the construction materials (Righi and Bruzzi, 2006). If building materials with high natural radioactivity concentration are employed, dose rates indoors will be elevated accordingly.

The assessment of the population exposure due to indoor radiation is very important and therefore knowledge of the concentrations of natural radionuclides in the construction materials is required. Knowledge of radioactivity present in building materials enables the assessment of any possible radiological risks to human health. This information also helps in assessing the level of potential radiological hazard for humans caused by the use of specific building materials (Al-Sulaiti *et al*., 2011).

Gamma spectroscopy is the most widely used method for measuring these concentrations. The most important natural radionuclides in building materials are ^{226}Ra, ^{232}Th and ^{40}K. The external dose rate that is due to these radionuclides and their progeny could reach several hundreds of nGy/h.
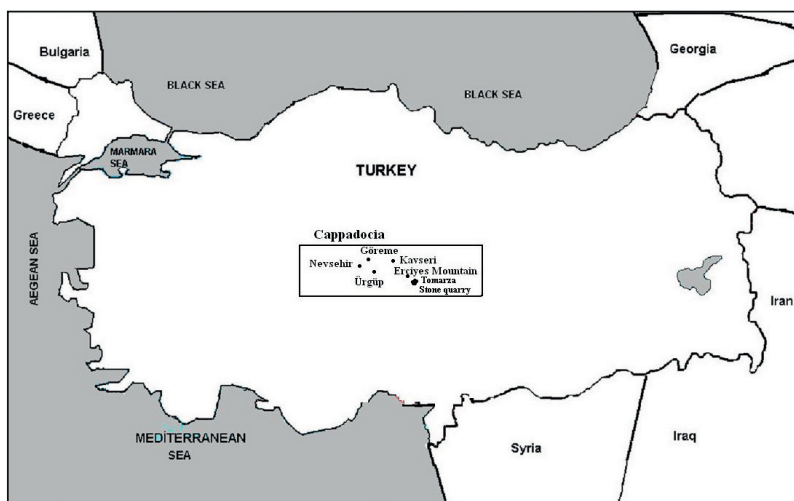
Figure 1 – *Sample taking area in Turkey.*

The main objectives of this study were to identify chemical contents and to determine natural radionuclide activity concentrations in 6 different colors of volcanic tuff stone samples which are commonly used in building and are decoration materials collected near the extinct Erciyes volcano, and to evaluate the annual effective dose from indoor terrestrial radiation. In addition, the natural gamma radiation coming from terrestrial radionuclides in air was also investigated in the Cappadocia region.

2. Materials and methods

Cappadocia, which is unique in the world and is a miraculous natural wonder, is the common name of the area covered by the provinces of Aksaray, Nevsehir, Nigde, Kayseri and Kirsehir in the Central Anatolian region (Fig. 1). The Cappadocia region, as a result of the volcanic eruptions that occurred in Erciyes, Hasandag and Gulludag, forms a large volcanic tuff plateau dissected by the erosion of the Kizilirmak river and wind over tens of thousands of years.

This study was planned to obtain the radioactivity of volcanic stones which are derived from the Cappadocia region and commonly used as building and decoration material in the Cappadocia region and around the world.

Six different colors of volcanic tuff stone samples were collected from a quarry in Tomarza village near the Erciyes extinct volcano (Fig. 1).

The mineralogical composition and formula of stone samples were determined by a Bruker AXS D8 Advance X-Ray powder diffractometer.

The stone samples were pulverized, dried, homogenized and sieved through 2-mm mesh. The meshed samples were transferred to Marinelli beakers of 1000 ml capacity. The samples were weighed, carefully sealed and stored for more than 30 days to allow secular equilibrium between radium and its decay products (Mollah *et al*., 1987).

Gamma spectroscopic measurements were performed using a coaxial HPGe detector with 16% relative efficiency. A detection system containing a Canberra Model 202 Amplifier and a Canberra S-85 Multi-Channel Analyzer with a Model 8087 4K ADC was used for the measurements. The detector was shielded in a 10-cm-thick lead well, internally lined with 2-mm-thick copper and 2-mm-thick cadmium foils. The overall detector resolution (FWHM) of 1.9 keV was obtained for the 1332 keV gamma line of ^{60}Co. Energy calibration and relative efficiency calibration of the gamma spectrometer were carried out using ^{109}Cd, ^{57}Co,^{113}Sn, ^{134}Cs, ^{137}Cs, ^{88}Y and ^{60}Co calibration sources in 1000-mL Marinelli beakers covering the energy range from 80 to 2500 keV. The counting time for each sample, as well as for background, was 50,000 s.

Gamma spectroscopy was used to determine the activities of ^{238}U, ^{232}Th, ^{40}K and ^{137}Cs. The activity concentrations of ^{232}Th and ^{238}U were calculated assuming secular equilibrium was established with their decay products. For concentrations of ^{232}Th and ^{238}U the following gamma transition lines were used; ^{232}Th series: ^{228}Ac (911 keV), ^{208}Tl (583.1 keV); ^{238}U series: ^{226}Ra (186.0 keV), ^{214}Pb (351.9 keV) and ^{214}Bi (609.2 keV). For the other radionuclides radioactive equilibrium between ^{214}Bi and ^{226}Ra is assumed. There is a contribution to the intensity of the 186 keV line of about 10 % from the 185 keV line which is the sure basis for the activity of ^{226}Ra (Varinlioglu *et al*., 1988; Varinlioglu and Kose, 2004). This line was used in this paper. The activity concentration of ^{40}K was determined from the peak area of the 1460 keV line. The 661.66 keV gamma transition was used to determine the ^{137}Cs concentration.

If radionuclide activity in soil is known, then the corresponding exposure dose rate in air at 1 m above the ground can be found. The conversion factor of ^{238}U, ^{232}Th and ^{40}K is 0.427, 0.662 and 0.043 nGy.h^{-1} per Bq.kg^{-1}, respectively (Beck, 1972).

The indoor absorbed gamma dose rate (D_{in}) in air was evaluated using data and formulae provided by the EC report (EC, 1999).

In the EC report, the dose conversion coefficients were calculated for the center of the room. The dimensions of the room are 4 m × 5 m × 2.8 m. The thickness of tiles on all walls and density of the structures are 3 cm and 2600 kg.m^{-3}, respectively. These coefficients correspond to 0.12 nGy.h^{-1} per Bq.kg^{-1} for ^{226}Ra, 0.14 nGy.h^{-1} per Bq.kg^{-1} for ^{232}Th and 0.0096 nGy.h^{-1} per Bq.kg^{-1} for ^{40}K (EC, 1999; Turhan, 2012):

$$D_{in}(\text{nGy.h}^{-1}) = 0.12C_{Ra} + 0.14C_{Th} + 0.0096C_K \tag{1}$$

where C_{Ra}, C_{Th} and C_K are the activity concentrations of Ra, Th and K (Bq.kg^{-1}), respectively.

The indoor annual effective dose equivalent (E_{in}) was calculated as follows:

$$E_{in} \text{ (mSv)} = D_{in} \text{ (nGy.h}^{-1}) \times F_c \text{ (Sv.Gy}^{-1}) \times T_E \text{ (h.y}^{-1}) \times 10^{-6} \tag{2}$$

where D_{in} is the indoor absorbed gamma dose rate, F_c is the conversion factor of 0.7 Sv.Gy^{-1} from the indoor absorbed gamma dose in air to the effective dose received by adults (UNSCEAR, 2000) and T_E is the annual exposure time of 7000 h.y^{-1}, implying that 80% of time is spent indoors.

Radium equivalent activity (Ra_{eq}) is used to assess the hazard associated with materials that contain ^{226}Ra, ^{232}Th and ^{40}K. This definition is based on the assumption that 1 Bq.kg^{-1} of ^{226}Ra, 0.7 Bq.kg^{-1} of ^{232}Th and 13 Bq.kg^{-1} of ^{40}K produce the same gamma dose rate. The Ra_{eq} of the sample (in Bq.kg^{-1}) can be determined using the following equation (UNSCEAR, 1988; Al-Sulaiti et al., 2011):

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K. \tag{3}$$

The annual external (gamma) index (H_{ex}) due to emitted gamma rays of each sample is given by the following equation:

$$H_{ex} = \frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \tag{4}$$

and the internal exposure due to ^{222}Rn and its radioactive progeny is controlled by the internal hazard index, which is given by:

$$H_{in} = \frac{C_U}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \tag{5}$$

where C_U, C_{Th} and C_K are the activity concentrations of U, Th and K in Bq.kg^{-1}, respectively.

2.1 Gamma index

In order to assess whether the safety requirements for building materials are being fulfilled, a gamma index proposed by the European Commission (EC, 1999) was used. It is defined as:

$$I_\gamma = \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} + \frac{C_K}{3000} \leq 1 \tag{6}$$

where C_{Ra}, C_{Th} and C_K are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively (in Bq.kg^{-1}). The gamma index should also take into account typical ways and amounts in which the material is used in a building. The limit values depend on the dose criteria, and also on the amount of the material and the manner in which it was used in a building and construction. For material used in bulk amounts, $I_\gamma \leq 1$ corresponds to an absorbed gamma dose rate of 1 mSv.y^{-1} (EC, 1990).

2.2 Alpha index

Assessment of the internal hazard originating from the alpha activity of building materials requires calculations of the alpha index, or internal hazard index. The alpha index is calculated by using the following equation:

$$I_\alpha = \frac{C_{Ra}}{200} \tag{7}$$

where C_{Ra} is the specific activity of ^{226}Ra. The safe use of materials in building construction requires I_α to be less than 1. This limit corresponds to the design action level for the ^{222}Rn concentration of 200 Bq.m^{-3} on an annual average basis for future buildings (EC, 1990; Stojanovska et al., 2010).

3. Results and discussion

The average radionuclide activity concentrations in 6 different colors of volcanic stone samples are reported in Tables I and II. Specific activities of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs are reported in Bq.kg^{-1} dry weight (Tab. I). The mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in stone samples are 50.68, 58.63 and 717.55 Bq.kg^{-1} respectively. The ^{226}Ra, ^{232}Th and ^{40}K activity concentrations are shown in figure 2. The mean activity concentrations of ^{238}U and ^{232}Th are 4.2 and 14.4 as ppm and ^{40}K is 2.4 wt% (Tab. II).

The light beige-colored tuff stone whose mineralogical composition name is albite intermediate and tridymite has the highest activity concentrations, with 97.2 Bq.kg^{-1}, 96.0 Bq.kg^{-1} and 1036 Bq.kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K,

TABLE I

^{226}Ra, ^{232}Th and ^{40}K activity concentrations of samples as Bq.kg^{-1}.

Material	Sample colors	Mineralogical composition name	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	^{137}Cs (Bq/kg)
T1	yellow	albite high tridymite	64.5 ±1.6	96.0 ± 2.3	1033.0 ± 29.0	<1.1
T2	dark gray	labradorite	42.4 ±0.8	38.8 ± 3.6	747.4 ± 18.6	<0.2
T3	light gray	andesine tridymite	50.0 ±0.8	61.6 ± 0.9	813.0 ± 21.0	<0.3
T4	light beige	albite intermediate tridymite	97.2 ±3.0	96.0 ± 2.2	1036.0 ± 31.5	<0.4
T5	red	andesine	32.2 ±0.6	42.0 ± 0.7	447.0 ± 11.7	<0.3
T6	gray	hatrurite gypsum	17.8 ±0.7	17.4 ± 1.0	228.9 ± 8.2	<0.5
	mean value		50.7	58.6	717.6	
	world average		35	30	400	

TABLE II

^{226}Ra, ^{232}Th and ^{40}K activity concentrations of samples as ppm and wt%.

Material	Sample colors	Mineralogical composition name	^{226}Ra (ppm)	^{232}Th (ppm)	^{40}K (wt%)
T1	yellow	Albite high tridymite	5.3	23.6	3.4
T2	dark gray	labradorite	3.5	9.5	2.5
T3	light gray	andesine tridymite	4.1	15	2.7
T4	light beige	albite intermediate tridymite	8	23.6	3.4
T5	red	andesine	2.6	10.31	1.5
T6	gray	hatrurite gypsum	0.6	4.3	0.8
	mean value		4.2	14.4	2.4

respectively. The highest and lowest activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were measured in the light beige-colored stone (T4) whose mineralogical composition is albite intermediate and tridymite and in the gray-colored stone (T6) whose mineralogical composition is hatrurite and gypsum, respectively. The worldwide average concentrations of these radionuclides are reported by UNSCEAR (2000) as 35, 30 and 400 Bq.kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. Our results are higher than the world average.

^{137}Cs was also seen in the samples and analyzed in this study. The anthropogenic radionuclide ^{137}Cs was deposited in the rock of the region presumably as a result of atmospheric fallout of radioactivity following the Chernobyl accident on April 26, 1986, and other previous atmospheric tests of nuclear devices around the world. The ^{137}Cs activity varied from <0.2 to <1.1 Bq.kg^{-1} (Tab. I).
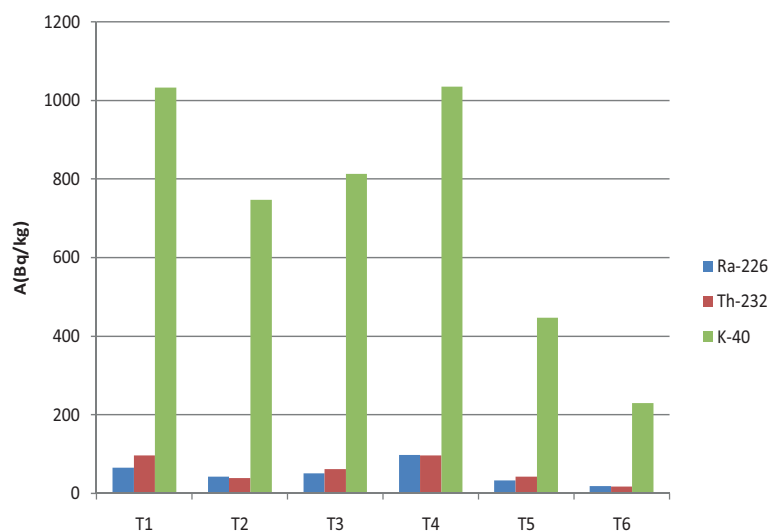
Figure 2 – *The natural radioactivity concentrations of the samples.*

TABLE III

Calculated absorbed dose rates (D_{in}), indoor annual effective doses (E_{in}), radium equivalent activity (Ra_{eq}), internal hazard indices (H_{in}), external hazard indices (H_{ex}), and alpha and gamma indices for all samples.

Sample code	Sample colors	Mineralogical composition name	D_{in} (nGy/h)	E_{in} (mSv)	Ra_{eq} (Bq/kg)	H_{in}	H_{ex}	Gamma index I_γ	Alpha index I_α
T1	yellow	albite high tridymite	31.1	0.15	281.3	0.9	0.8	1.0	0.3
T2	dark gray	labradorite	17.6	0.09	155.4	0.5	0.4	0.6	0.2
T3	light gray	andesine tridymite	22.4	0.11	200.7	0.6	0.5	0.8	0.3
T4	light beige	albite intermediate tridymite	35.1	0.17	314.3	1.1	0.9	1.2	0.5
T5	red	andesine	14.1	0.07	126.7	0.4	0.3	0.5	0.2
T6	gray	hatrurite gypsum	6.8	0.03	60.3	0.2	0.2	0.2	0.1
	mean value		21.18	0.1	189.8	0.6	0.5	0.7	0.3
	acceptable level		84	0.3	370	1	1	1	1

The calculated values for the indoor annual effective dose (E_{in}) ranged from 0.03 mSv to 0.17 mSv, with a mean value of 0.1 mSv. The results for the indoor annual effective dose (E_{in}) are given in Table III. The indoor annual effective dose
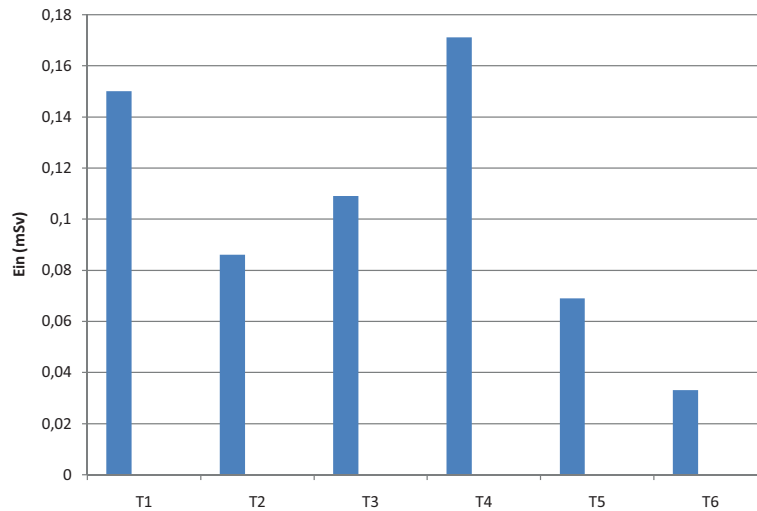
Figure 3 – *Indoor annual effective dose equivalent for all samples.*

rates for all samples are shown in Figure 3. The indoor annual effective dose rates of the yellow-colored stone whose chemical name is albite high and tridymite and the light beige-colored stone whose chemical name is albite intermediate and tridymite are higher than the other stone samples. It can be seen from Table III that all values of E_{in} are significantly lower than the exemption dose criterion of 0.3 mSv.

The indoor gamma dose rates (I_{in}) calculated from the measured activities in stone samples are also given in Table III. The absorbed dose rates in indoor air ranged from 6.8 nGy h^{-1} to 35.1 nGy.h^{-1} with a mean of 21.2 nGy.h^{-1}. All calculated indoor absorbed dose rates are lower than the world average. The indoor gamma dose rates due to natural radioactivity for all samples are shown in Figure 4.

The results for radium equivalent activity (Ra_{eq}) calculated using equation (3) are shown in Table III. These values range from 60 Bq.kg^{-1} to 314 Bq.kg^{-1} (Tab. III). Ra_{eq} values of all the measured samples were lower than the recommended maximum values 370 Bq.kg^{-1} given by the Organization for Economic Cooperation and Development (OECD, 1979) (Fig. 5).

Internal hazard indices (H_{in}) range from 0.2 to 1, with a mean value of 0.6 (Tab. III). Only one sample is higher than 1, the recommended value (Fig. 6).
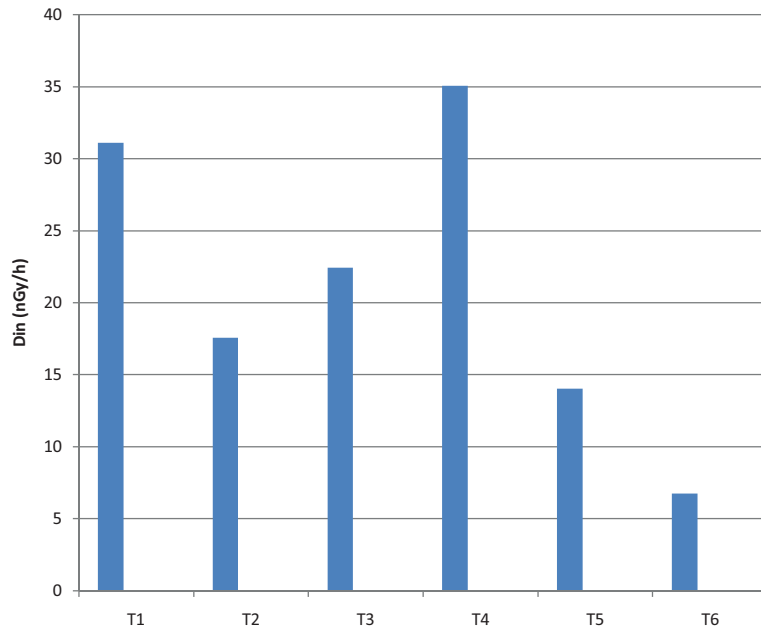
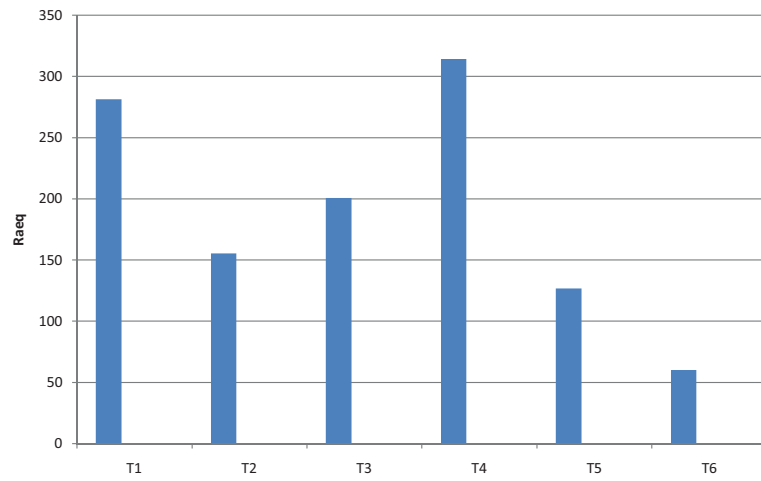**Figure 4 –** *Indoor absorbed gamma dose rate due to the natural radioactivity for all samples.*

Figure 5 – *Radium equivalent activity (Ra_{eq}) of the samples.*
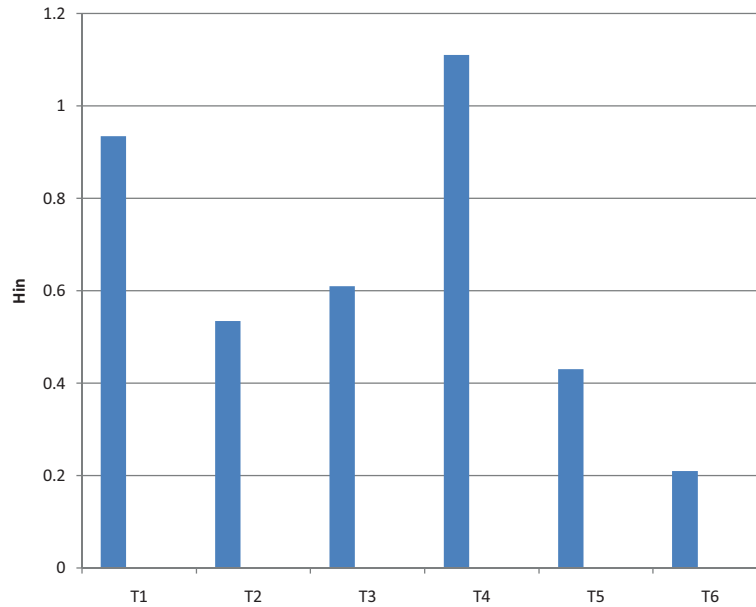
Figure 6 – *Internal hazard index of the samples.*

Calculated external (H_{ex}) and internal hazard index results are shown in Table III. The value of these indices must be less than unity in order for the radiation hazard to be negligible. The calculated H_{ex} values range from 0.16 to 0.85, with a mean value of 0.51. None of the H_{ex} results exceed the recommended limit equal to1 (Fig. 7).

The calculated gamma (I_γ) and alpha (I_α) indices are shown in Table III. The gamma index ranges from 0.2 to 1.2, with a mean value of 0.7. The alpha index ranges from 0.1 to 0.5, with a mean value of 0.25. I_α values for all samples studied are below the recommended upper level. The recommended upper limit concentration of ^{226}Ra is 200 Bq.kg^{-1}, for which $I_\alpha = 1$.

The mineralogical composition and formula of 6 different colors of volcanic stones are shown in Table IV.

The comparisons of radioactivity with other building materials in Turkey and worldwide are shown in Table V. The radioactivity comparison of volcanic rocks in the same area is shown in Table VI.
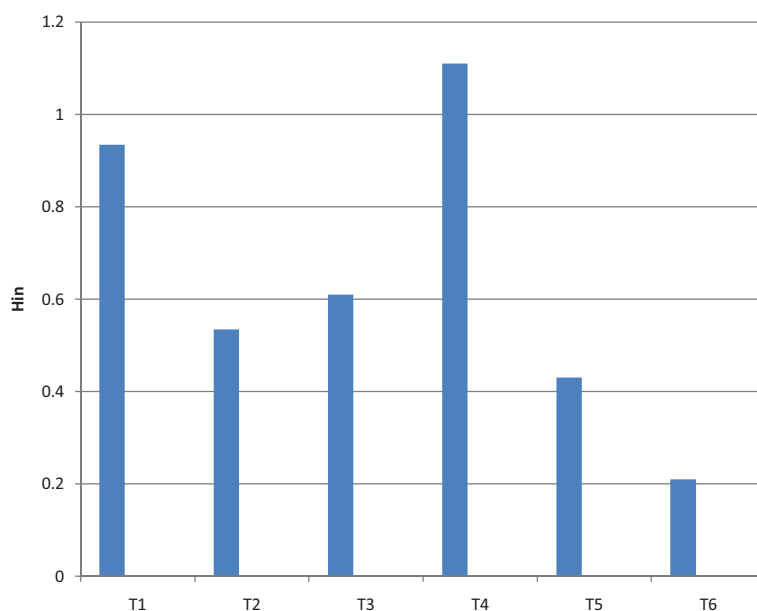
Figure 7 – *External hazard index of the samples.*

TABLE IV
The mineralogical composition and formula of stone samples.

mineral number	mineralogical composition	
	T1	
1	albite high	$Na(AlSi_3O_8)$
2	tridymite	SiO_2
	T2	
1	labradorite	$Ca_{0.65}Na_{0.32}(Al_{1.62}Si_{2.38}O_8)$
	T3	
1	andesine	$Na_{0.499}Ca_{0.491}(Al_{1.488}Si_{2.506}O_8)$
2	tridymite	SiO_2
	T4	
1	albite intermediate	$Na_{1.08}(Al_{1.08}Si_{2.92}O_8)$
2	tridymite	SiO_2
	T5	
1	andesine	$Na_{0.685}Ca_{0.347}Al_{1.46}Si_{2.54}O_8$
	T6	
1	hatrurite	Ca_3SiO_5
2	gypsum	$Ca(SO_4)(H_2O)_2$

TABLE V
The comparison of radioactivity with other building materials in Turkey and worldwide.

	^{226}Ra (Bq.kg^{-1})	^{232}Th (Bq.kg^{-1})	^{40}K (Bq.kg^{-1})	References
Turkey (granite)	88	95	1055	Turhan (2012)
Turkey (marble)	10-92	4-122	28-676	Cevik et al. (2010)
Turkey, Sivrihisar (granite)	67	153	1058	Örgün et al. (2005)
Turkey, Ezine (granite)	175	205	1172	Örgün et al. (2007)
Red Mud Turkey	210	539,0	112,0	Akinci and Artir (2008)
natural building stones	60	60	640	EC (1999)
worldwide	42	73	1055	Kitto et al. (2009)
Nevsehir (Turkey) volcanic tuff stones	50,7	58,6	717,6	present work

TABLE VI
The comparison of radioactivity with volcanic rocks in the same area.

^{238}U (ppm)	^{232}Th (ppm)	^{40}K (wt %)	References
2.3	10	1.2	Aydin et al., 2006
4.2	14.4	2.4	present work

4. Conclusion

The specific activities of ^{226}Ra, ^{232}Th and ^{40}K in the different colors of volcanic tuff stones collected from a quarry in Tomarza village, located just near Erciyes extinct volcano, were measured using the gamma spectroscopy technique. The mineralogical composition and formula of stone samples were determined by a Bruker AXS D8 Advance X-Ray powder diffractometer.

The mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in stone samples are 50.68, 58.63 and 717.55 as Bq.kg^{-1} and respectively. The mean activity concentrations of ^{238}U and ^{232}Th are 4.2 and 14.4 as ppm and ^{40}K is 2.4 wt% . The average activity concentrations of ^{238}U, ^{232}Th and ^{40}K are 50.7, 58.6 and 717.6 Bq.kg^{-1}, which are higher than the world averages of 35, 30 and 400 Bq.kg^{-1}, respectively.

The absorbed dose rates in indoor air (D_{in}) ranged from 6.8 nGy·h^{-1} to 35.1 nGy·h^{-1} with a mean of 21.2 nGy·h^{-1}. The average indoor absorbed dose rate (D_{in}) for volcanic tuff stones, calculated to be 21.18 nGy·h^{-1}, is lower than the world average of 84 nGy·h^{-1}.

The radium equivalent activity (Ra_{eq}), the external hazard (gamma) index (H_{ex}), internal hazard index (H_{in}), gamma index (I_{γ}), alpha index (I_{α}), indoor annual effective dose equivalent and indoor absorbed gamma dose rate were determined to assess the radiological hazard from volcanic tuff stones in the

Cappadocia region. The results showed that our results for ^{226}Ra, ^{232}Th and ^{40}K are higher than the world average, which is 35 Bq.kg^{-1} for ^{226}Ra, 30 Bq.kg^{-1} for ^{232}Th and 400 Bq.kg^{-1} for ^{40}K.

The anthropogenic radionuclide ^{137}Cs activity varied from <0.2 to <1.1 Bq.kg^{-1}.

The mean value of the indoor annual effective dose (E_{in}) was found to be 0.1 mSv. The indoor effective dose equivalent of T_1 and T_4 was found to be higher than the other samples. All values of E_{in} are significantly lower than the exemption dose criterion of 0.3 mSv.

The mean value of radium equivalent activity (Ra_{eq}) was calculated as 189.78 Bq.kg^{-1}. This value is lower than the world average, which is 370 Bq.kg^{-1} for Ra_{eq} (OECD, 1979; UNSCEAR, 1988).

The internal hazard index's (H_{in}) mean value was found to be 0.6. Only one sample (T_4) is higher than the recommended value of 1 for H_{in}.

The mean value of the external hazard index was calculated to be 0.51. No H_{ex} results exceeded the recommended limit, which is equal to 1.

A mean value of 0.25 was found for the alpha index (I_α) and 0.7 for the gamma index (I_γ). I_α values for all samples are below the recommended upper level. The recommended upper limit concentration of ^{226}Ra is 200 Bq.kg^{-1}, for which $I_\alpha = 1$. The gamma indices of T_1 and T_4 were found to be higher than the recommended value, which is 1 for I_γ.

To the best of our knowledge, this is the first detailed study of radioactivity concentrations and radiation hazard in the different colors of volcanic tuff stones which are commonly used in building and decoration materials.

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