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Natural radioactivity measurements and dose rate assessment of selected ceramic and cement types used in Riyadh, Saudi Arabia

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ABSTRACT

The natural radioactivity of ceramic and cement samples collected from Riyadh, Saudi Arabia, was analyzed using a gamma-ray spectrometry system with a high-purity germanium detector. The specific activities of ^{226}Ra, ^{232}Th, and ^{40}K ranged from 45.0 ± 4.2 to 177.8 ± 7.5 Bq/kg, 49.1 ± 2.6 to 228.4 ± 6.8 Bq/kg, and 370.0 ± 5.3 to 1269.0 ± 12.2 Bq/kg, respectively, for the ceramic samples and from 11.4 ± 2.0 to 28.7 ± 5.3 Bq/kg, 8.4 ± 1.3 to 10.8 ± 1.1 Bq/kg, and 50.7 ± 2.1 to 209.7 ± 3.5 Bq/kg, respectively, for the cement samples. The radium equivalent activity, external hazard index, absorbed dose rate, and annual effective dose were calculated using the above measurements in order to assess the radiological hazard associated with the studied building materials. The average values of these radiological indices for the ceramic samples were 299.4 ± 94.8 Bq/kg, 0.8 ± 0.3, 138 ± 42.4 nGy/h, and 0.68 ± 0.21 mSv/y, respectively, and for the cement samples, these values were 36.8 ± 7.74 Bq/kg, 0.12 ± 0.02, 20.35 ± 4.39 nGy/h, and 0.10 ± 0.02 mSv/y, respectively. The radiological indices of the studied samples were found to be within the range of those reported in recent similar studies conducted in other countries. The majority of the ceramic samples can be safely used as building materials for dwelling construction, although some samples slightly exceeded the average radium equivalent of 370 Bq/kg and the external hazard index limit of 1; the hazard indices for the cement samples, however, were all below the recommended world limits and can be considered safe for inhabitants.

1. Introduction

Human beings are constantly subjected to ionizing radiation from radionuclides in minerals and raw materials of natural origin. Naturally occurring radioactive materials (NORM) are the radionuclides found in the uranium and thorium decay series, and radioactive potassium presents a radiological risk to humans. NORM is the result of specific human activities that enhance human exposure to the radionuclides that emerge from the Earth's crust; therefore, they can be found in water, air, food, building materials, and the human body (IAEA, 2015; NORM V, 2007; Raghu et al., 2017).

Individuals spend an average of 80% of their time indoors (UNSCEAR 1993; Stoulos et al., 2003). Therefore, it is essential to estimate how much radiation exposure from building materials they may experience. Building materials are normally extracted from rocks, sand, and soil and contain varying levels of radionuclides depending on the raw materials from which they are derived (Rahman et al., 2012; Lu et al., 2014). The radiation hazard is due to these radioactive isotopes via external and internal exposure. External exposure is related to direct gamma radiations emitted from isotopes in the above-mentioned series, as well as from the main ^{40}K gamma line. Internal exposure is caused by the inhalation of the radioactive inert gases radon ^{222}Rn, thoron ^{220}Rn, and their short-lived progeny radioisotopes (Ngachin et al., 2007; Al-Sulaiti et al., 2011; Khandaker et al., 2012).

Health hazards related to exposure to radiation from building materials used indoors have been studied by numerous researchers worldwide (Amana, 2017; Amin and Naji, 2013; Majid et al., 2013; Baz, 2015; Damla et al., 2010; El-Taher A., 2012; Hassan et al., 2015; Gbenu et al., 2016; Lu et al., 2014; Ravisankar et al., 2012; Righi and Bruzzi, 2006). In addition, international organizations such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), European Commission, and International Commission on Radiological Protection have produced several publications regarding limits on the constituent

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concentrations in some building materials and have issued restrictions on materials with excessive levels of radioactivity (EC, 1999; ICRP, 1999; ICRP, 2015; UNSCEAR, 2000). Over the past decades, the majority of published data on radiation health risks due to building materials did not present significant findings. However, the accumulation of radioactivity from building materials over time combined with poor ventilation may increase the probability of occurrence of cancer in the building occupants.

In recent decades, cities in Saudi Arabia have grown significantly, with the population of the capital city of Riyadh exceeding five million people. This growth was accompanied by a rising demand in the residential sector, and it is estimated that 150,000 to 200,000 housing units are being built annually. Presently, the most common material tiles used in Saudi Arabian dwellings are ceramic, with various new brand names entering the market, both local and imported. In addition, cement is still an essential material in the construction of houses and buildings all over the country. The cement sector in Saudi Arabia is the third largest in the Middle East and North Africa, with a cement capacity of over 70 million tons and a local demand of approximately 47 million tons in 2017 (Balakrishnan and Al-Moammar, 2018). In the case of ceramics, Saudi Arabia's 2016 vol of imported ceramics was estimated to be approximately 167 million m^3, which is approximately two thirds of the national consumption (ACIMAC, 2017).

The current study aimed to investigate ceramic tiles and cement for levels of natural radioactivity. The scope of this study is to determine the specific activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in different ceramic and cement samples commonly used in Riyadh. The measured values will be used to calculate the average radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), absorbed dose rate (D), and annual effective dose (AED) hazard indices, which will be compared with those published by other researchers and the UNSCEAR safety limits. The objectives of this work were to compare current data to previously published data on cement samples in Saudi Arabia and other parts of the world and to set a reference background for future extensive measurements of cement and ceramic bricks used as building materials in Saudi Arabia.

2. Materials and methods

2.1. Sampling and sample preparation

A total of 24 ceramic and cement samples were collected from various local dealers in Riyadh, Saudi Arabia. Twenty ceramic samples were selected, the majority of which were imported from foreign manufacturing companies. Four cement samples (three grey and one white) were also selected from the local market; three were of Saudi Arabian origin and one was imported from Qatar during the 2000 s.

The samples were powdered into fine grains using a laboratory-crushing machine, air-dried, homogenized, and then placed into airtight plastic containers. The corresponding net weights of the prepared samples were recorded. The containers were closed tightly using an adhesive sealing tape and the samples were stored for four weeks to ensure a secular equilibrium between ^{226}Ra and its short-lived decay products. During the storage period, the containers were stored in a deep freezer at – 17 °C to inhibit radon animation from the sample to the air layer in the container.

2.2. Analytical technique

The concentrations of natural radioactivity (^{226}Ra, ^{232}Th, and ^{40}K) in the prepared samples were measured using an extended-range high-purity germanium (HPGe) detector (Canberra model GX4018) associated with the preamplifier model 2002CSL, amplifier model 2025, and 16 k digital multichannel analyzer multiport II. To ensure a low background environment, the HPGe detector was enclosed within a 10-cm lead shield coated internally with a 2-mm copper layer. The detector has an efficiency of 40% and an energy resolution of 1.8 keV at 1.3 MeV photons. The system is supported by the Genie 2000 software for identifying and recording the gamma energy photopeak spectra. The absolute photopeak efficiency calibration of the HPGe gamma ray-system was conducted using a powder of an IAEA, RGU-1 certified reference uranium ore sample. This is a well-known reference material that is used to obtain accurate absolute photopeak efficiency calibration curves (Ebaid and Khater, 2017).

The background radioactivity was determined using an empty container with the same geometry as that used for the prepared samples; this was sealed and stored for 4 weeks before determining the background measurement. After performing a correction for the background spectra, the specific activity concentration of natural radioactivity in the samples (Bq/kg) was calculated based on the count spectra of each sample using the gamma-ray photon peaks. The ^{226}Ra activity concentration was calculated indirectly using the gamma-ray peak values of its radon daughters: ^{214}Pb (295, 352 keV) and ^{214}Bi (609.31, 1120.29, 1764.49 keV). The gamma-ray peaks of ^{228}Ac (338.32, 911.20 keV) and ^{208}Tl (583.19 keV) were used to assess the activity concentration of ^{232}Th. The ^{40}K activity concentration was directly measured using its 1460.83-keV energy photopeak.

The specific activity concentration A (Bq/kg) for the natural radionuclides in the measured samples was calculated using the following formula (Amrani and Tahtat, 2001; Baykara et al., 2011)

$$A = \frac{C}{pwt\varepsilon} \quad (1)$$

where C is the net count above the background radioactivity, p is the absolute transition probability of gamma-decay, w is the mass of the sample, t is time, and ε is the detector efficiency for the specific gamma ray.

2.3. Assessment of radiological hazards

The use of a number of indices has been suggested by previous researchers for assessing the radiological hazards associated with the use of building materials in dwellings. The most common among these indices are presented below along with the corresponding formulas used for their calculation.

2.3.1. Radium equivalent activity (Ra_{eq})

Ra_{eq} is the weighted sum of activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K based on the assumption that 370 Bq/kg of ^{226}Ra, 259 Bq/kg of ^{232}Th, and 4810 Bq/kg of ^{40}K produce the same gamma radiation dose rates (Dabayneh et al., 2008; Agbalagba et al., 2014). Ra_{eq} is calculated using the following equation (Khandaker et al., 2012; Ngachin et al., 2007).

$$Ra_{eq}(Bq/kg) = A_{Ra} + 1.43\,A_{Th} + 0.077\,A_K \quad (2)$$

where A_{Ra}, A_{Th}, and A_K are the specific activity concentrations (Bq/kg) of ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

2.3.2. External hazard index (H_{ex})

H_{ex} is an important measure used to set a limit of 1.5 mSv on the radiation dose from building materials in dwellings. H_{ex} is associated with the external hazard index and is calculated using Eq. (3) (Khandaker et al. (2012) and Ngachin et al. (2007)):

$$H_{ex} = \frac{\mathbf{A_{Ra}}}{370\ \mathbf{Bq/kg}} + \frac{A_{Th}}{259\ Bq/kg} + \frac{A_K}{4810\ Bq/kg} \quad (3)$$

H_{ex} should be less than unity for the safe use of building materials in dwellings.

2.3.3. Absorbed dose rate (D)

The external absorbed dose rate (D) of air 1 m above the ground due to ^{226}Ra, ^{232}Th, and ^{40}K is calculated using the Monte Carlo method (Khandaker et al., 2012; Ngachin et al., 2007; Rahman et al., 2012; UNSCEAR, 1988):

$$D(nGy/h) = 0.427\,A_{Ra} + 0.662\,A_{Th} + 0.043\,A_K \quad (4)$$

where A_{Ra}, A_{Th}, and A_K are the specific activity concentrations (Bq/kg) of ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

Table 1
Activity concentration of ^{232}Th, ^{226}Ra, and ^{40}K for ceramic samples.

Sample code	Activity concentration (Bq/kg)		
	^{226}Ra	^{232}Th	^{40}K
O1	134.5 ± 8.3	135.1 ± 5.6	912.3 ± 11.8
E1	135.7 ± 5.2	106.8 ± 3.0	370.0 ± 5.3
E2	177.8 ± 7.5	131.0 ± 4.2	623.2 ± 8.4
E3	98.8 ± 7.8	108.3 ± 4.7	518.1 ± 9.7
I1	53.5 ± 4.5	49.1 ± 2.6	435.5 ± 6.6
N1	54.1 ± 4.0	81.2 ± 2.7	386.9 ± 5.4
C1	66.1 ± 4.6	94.4 ± 3.2	398.8 ± 5.8
E4	80.9 ± 6.6	92.2 ± 4.0	1130.6 ± 11.5
I2	155.1 ± 10.3	228.4 ± 6.8	630.9 ± 12.3
E5	50.7 ± 3.9	77.1 ± 2.4	1086.4 ± 7.7
E6	53.1 ± 4.7	83.5 ± 2.9	1155.2 ± 9.4
E7	78.9 ± 5.3	86.3 ± 3.2	1081.9 ± 9.5
N2	57.9 ± 6.4	101.7 ± 4.5	473.5 ± 8.7
G1	114.3 ± 7.5	188.8 ± 4.8	600.6 ± 9.3
G2	58.1 ± 4.9	82.7 ± 3.0	819.2 ± 8.4
C2	144.4 ± 8.2	127.6 ± 4.7	851.0 ± 10.9
S1	45.0 ± 4.2	62.8 ± 2.7	633.7 ± 7.3
C3	87.1 ± 9.2	116.6 ± 5.8	1218.1 ± 16.3
G3	54.4 ± 5.1	69.4 ± 3.4	862.8 ± 9.3
P1	80.1 ± 6.7	87.6 ± 3.9	1269.0 ± 12.2
Standard Deviation	40.6	42.2	304.3
Average	89.0	105.5	772.9
Maximum	177.8	228.4	1269.0
Minimum	45.0	49.1	370.0

2.3.4. Annual effective dose (AED)

This index can be calculated in terms of D using the equation below (Khandaker et al., 2012; Ngachin et al., 2007; Rahman et al., 2012; UNSCEAR, 2000):

$$AED(mSv/y) = D \times O \times CF \times 10^{-6} \quad (5)$$

where O is the indoor occupancy time, and CF (0.7 Sv G/y) is the conversion factor between the absorbed dose in air to the effective dose received by an adult (UNSCEAR, 1988; UNSCEAR, 2000). Using 0.8 as the average time spent indoors (UNSCEAR, 1988; UNSCEAR, 2000), O is calculated as follows:

$O = 0.8 \times 24\ h\ d^{-1} \times 365.25\ d/y$.

3. Results and discussion

The natural radioactivity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K found in the 20 ceramic samples are listed in Table 1. The specific activity concentrations for ^{226}Ra, ^{232}Th, and ^{40}K were found to vary from 45.0 ± 4.2 (S1) to 177.8 ± 7.5 Bq/kg (E2) with a mean ± standard deviation of 89.0 ± 40.6 Bq/kg for ^{226}Ra, 49.1 ± 2.6 (I1) to 228.4 ± 6.8 Bq/kg (I2) with a mean ± standard deviation of 105.5 ± 42.2 Bq/kg for ^{232}Th, and 370.0 ± 5.3 (E1) to 1269.0 ± 12.2 Bq/kg (P1) with a mean ± standard deviation of 772.9 ± 304.3 Bq/kg for ^{40}K. The above specific activity concentrations were higher than the global average values of ^{226}Ra, ^{232}Th, and ^{40}K in the Earth's crust, which are estimated to be 50, 50, and 500 Bq/kg, respectively (UNSCEAR, 1993). The results for the above radionuclides can be more clearly observed when plotted as a frequency distribution, as shown in Fig. 1. The range of 45–100 Bq/kg includes 70% and 50% of the samples for ^{226}Ra and ^{232}Th, respectively, while the range of 370–635 Bq/kg includes 80% of the samples for ^{40}K.

Fig. 2 presents the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the four cement samples. The specific activity concentrations for ^{226}Ra, ^{232}Th, and ^{40}K were found to vary from 11.4 ± 2.0 (S-W) to 28.7 ± 5.3 Bq/kg (S-B) with a mean ± standard deviation of 21.7 ± 7.4.6 Bq/kg for ^{226}Ra, 8.4 ± 1.3 (B-B) to 10.8 ± 1.1 Bq/kg (Q-B) with a mean ± standard deviation of 9.8 ± 1.0 Bq/kg for ^{232}Th, and 50.7 ± 2.1 (B-B) to 209.7 ± 3.5 Bq/kg (Q-B) with a

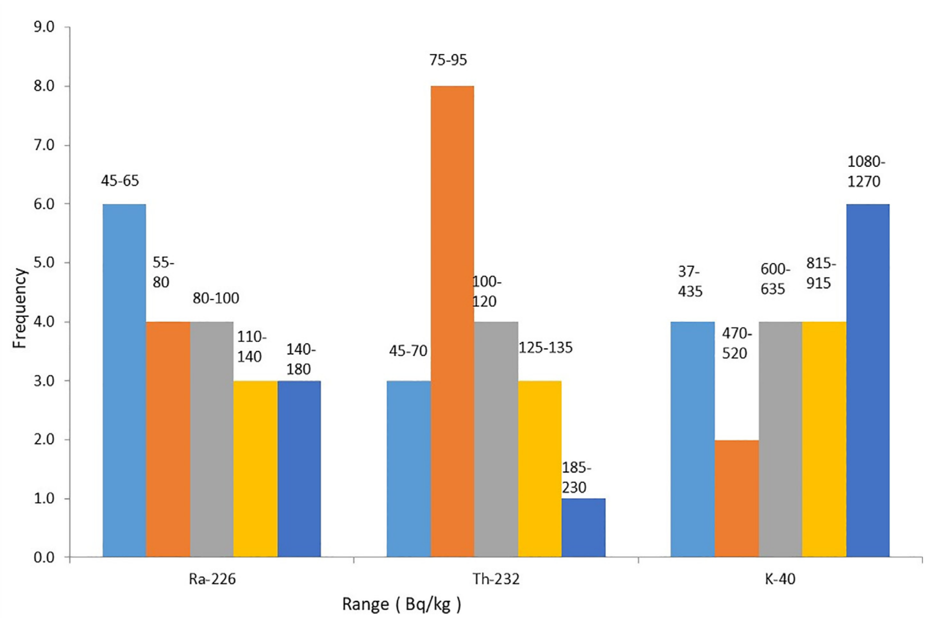

Fig. 1. Frequency distribution of the activity concentrations of ^{226}Ra,^{232}Th, and ^{40}K (Bq/kg) for the ceramic samples.

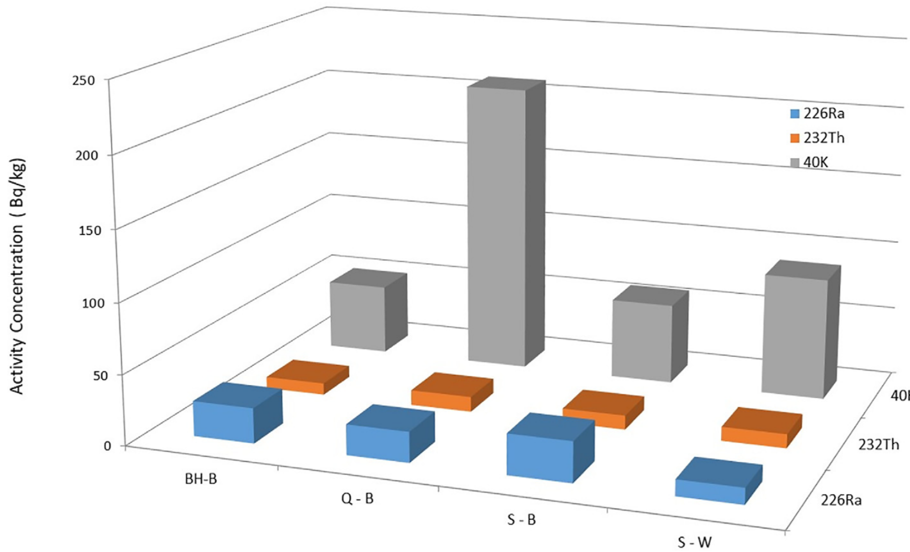

Fig. 2. Concentrations of ^{226}Ra,^{232}Th, and ^{40}K (Bq/kg) for the cement samples.

Table 2
Radiation hazard indices for ceramic samples.

Sample code	Ra_{eq} (Bq/kg)	H_{ex}	D (nGy/ h)
O1	397.9	1.1	183.9
E1	317.0	0.9	144.2
E2	413.2	1.1	189.2
E3	293.5	0.8	134.3
I1	157.2	0.4	73.3
N1	200.0	0.5	91.5
C1	231.8	0.6	105.7
E4	299.8	0.8	141.9
I2	530.2	1.4	239.4
E5	244.6	0.7	116.7
E6	261.6	0.7	124.8
E7	285.5	0.8	135.2
N2	239.8	0.6	109.6
G1	430.5	1.2	194.9
G2	239.4	0.6	112.4
C2	392.4	1.1	181.3
S1	183.5	0.5	86.2
C3	347.6	0.9	163.5
G3	220.1	0.6	104.3
P1	303.2	0.8	144.5
Standard Deviation	94.8	0.3	42.4
Average	299.4	0.8	138.8
Maximum	530.2	1.4	239.4
Minimum	157.2	0.4	73.3

Table 3
Radiation hazard indices for cement samples.

Sample code	Ra_{eq} (Bq/kg)	H_{ex}	D(nGy/h)	AED (mSv/y)
BH-B	40.99	0.11	18.87	0.09
Q - B	37.20	0.14	25.47	0.12
S - B	43.22	0.13	21.91	0.11
S - W	25.82	0.09	15.15	0.07
Standard Deviation	7.74	0.02	4.39	0.02
Average	36.80	0.12	20.35	0.10
Maximum	43.22	0.14	25.47	0.12
Minimum	25.82	0.09	15.15	0.07

mean ± standard deviation of 101.6 ± 73.8 Bq/kg for ^{40}K. It is apparent that the specific activity concentrations of the three measured radionuclides in the cement samples are all below the global averages published by UNSCEAR (1993).

Radiation hazard indices were calculated for both the ceramic and cement samples. Table 2 presents the Ra_{eq} values for the studied ceramic samples. The Ra_{eq} results ranged from 157.2 (I1) to 530 Bq/kg (I2), with a mean value of 299.4 Bq/kg. This is lower than the recommended world value for their safe use in building materials: 370 Bq/kg (El-Taher et al., 2010). Five of the ceramic samples, however, exceeded this limit: C2: 392.4 Bq/kg, O1: 397.9 Bq/kg, E2: 413.2 Bq/kg, G1:430.5 Bq/kg, and I2: 530.2 Bq/kg. The Ra_{eq} values for the cement samples ranged from 25.8 (S-W) to 43.2 Bq/kg (S-B) with a mean value of 36.8. Bq/kg. The Ra_{eq} results of all the cement samples were well below the global safe value.

As shown in Table 2, the samples with higher Ra_{eq} values also had high H_{ex} values that exceeded the $H_{ex} \leq 1$ limit. The H_{ex} minimum, maximum, and mean values were 0.4, 1.4, and 0.8, respectively. Table 3 shows the H_{ex} values for the cement samples with their minimum, maximum, and mean values of 0.09, 0.14, and 0.12, respectively.

Table 2 also shows the D values for the ceramic samples, which were found to vary from 73.3 to 239.4 nGy/h, with a mean value of 138.8 nGy/h. The obtained values of D were all greater than the recommended value of 55 nGy/h (UNSCEAR, 1993). However, Table 3 also shows that all the cement samples have safe D values, with the minimum, maximum, and mean values of 15.15, 25.47, and 20.35 nGy/h, respectively.

The AED was calculated using Eq. (4), and the results for the ceramic samples are presented in Table 2. The admissible AED value of 1 mSv/y (UNSCEAR, 2000) was satisfied by all the ceramic samples, except sample I2, which also exhibited the highest Ra_{eq} and H_{ex} index values. The AED range and mean for the ceramic samples were 0.36–1.17 and 0.68 mSv/y, respectively. Table 3 also shows the AED values for the cement samples; it is apparent that all the indicated values are significantly lower than the safe world limit value. The AED range and mean values for the cement samples were 0.07–1.12 and 0.10 mSv/y, respectively.

Comparisons of the data reported in this study with recently published studies in different countries are presented in Tables 4 and 5 for the ceramic and cement samples, respectively. Table 4 demonstrates that although the mean concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in this study were greater than those reported previously, they are still comparable with some recently reported values (Michael et al., 2010; Amin and Naji, 2013; Gbenu et al., 2016).

Table 4
Activity concentration and radium equivalent activities of ceramic samples compared with other countries.

Activity concentration (Bq/kg)					
Country of study	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	Refs.
Italy	48.0	42.0	460.0	143.5	Righi and Bruzzi (2006)
Cameroon	12.0	20.0	319.0	65.0	Ngachin et al. (2007)
Palestine	73.7	58.2	624.0	205.2	Dabayneh (2008)
Cyprus	75.6	84.0	620.0	302.0	Michael et al. (2010)
India	17.5	38.9	298.6	96.2	Rajamannan et al. (2013)
Turkey	31.0	28.0	358.0	81.0	Tufan and Disci (2013)
Yemen	169.1	75.2	400.7	307.5	Amin and Naji, 2013
Bangladesh	60.9	70.8	1000.2	239.0	Asaduzzaman et al. (2014)
Egypt	51.1	40.5	682.6	161.6	Shoeib and Thabayneh (2014)
Egypt	59.7	47.1	703.2	181.1	Hassan et al. (2016)
Nigeria	24.0	128.0	850.0	272.0	Gbenu et al. (2016)
Iraq	101.7	70.0	316.6	226.2	Amana (2017)
Saudi Arabia	89.0	105.5	772.9	299.4	Present study

Table 5
Activity concentrations and radium equivalent activities of cement samples obtained in Saudi Arabia as compared with recent measurements obtained in Saudi Arabia and other countries.

Activity concentration (Bq/kg)					
Country of study	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	Refs.
Turkey	52.0	40.0	324.0	132.4	Damla et al. (2010)
Qatar	23.4	12.2	158.8	52.4	Al-Sulaiti et al. (2011)
Qatar	23.5	8.0	81.0	40.6	Al-Sulaiti et al. (2011)
Saudi Arabia	38.4	45.3	86	108.2	El-Taher (2012)
India	38.0	34.9	188.1	102.4	Ravisankar et al. (2012)
Malaysia	34.7	32.9	190.6	96.4	Majid et al. (2013)
Nigeria	30.2	24.6	251.3	84.7	Agbalagba et al. (2014)
Nigeria	41.9	30.9	340.2	111.1	Agbalagba et al. (2014)
China	118.7	36.1	354.6	204.5	Lu et al. (2014)
Egypt	44.6	10.4	51.1	63.4	Shoeib and Thabayneh (2014)
Saudi Arabia	32.2	23.3	177.3	79.3	Baz (2015)
Saudi Arabia	23.9	25.6	125.6	76.8	Baz (2015)
Saudi Arabia	12.5	16.4	108.3	43.1	Al Mugren and El-Taher (2016)
Saudi Arabia	21.7	9.8	101.6	36.8	Present study

Table 5 shows that the specific activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the studied cement samples compare well with other recent studies conducted in Saudi Arabia and other countries.

Table 4 presents the Ra_{eq} values of the ceramic samples, wherein the results of approximately half of the published studies compare well with the present study. Table 5 presents the corresponding Ra_{eq} values of the cement samples wherein the values obtained in this study are the lowest, although they are close to the most recent study conducted by Al Mugren and El-Taher (2016) in Saudi Arabia.

4. Conclusions

A typical high-resolution gamma-ray spectrometry system was used for the activity measurements of ^{226}Ra, ^{232}Th, and ^{40}K in ceramic and cement samples collected from local markets in Riyadh, Saudi Arabia. The radiation hazard indices for the cement samples were all found to be well below the recommended world limits and confirm the works recently published by other researchers in this country. Therefore, they can be considered to be safe for residential use.

The average specific activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K of the twenty ceramic samples were found to be 89.0 ± 40.6, 105.5 ± 44.2, and 772.9 ± 304.3 Bq/kg. In the case of the four cement samples, these values were 21.7 ± 7.4, 9.8 ± 1.0, and 101.6 ± 73.8 Bq/kg, respectively. The Ra_{eq}, H_{ex}, D, and AED indices were calculated from the above measurements in order to assess the radiological hazard associated with the studied building materials. The average values of these radiological indices for the ceramic samples were 299.4 ± 94.8 Bq/kg, 0.8 ± 0.3, 138 ± 42.4, and 0.68 ± 0.21, respectively. The corresponding average values of the cement samples were 36.8 ± 7.74 Bq/kg, 0.12 ± 0.02, 20.35 ± 4.39, and 0.10 ± 0.02, respectively.

Five ceramic samples (C2, O1, E2, G1, and I2) slightly exceeded the Ra_{eq} and H_{ex} standard global limits by factors of (6%, 10%), (8%, 10%), (12%, 10%), (16%, 20%), and (43%, 40%), respectively.

The obtained values of D for the ceramic samples were all greater than the recommended value of 55 nGy/h, with their mean value exceeding the recommended value by a factor of 152%. The AED of 1 mSv/y was met for all the ceramic samples except for sample I2, which had an AED value of 1.17.

Based on the above results, the majority of the ceramic samples can be considered to be marginally safe for use as building materials for residential construction, while five of the samples require further assessment before usage to minimize long-term effects due to chronic radiation exposure.

This work on cement and ceramic tiles could be used as reference data for future studies. More extensive measurements are required to be conducted with the aim of minimizing public exposure as low as reasonably achievable.

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