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^{226}Ra, ^{232}Th and ^{40}K ACTIVITY CONCENTRATIONS AND RADIOLOGICAL HAZARDS OF BUILDING MATERIALS IN MUGLA, TURKEY

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Abstract

The activity concentrations of natural gamma-emitting radionuclides in the samples of some commonly used building materials were measured by using a high resolution gamma-ray spectrometer. The results associated radiation hazard indexes due to ^{40}K, ^{226}Ra and ^{232}Th were determined in samples collected from building material suppliers from southwest part of Turkey (Muğla). Different criterion formulas as radium equivalent activity, the external/internal hazard indices, the alpha/gamma indexes and the absorbed dose rate in indoor air were determined. Although indoor absorbed dose rate is relatively higher than the world population-weighted average value and international limit for studied brick and cement samples they could be used safely as building materials because radium equivalent activity, alpha/gamma indices and hazard indices of those materials have been found to be within the recommended limits. All the values for all criterion formulas for marble samples are found to be well below the safety limits recommended by UNSCEAR. It can be concluded that examined materials can be used for construction of buildings for interior and external works.
Keywords: Building materials, natural radioactivity, radiological hazard, gamma-ray spectrometry

MUĞLA'DA KULLANILAN İNŞAAT MALZEMELERİNİN ^{226}Ra, ^{232}Th VE ^{40}K AKTİVİTE DERİŞİMLERİ VE RADYOLOJİK ZARARLARI

Özet

Bu çalışmada sık kullanılan bazı inşaat malzemelerinin içerdiği doğal gama yayıcı radyonüklitlerin aktivite derişimleri yüksek çözünürlüklü gama spektrometresi ile ölçülmüştür. Türkiye'nin güney batısında (Muğla) bulunan yapı malzemeleri tedarikçilerinden toplanan örneklerin ^{40}K, ^{226}Ra ve ^{232}Th içeriklerinden kaynaklanabilecek radyasyon zararları belirlendi. Radyum eşdeğer aktivitesi, dâhili/harici zarar indisleri, alfa/gama indeksleri ve kapalı alanda absorplanan doz miktarları gibi farklı kriterler hesaplandı. Elde edilen sonuçlardan, çimento ve tuğla örneklerinin kapalı alan absorblanan doz miktarının dünya popülasyon ağırlıklı ortalamasından yüksek olduğu ancak radyum eşdeğer aktivitelerinin, dahili/harici zarar indislerinin ve alfa/gama indekslerinin önerilen maksimum güvenlik limitlerinin altında olduğu görüldü. Mermer örnekleri için ise tüm kriterlerin UNSCEAR tarafından önerilen güvenlik limitlerinin altında olduğu belirlendi. Sonuç olarak incelenen yapı malzemelerinin kullanımında insan sağlığı açısından bir sakınca olmadığı görüldü.
Anahtar Kelimeler: Yapı malzemesi, , doğal radyoaktivite, radyolojik tehlike , gama spektrometresi

1 Introduction

Humans are exposed to ionizing radiation because of the naturally occurring radioisotopes ^{238}U, ^{232}Th, their decay products and natural ^{40}K that exists depending on the geological formations and geochemical characteristics of those materials at different regions of the Earth's environment in varying concentrations. Some waste or raw materials from mining and industry, such as fly ash from coal-fired power plants, phosphate fertilizer industry, red mud, alum shale industries etc., are often used as additives in production of building materials with naturally or technologically enhanced levels of exposed natural radionuclides [1], [2].

Hence some building materials such as clay bricks, marbles, cements etc. derived from rock, soil and aggregate, fly ash additives etc. contain various amounts of mainly natural radionuclides according to raw materials used in production and are the main source of indoor radiation exposures. All building materials based on mineral origin contain some amount of natural radionuclides that cause exposure of people to ionizing radiation at varying levels. The radiological impact of the radionuclides in red bricks, rocks, marbles and granites is due to the internal irradiation by the alpha particles emitted from radon and its short-lived daughters by inhalation, digestion and leading to deposition [3]. In some cases the inhalation of radon and its short-lived daughter products may be high enough to result in significant radiation dose and it is claimed that are comparative or even greater than the exposures from the medical use of ionizing radiations [4]-[6]. Besides that the external irradiation by gamma rays emitted from radionuclides present in used building materials.

The dose assessment is an important point to determine the radiation hazards from the naturally occurring radionuclides existed in building materials since it is considered that most of the people spent about 80% of their time indoors [7]. Measurement of natural ionizing radiation from these materials, and consequently the determination of possible radiological risks to human health, helps to find out if they are above the recommended limits. The knowledge of hazard risks is required to take protective precautions to decrease the exposure of the population to ionizing radiation.

Building materials are one of the main sources which contribute directly to radiation doses received by the general population and the amount of ^{226}Ra, ^{232}Th and ^{40}K in these materials is of major interest with regard to the radioactivity indoors.

According to international recommendations [8], the use of building materials containing enhanced concentrations of NORM should be controlled and restricted under the application of the radiation safety standards.

In this study, the natural radioactivity of some local building materials such as marble, clay brick and cement used in Muğla region of Turkey were investigated. Bricks are made of soil/clay and are baked in kilns. Bricks are the largest component of building materials used as building materials for about 4000 years in this part of the world [9]. Cement is an important construction material for houses and buildings in urban areas of Turkey. Likewise marble is mostly preferred as floor, wall and kitchen counter decorations.

The objective of this study was to determine the natural radioactivity concentrations in common building construction material samples collected from different places and to estimate potential radiological hazards associated to the external gamma dose rates. The average radium equivalent activity, the internal/external hazard indices, the alpha/gamma indexes and the indoor absorbed gamma dose rate have also been estimated and compared with the worldwide average value and with the recommended limits from UNSECAR data [10]. These results were important from the viewpoint of selecting proper materials for constructions and of course suitable for human health.

2 Materials and Method

2.1 Sample Collection

Geological samples commonly used as building materials in Turkey are red bricks, concrete, sand, gravel, manufactured tiles, marbles, cement, aggregate and fly ash additive among others. A total of 55 commonly used commercial building material samples were collected from different locations of southwest part of Anatolian. Three types of clay brick samples, three types of cement samples and five types of marble samples were prepared and investigated by using gamma-ray spectrometry. Five sub-samples were collected for each of the sample types to satisfy homogeneity and representativeness. Samples were collected from main local raw building material suppliers of Muğla and tested for their natural radioactivity content.

2.2 Preparation of Samples

Materials were studied in their natural form without any chemical processing. All samples were crushed, grounded and sieved into a fine powder with a particle size less than 0.21 mm. Samples were then homogenized by blending and oven dried at 100°C to constant weight. After moisture removal, these samples were weighted and transferred in 1 liter sample containers with Marinelli geometry. Sample containers were hermetically sealed for a period of 30 days to achieve secular equilibrium between ^{226}Ra, ^{222}Rn and its short lived daughters. Significant non-equilibrium is uncommon in rocks older than 10^6 year and the ^{232}Th series is considered in equilibrium in most geological environments [6].

2.3 Radiometric Procedures and Parameters

The activity measurements were performed with a 110 cm^3 well-type HPGe detector coupled with a 16k channel analyzer. The system had a resolution of 3.78 keV at 1.33 MeV gamma-ray peak of ^{60}Co. The detector was housed in a lead shielding 10 cm thick lined with 1.5 mm thick tin and 1.0 mm thick copper in order to reduce the X-ray interferences.

2.3.1 Efficiency Calibration and Activity Calculation

For efficiency calibration of the low background counting system, a secondary standard which was calibrated with the primary standards in same Marinelli containers was used. Efficiency values were plotted against energy and fitted by least squares method to an empirical relation that takes care of the nature of efficiency curve for the HPGe detector. The efficiency calibration of detection system was checked by measuring samples doped with known amounts of ^{40}K, ^{226}Ra and ^{232}Th by keeping the sample size and geometry the same.

To suppress of background effect on counts, the environmental gamma-ray background acquisition of equal duration was determined by using powdered sugar filled Marinelli beakers under identical measurement conditions as the samples prior to sample measurement. After measurements and subtraction of the background, the activity concentrations of the radionuclides were calculated. The data acquisitions were performed for a period of 300000 s. The spectra were carried out using the software program Maestro-ORTEC.

The activity concentrations of each nuclide in the measured samples were computed using the following expression

$$A_i = \frac{C_i}{\varepsilon(E) \times f_\gamma \times m_s} \quad (1)$$

where C_i is the background subtracted net counting rate (counts per second) of the prominent peak at energy E, ε (E) is the detector efficiency at energy E, f_γ is the absolute transition probability of gamma-decay of the nuclide at energy E, m_s (kg) is the mass of the sample.

In spectra evaluation, the isotopes of ^{238}U, ^{232}Th decay series and ^{40}K were taken into consideration because they mostly occur in relatively high levels in the majority of the building materials and they represent the main external source of irradiation to the human body. In the ^{238}U series, the decay chain starting from ^{226}Ra is radiologically the most important and, therefore, reference is often made to ^{226}Ra activity instead of the parent^{238}U activity. The activity concentrations of ^{226}Ra were estimated using gamma-ray photopeaks of 351.9 keV from ^{214}Pb, 609.3 keV and 1764.5 keV from ^{214}Bi decay products. The activity concentrations of ^{232}Th were estimated using gamma-ray photopeaks of 583.1 keV and 2614.6 keV from ^{208}Tl, 911.1 keV from ^{228}Ac radioisotopes. The activity concentrations of ^{40}K were estimated using its single gamma-ray peak, 1460.8 keV.

For a nuclide having more than one peak in the spectrum, the activity concentrations were obtained by arithmetical mean of activity obtained at each peak. The activities of the parents were obtained using the Bateman equation by assuming the daughter activities to be in secular equilibrium.

Minimum detection limits (MDL) of the present measurement system were calculated as follows [11], [12]:

$$MDL \geq \frac{(6 \times (b/t_b)^{1/2} + 9/t_b)}{\varepsilon \times f_\gamma \times m_s} \quad (2)$$

where MDL is in Bqkg^{-1}(confidence level 95%), b is the net peak area of the background at energy E, ε is the efficiency of the detector, f_γ is the absolute transition probability of gamma-decay of the nuclide at energy E, t_b is the background measurement time in seconds and m_s is the mass of the sample expressed in kg. MDL values were found to be 0.14 Bqkg^{-1} for ^{226}Ra, 0.19 Bqkg^{-1} for ^{232}Th and 3.57 Bqkg^{-1} for ^{40}K.

2.3.2 Radium Equivalent Activity (Ra_{eq})

To compare the specific radioactivities of ^{40}K, ^{226}Ra and ^{232}Th directly and to assess the radiation hazard associated with building materials it is generally preferred to use the Ra_{eq} index [13], [14]. This is the weighted sum of the activities of these three radionuclides derived from the estimation that 370 $Bqkg^{-1}$ of ^{226}Ra, 260 $Bqkg^{-1}$ of ^{232}Th and 4810 $Bqkg^{-1}$ of ^{40}K produce the same gamma dose rates to the habitants of the building. Therefore, the radium equivalent activity of the sample can be expressed as:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \tag{3}$$

Where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K respectively, which is expressed in $Bqkg^{-1}$.

2.3.3 Alpha-Index (I_α)

The radon inhalation due to alpha radiation emitted from building materials are denoted by several indexes. In this study I_α of the samples were calculated by Eq.(3) given by European Commission [15].

$$I_\alpha = \frac{A_{Ra}}{200} \tag{4}$$

Where A_{Ra} is activity concentration($Bqkg^{-1}$) of ^{226}Ra in the building material. The radon exhalation from the material cause indoor radon concentration over the value of 200 Bqm^{-3} when ^{226}Ra activity concentration exceeds 200 $Bqkg^{-1}$. Thus the recommended upper level of ^{226}Ra activity concentration is 200 $Bqkg^{-1}$ for building materials that is suggested by the radiation protection Authorities of Denmark, Finland, Iceland, Norway and Sweden [16].

2.3.4 Gamma-Index ($I\gamma$)

$I\gamma$ (representative level index) is another way to express radiation hazard and is derived to identify whether a dose criterion is met. The European Commission [15] defined gamma index as :

$$I\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \tag{5}$$

Where A_{Ra}, A_{Th} and A_K in $Bqkg^{-1}$ are activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively. This index can be used to estimate the level of gamma-radiation hazard by natural radionuclides in building materials. The values $I\gamma \leq 0.5$ corresponds to dose rate criterion less or equal to 0.3 $mSvy^{-1}$, $I\gamma \leq 1.0$ corresponds to dose rate criterion less or equal to 0.3 $mSvy^{-1}$ and $I\gamma \leq 6$ corresponds to 1 $mSvy^{-1}$ dose rate criterion due to external gamma radiation [15]. The upper limit of annual effective dose rate for population is given as 1 $mSvy^{-1}$ [7]. Thus the building materials with $I\gamma > 6$ should not be used for construction since they have does rates higher than 1$mSvy^{-1}$.

Here is necessary to express that in case the gamma-index exceeds the recommended value for a sample, the annual effective dose can be below the upper limit [15].

2.3.5 Radiation Hazard Indices

Another way to define the radiation hazard is to use the indices of external radiation hazard (H_{ex}) and internal radiation hazard (H_{in}). These indices and limits are calculated from the expected exposure rates in construction which contain radioactive materials. They are derived from the radiation dose limits (0.5 $mSvyr^{-1}$) set by national authorities and based on ICRP recommendations [17]-[19].

External hazard indices

The annual external radiation dose of building materials is obtained by taking different assumptions into account by several authors [20], [21].

$$H = \frac{A_{Ra}}{740} + \frac{A_{Th}}{520} + \frac{A_K}{9620} \tag{6}$$

Thus the annual radiation dose from building materials limit is given by many different equations. Another criterion, known as the H_{ex}, has also been defined in the literature [13]. The same information, however, is being provided by the Ra_{eq} activity and therefore our results were not applied as Ra_{eq} but evaluated as external hazard indices.

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{7}$$

Where A_{Ra}, A_{Th} and A_K are specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively. The maximum value of the H_{ex} must be unity for a negligible radiation hazard that corresponds to the upper limit of Ra_{eq} 370 $Bqkg^{-1}$.

Internal hazard indices

The radon and its short-lived daughters are also hazardous for health in addition to external hazard. The internal exposure to ^{222}Rn and its radioactive progeny is controlled by the H_{in}. In order to limit the radiation dose, from bricks and other construction materials, to 1.5 $mSvyr^{-1}$, a number of indices for indoor exposure were suggested by some workers and are given below [13], [22], [23], [24]:

$$HI(1) = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{8}$$

$$HI(2) = \frac{A_{Ra}}{150} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{9}$$

$$HI(3) = \frac{A_{Ra}}{1000} + \frac{A_{Th}}{700} + \frac{A_K}{10000} \tag{10}$$

$$HI(4) = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \tag{11}$$

$$HI(5) = \frac{A_{Ra}}{150} + \frac{A_{Th}}{185} + \frac{A_K}{3500} \tag{12}$$

Where A_{Ra}, A_{Th} and $A_K$in $Bqkg^{-1}$ are activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively. For radiation safe use of building materials in construction the values of H_{in} indices should be again less than unity.

2.3.6 Absorbed dose rate in indoor air

The total absorbed gamma radiation dose rates in $nGyh^{-1}$ can be calculated using the formulas proposed by UNSCEAR [7], [15] for radiation emission from ^{226}Ra, ^{232}Th and ^{40}K radioisotopes., dose rates in indoor air can be calculated using the following equations:

a) For gypsum, cement and bricks:

$$D = 0.92A_{Ra} + 1.1A_{Th} + 0.08A_K \tag{13}$$

b) For marbles:

$$D = 0.12A_{Ra} + 0.14A_{Th} + 0.0096A_K \tag{14}$$

Here A_{Ra}, A_{Th} and A_K are specific activities of ^{226}Ra, ^{232}Th and ^{40}K in $Bqkg^{-1}$, respectively. The equations are derived for a standard room model with dimensions of 4x5x2.8 m^3, wall thickness of 20 cm and structure density of 2350 kgm^{-3}. These coefficients are correspond to 0.92, 1.1 and 0.08 $nGyh^{-1}$ per $Bqkg^{-1}$ (cement and brick samples) and 0.12, 0.14 and 0.0096 $nGyh^{-1}$ per $Bqkg^{-1}$ (marble samples) for ^{226}Ra, ^{232}Th and ^{40}K, respectively [15].

The world population-weighted average values of absorbed gamma dose rate in indoor air and international limit are 84 $nGyh^{-1}$ and 55 $nGyh^{-1}$, respectively.

3 Results and Discussion

3.1 Specific Radioactivity

The determined specific activity values are generally important in evaluation of radiological hazards associated with measured samples. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K radioisotopes in the building material samples were determined as mentioned in 2.3.1. The results are presented in Table 1. It should be noted that the values given in the Table 1 are not the representative for Turkey but for the locations from where the samples have been collected.

Table 1.

Specific activity values of ^{226}Ra, ^{232}Th and ^{40}K radioisotopes in the building material samples.

Sample	^{226}Ra Activity Conc. (Bqkg^{-1})	^{232}Th Activity Conc. (Bqkg^{-1})	^{40}K Activity Conc. (Bqkg^{-1})
Marble-1	<MDL	<MDL	<MDL
Marble-2	1.2±0.1	<MDL	<MDL
Marble-3	0.4±0.04	<MDL	<MDL
Marble-4	4.5±0.5	<MDL	<MDL
Marble-5	2.0±0.1	0.4±0.03	<MDL
Brick-1	30±3	37±4	545±50
Brick-2	28±3	37±4	497±45
Brick-3	28±2	34±3	520±48
Cement-1	31±3	55±5	560±52
Cement-2	72±6	71±7	469±47
Cement-3	75±7	45±4	410±40

As can be seen from Table 1, the highest ^{226}Ra activity concentration was 4.5 Bqkg^{-1} for marble samples, 30 Bqkg^{-1} for brick samples and 75 Bqkg^{-1} for cement samples that are related to Marble-4, Brick-1 and Cement-3, respectively. The highest ^{232}Th activity concentration was 0.4 Bqkg^{-1} for marble samples, 37 Bqkg^{-1} for brick samples and 71 Bqkg^{-1} for cement samples that are related to Marble-5, Brick-2 and Cement-2, respectively. Finally, the highest ^{40}K activity concentration was 545 Bqkg^{-1} for brick samples and 560 Bqkg^{-1} for cement samples that are related to Brick-1 and Cement-1, respectively. All the marble samples had ^{40}K activity below detection limit of the detector.

According to the comparison of building material groups, cement samples had the highest ^{226}Ra, ^{232}Th and ^{40}K activity concentration while marble samples had the lowest ones that are generally under the MDL of the detector used. Therefore, cement was major source of activities followed by brick and marble materials. Fly ash from coal fired power plants are the mostly used as additive material in cement production in Turkey. And the big part of inorganic incombustible materials like thorium and uranium stay in the fly ash as being enhanced. Thus, besides that its own radiological character of raw cement, the adding of fly ash raises the level of radioactive element concentration. This is the reason of why cement samples have the highest radioactivity level.

It can be seen from Table 1 that the calculated ^{40}K activities in the materials were in the range of 410-560 Bqkg^{-1} and ^{40}K contributes the highest activity concentration, than those of ^{226}Ra and ^{232}Th. However, the most contribution comes from ^{226}Ra and to a lesser extent from ^{232}Th and ^{40}K while taking into account the chemical and biological action of each isotope on human beings.

The arithmetic mean values of marble, brick and cement samples' activity concentrations were (by taking the values under MDL equal to MDL values) 2.6, 29, 59 Bqkg^{-1} for ^{226}Ra, 0.2, 36, 57 Bqkg^{-1} for ^{232}Th and 3.6, 520, 480 Bqkg^{-1} for ^{40}K, respectively while the worldwide average values are 35, 30 and 400 Bqkg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K respectively [7]. The ^{226}Ra activity concentration mean values of brick and marble building material samples were lower than the worldwide average values. On the other hand, the ^{232}Th activity concentration mean values were higher for both brick and cement samples. The ^{40}K and ^{226}Ra activity concentration mean values of cements were also higher than the worldwide average values. Activity concentrations of different building materials and worldwide values are shown in Fig. 1.

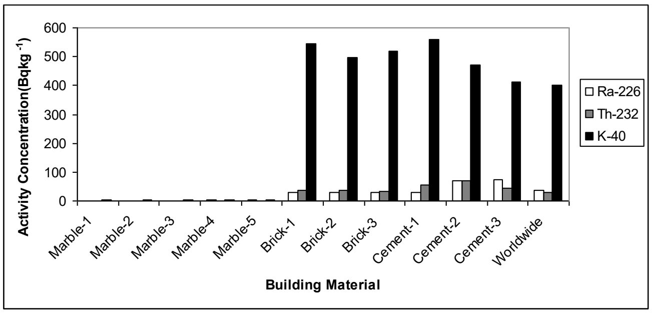


Fig. 1. ^{226}Ra, ^{232}Th, ^{40}K activity concentrations of building materials and world-wide values.

3.2 Radium Equivalent Activity (Ra_{eq})

The Ra_{eq} values were calculated for the building material samples by using the Eq.(3). The calculated Ra_{eq} values for all building material samples studied are summarized in Table 2. Current Ra_{eq} criteria values of the samples did not exceed unity by a maximum value of 0.2810 as it is seen from Table 2. In spite of determining the Ra_{eq} it was not considered in our discussions. The average values of the Ra_{eq} activities were calculated within the range 0.7 Bqkg^{-1} (Marble-1)-208 Bqkg^{-1} (Cement-2) and were highly below the upper limit of 370 Bqkg^{-1}. The maximum admissible value of 370 Bqkg^{-1} is determined to be equivalent to an external dose of 1,5 mSvyr^{-1}[25]. By realizing that the criterion limit for building materials it can be claimed that the investigated samples had Ra_{eq} value lower than the recommended value and to use these building materials for construction does not pose any radiological hazard.

Table 2. Calculated activity concentrations, radium equivalent activities and criteria values of samples of samples.

Sample	Ra_{eq} (Bqkg^{-1})	Criteria value
Marble-1	0.7±0.05	0.0009
Marble-2	1.7±0.2	0.0023
Marble-3	0.1±0.08	0.0013
Marble-4	5.0±0.6	0.0068
Marble-5	2.8±0.3	0.0038
Brick-1	124±12	0.1684
Brick-2	119±12	0.1616
Brick-3	116±14	0.1566
Cement-1	152±16	0.2056
Cement-2	208±20	0.2810
Cement-3	170±17	0.2305

3.3 Alpha-Index (I_α)

In this study I_α of the samples were calculated by using Eq.(4). The I_α of the building material samples investigated in this study is given in Table 3. The alpha-indexes were lower than unity as it is seen in the table. Thus the radon inhalation from investigated building materials was below the upper level and the building materials are safe from the view of environmental radiation hazard.

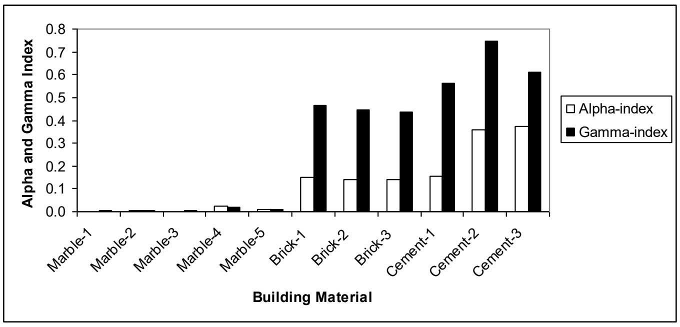
Table 3.
Alpha-indexes, gamma-indexes and radiation hazard indices of building materials.

Sample	I_α	I_γ	H_{ex}	H_{in}	D
Marble-1	0.0007	0.0026	0.0019	0.0022	0.0777
Marble-2	0.0059	0.0061	0.0047	0.0079	0.203
Marble-3	0.0022	0.0036	0.0027	0.0039	0.114
Marble-4	0.0223	0.0170	0.014	0.0256	0.596
Marble-5	0.0098	0.0098	0.0076	0.0129	0.327
Brick-1	0.150	0.467	0.338	0.418	111
Brick-2	0.142	0.4463	0.324	0.400	106
Brick-3	0.138	0.435	0.314	0.388	104
Cement-1	0.156	0.564	0.412	0.496	133
Cement-2	0.357	0.747	0.563	0.756	180
Cement-3	0.373	0.612	0.462	0.663	151

3.4 Gamma –index (I_γ)

The I_γ of the building material samples were calculated via Eq.(5) and the results are given in Table 3. The I_γ values ranged from 0.003 to 0.75 for all building materials. Therefore because all gamma-index values of studied samples were lower than the criteria value 6 and also unity, it may be concluded that the building materials are safe and does not pose any significant radiation hazards. Fig. 2 shows the I_α and I_γ of the samples.

Fig. 2. Alpha and gamma-indexes of building materials.



3.5 Radiation Hazard Indices

External Hazard Indices (H_{ex})

The external hazard index (H_{ex}) due to gamma-ray corresponds to a maximum Ra_{eq} of 370 $Bqkg^{-1}$ for the material. This value of 370 $Bqkg^{-1}$ is found according to ICRP, 1977 limitation of the external gamma radiation dose rate from building materials to be less or equal to 1.5 $mSvyr^{-1}$. The H_{ex} values were calculated using Eq.(7) by assuming infinitely thick walls without windows and doors [21].

The calculated H_{ex} values for the building material samples studied are given in Table 3. As it is seen the maximum level for H_{ex} was obtained for cement samples as 0.56 while the minimum values for marble samples as 0.002. Therefore the H_{ex} values for all studied samples were found to be below unity and it can be concluded that the studied building materials are safe to be used for construction.

Internal hazard index (H_{in})

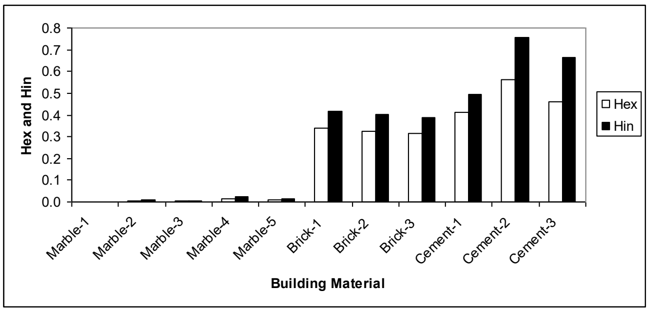
In addition to the external radiation dose, radon and its short-lived products are also harmful in case of inhalation. The H_{in} values were calculated for the building material samples studied using Eq.(8) that is proposed by Krieger [21].

Table 3 lists the H_{in} for all samples. For the safe use of building materials H_{in} must be less than unity and as it is seen all the values were below unity for samples studied.

The H_{in} results obtained for cement samples were found to be the highest compared to those of other building materials.

Fig. 3 shows the both external and internal radiation hazard indices of the building samples.

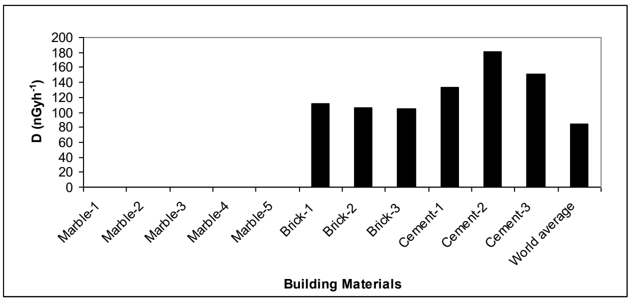
Fig. 3. External and internal radiation hazard indices of the building materials.



3.6 Absorbed dose rate in indoor air

The absorbed dose rates of building materials in indoor air were calculated according to Eq.(13) for brick and cement samples and Eq.(14) for marble samples. The results are summarized in Table 3 and Fig. 4.

Fig. 4. Absorbed dose rates of building materials in indoor air.



The dose rates varied from 0.0777 $nGyh^{-1}$ to180.9044 $nGyh^{-1}$ per $Bqkg^{-1}$. The average absorbed dose rates were 0.2633, 107 and 155 $nGyh^{-1}$ per $Bqkg^{-1}$ for marble, brick and cement samples, respectively. According to the calculated absorbed dose rates it can be noticed that all the brick and cement samples were containing higher ^{226}Ra, ^{232}Th and ^{40}K and consequently they produce relatively higher dose rates than the world average values (84 $nGyh^{-1}$) and international limit (55 $nGyh^{-1}$) while the marble samples had very low dose rates. The lowest dose was found in the marbles and only marble materials satisfied the safety criteria and do not pose any health hazard problems.

4. Conclusion

In this study activity concentrations of marble, clay brick and cement from southwest part of Turkey were determined in order to assess the radiological impact used as building materials. Ra_{eq}, I_α, I_γ, H_{in}, H_{ex} and absorbed dose rate in indoor air were calculated by using the activity concentration results.

The results showed that the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K radioisotopes in cements and bricks are higher than worldwide values. The Ra_{eq} values of the samples range from 0.69 to 208 Bgkg^{-1} which were well below the internationally accepted value 370 Bqkg^{-1} set in the UNSCEAR report.

H_{in}, H_{ex} and I_{α}, $I\gamma$ found in this study show that samples do not exceed values recommended safety limits by EC.

Absorbed dose rate in indoor air was found ranged from 0.08 nGyh^{-1} to181 nGyh^{-1} per Bqkg^{-1} while the world population-weighted average indoor absorbed gamma dose rate is 84 nGyh^{-1}.

Marble activities would suggest that the use of such kind of building materials do not emit any significant radiation exposure to the habitants because they have radioactivity mostly below the proposed acceptable levels.

As a result, this study showed that the investigated building materials do not pose any significant radiation hazard and safe for use in constructions.

It is concluded that the results found in this study will help to accumulate the data on radionuclides content in domestic building materials used in Muğla region of southwest of Turkey in assessing the associated radiation hazard. Because a limited number of samples were used in this study, to get more representative results for Turkey in general, a higher number of samples can be studied. In the light of the above-mentioned facts, it is, therefore, important to control and to limit the content of radioactive materials in common building constructions.

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