YYU JINAS, Volume 30, Issue 2 (August), 524-536, 2025 https://doi.org/10.53433/yyufbed.1674395

Yuzuncu Yil University
Journal of the Institute of Natural & Applied Sciences
https://dergipark.org.tr/en/pub/yyufbed

Research Article

Natural Radionuclide Analysis in Building Materials Used in Bursa

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Abstract: In this study, a total of 27 samples of cement, brick, sand and plaster used as construction materials and marble, tile and grout from surface materials in Bursa province were randomly collected. ^{226}Ra, ^{232}Th and ^{40}K radionuclide activity concentrations of the samples were measured by NaI(Tl) gamma-ray spectrometer. When the results were analyzed, it was observed that ^{226}Ra, ^{232}Th and ^{40}K activity concentrations varied between BDL (Below Detection Limit) - 81.16 Bq kg^{-1}, BDL - 94.22 Bq kg^{-1}, BDL - 781.26 Bq kg^{-1}, respectively. The highest mean values of ^{226}Ra and ^{232}Th activities belong to the cement samples with 33.6 and 43.2 Bq kg^{-1}, respectively, while the highest average value measured for ^{40}K belongs to the brick samples with 771.2 Bq kg^{-1}. In addition, to evaluate the radiological hazards in the samples, radium equivalent activity (Ra_{eq}), indoor air absorbed dose rate (D_{in}), annual effective dose rate ($AEDE_{in}$), external hazard index (H_{ex}), internal hazard index (H_{in}), and gamma index (I_g) were calculated using the obtained activity values. Ra_{eq} values are below the internationally accepted limit value of 370 Bq kg^{-1}. D_{in} values for all construction materials except Cement 2, Cement 4 and Cement 7 samples are within the acceptable limit value range. For these building materials, the $AEDE_{in}$, H_{in}, H_{ex} and I_g values are below the recommended unit limit and do not pose radiological risk. With these properties, these materials can be recommended as construction materials.

Keywords: Building materials, Gamma activity concentration index, NaI(Tl) detector, Radium equivalent activity

Bursa'da Kullanılan Yapı Malzemelerinde Doğal Radyonüklit Analizi

Özet: Bu makalede, Bursa ilinde yapı malzemesi olarak kullanılan çimento, tuğla, kum ve alçı ile yüzey malzemelerinden mermer, fayans ve derz dolgu örnekleri (27 adet) rastgele toplandı. Örneklerin ^{226}Ra, ^{232}Th ve ^{40}K radyonüklit aktivite konsantrasyonları NaI(Tl) gama ışını spektrometresi ile ölçüldü. Sonuçlar analiz edildiğinde, ^{226}Ra, ^{232}Th ve ^{40}K aktivite konsantrasyonlarının sırasıyla BDL - 81.16 Bq kg^{-1}, BDL - 94.22 Bq kg^{-1}, BDL – 781.26 Bq kg^{-1} arasında değiştiği gözlendi. ^{226}Ra ve ^{232}Th aktivitesinin en yüksek ortalama değerleri sırasıyla 33.6 ve 43.2 Bq kg^{-1} ile çimento örneklerine ait iken ^{40}K için ölçülen en yüksek ortalama değer 771.2 Bq kg^{-1} ile tuğla örneklerine aittir. Ayrıca numunelerdeki radyolojik tehlikeleri değerlendirmek için, elde edilen aktivite değerleri kullanılarak radyum eşdeğer aktivitesi (Ra_{eq}), iç hava emilen doz hızı (D_{in}), yıllık etkin doz hızı ($AEDE_{in}$), dış tehlike indeksi (H_{ex}), iç tehlike indeksi (H_{in}) ve gama indeksi hesaplandı (I_g). Ra_{eq} değerleri, uluslararası olarak kabul edilen 370 Bq kg^{-1} sınır değerinin altındadır. Çimento 2, Çimento 4 ve Çimento 7 numuneleri dışında tüm yapı malzemeleri için D_{in} değerleri kabul edilebilir limit değer aralığındadır. Bu yapı malzemeleri için, $AEDE_{in}$, H_{ex}, H_{in} ve I_g değerleri önerilen birim sınırın altındadır ve radyolojik risk oluşturmazlar. Bu özellikleri ile söz konusu malzemeler inşaat malzemesi olarak önerilebilir.

Anahtar kelimeler: Gama aktivite konsantrasyon indisi, Na(I)Tl dedektörü, Radyum eşdeğer aktivitesi, Yapı malzemeleri

Received: 11.04.2025
Accepted: 01.07.2025

How to cite: Baş, M., Mavi, A., & Yıldız Yorgun, N. (2025). Natural radionuclide analysis in building materials used in Bursa. *Yuzuncu Yil University Journal of the Institute of Natural and Applied Sciences*, *30*(2), 524-536. https://doi.org/10.53433/yyufbed.1674395

1. Introduction

Although buildings offer protection against external sources of radiation such as cosmic and terrestrial radiation, they can also be a source of indoor radiation due to naturally occurring radioactive materials present in construction components (United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR], 2000).

Naturally occurring radionuclides such as ^{238}U (uranium), ^{232}Th (thorium) and ^{40}K (potassium) are found in different amounts in soils, rocks and building materials derived from them (Kayakökü, 2024). These radionuclides found in building materials cause exposure to external and internal radiation to individuals living in dwellings.

External exposure mainly comes from gamma rays emitted by ^{238}U, ^{232}Th, ^{40}K, and their decay products. Internal exposure results inhaling radon (^{222}Rn) and thoron (^{220}Rn) gases, their short-lived decay products (Lu et al., 2012).

Cement, one of the building materials, is used as a binding material and its ^{226}Ra, ^{232}Th and ^{40}K contents depending on their chemical composition (Eštoková & Palaščáková, 2013). Sand, another common building material, is a natural granular substance formed by the weathering and erosion of rocks. The most common component of sand is silica (SiO_2), typically found as quartz. Other common minerals in sand include feldspar, clay and carbonates (Chandrasekaran et al., 2021). The levels natural radionuclides in sand vary depending on the geochemical composition of the rocks that make up the sand (Barbosa da Silva et al., 2024). Plaster is widely used as a finishing material for walls and ceilings (Salim et al., 2019). Traditional types of plaster include lime plaster (a mixture of calcium hydroxide and sand), hydraulic lime plaster (calcium hydroxide contains impurities such as calcium silicates) and cement plaster (a mixture of sand and cement) (Melià et al., 2014). Brick, among the oldest and most widely used in construction materials, are made from clay that is fired in a high-temperature kiln (Zhang, 2013). Marble is a metamorphic rock formed from limestone under to high heat and pressure. It mainly consists of calcite ($CaCO_3$), dolomite or serpentine minerals in crystalline form (Baker, 2017). Ceramic wall tiles are usually made from a combination of clay, silica, feldspar sand, kaolin and carbonates (Tarhan et al., 2016). Joint fillers, on the other hand, generally contain calcite, cement, polymers, cellulose and silicon (Rizaoğlu et al., 2022).

The concentrations of ^{226}Ra, ^{232}Th and ^{40}K in building materials vary depending on the formation and composition of rocks and soils in a region (geological conditions), environmental factors such as wind, water flow and erosion (geographical conditions), and the chemical composition of the minerals that make up building materials (geochemical properties) (Lu et al., 2012). For example, igneous rocks such as granite have high uranium and thorium activities (Tzortzis et al., 2003), while building materials such as basalt and limestone have low radium content (UNSCEAR, 2000). In recent years, many studies have been conducted to investigate the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in various building materials (Baykara et al., 2011; Ding et al., 2013; El-Mageed et al., 2014; Erkan, 2007; Tuo et al., 2020; Turhan et al., 2008, 2018; Yang et al., 2013).

Knowing the radioactive content and radiological parameters of these materials is essential to evaluate the radiation exposure risks to people. In this study, the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were measured in various building materials collected from Bursa Province, and radiological risk parameters were calculated.

2. Material and Methods

2.1. Sample preparation

In this research, dwelling materials commonly utilized in Bursa province such as cement, sand, gypsum, bricks, tiles and joint fillers were randomly collected from the places where the construction sites and from building material suppliers. A total of twenty-seven building materials were brought to the laboratory and crushed into powder with the help of a grinder. The samples were oven dried at 105 °C for 24 hours to remove moisture. Each sample was then sieved through a 500 µm (35 mesh) stainless steel sieve and placed in 100 ml plastic cups. The net weight of the samples was noted. The edges of the lid were wrapped with parafilm to limit gas escape from the cups. The tightly sealed containers were then stored to reach equilibrium between ^{226}Ra and ^{222}Rn (minimum 30 days). In the uranium (^{238}U) series, the decay chain starting from radium (^{226}Ra) is the most radiologically significant and is therefore often referred to as radium rather than uranium.

2.2. Gamma spectrometric analysis of samples

The concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the building material samples were measured using a gamma ray spectrometry system. The experimental included a 3″×3″ cylindrical NaI(Tl) scintillation detector, Canberra AMP/TSCA (Model 2015A) amplifier, Canberra Multiport II and Genie 2000 gamma spectroscopy software. The detector was enclosed in a cylindrical lead shielding with a thickness of 10 cm and a diameter of 40 cm.

The energy resolution of the spectrometer was approximately 8% at 662 keV (^{137}Cs), and the relative counting efficiency was about 20%. Prior to the sample measurements, the energy calibration of the detector was performed using gamma-ray sources of ^{137}Cs (661.6 keV) and ^{60}Co (1173 keV and 1332 keV).

To determine the environmental background radioactivity level in the laboratory, a measurement was performed using an empty plastic container identical in size and shape to the sample containers.

For efficiency calibration, standard reference materials with the same geometry and density as the samples were used: RGU (4940 Bq/kg), RGTh (3260 Bq/kg) and, RGK (3500 Bq/kg), all certified by the IAEA. The absolute efficiency of the detector (ε_γ) was calculated using the following equation (Ramadhan and Abdullah, 2018):

$$\varepsilon_\gamma = \frac{N}{P_\gamma . A_S . T} \times 100\% \qquad (1)$$

in this equation, N represents the net count rate corresponding to the photopeak of the gamma-ray within the region of interest, P_γ denotes the emission probability of that gamma-ray, A_S refers to the activity of the reference material, and T is the counting time.

Gamma rays emitted from the samples were recorded over a counting time of 80,000 seconds, and each measurement was repeated three times for each sample. The resulting spectra were analyzed using the Genie 2000 software. Background radiation was subtracted from the total counts to obtain the net count values. The activity concentrations of ^{226}Ra and ^{232}Th were determined based on the gamma-emitting daughter isotopes in their respective decay chains. ^{226}Ra activity was used as an indicator of ^{238}U in the present study.

The activity concentration of ^{226}Ra was determined from the 1765 keV gamma line at of ^{214}Bi, while the 2614 keV gamma line of ^{208}Tl, assumed to be in secular equilibrium with ^{232}Th, was used for ^{232}Th activity determination. The ^{40}K activity was measured directly from its characteristic gamma line at 1461 keV. From the analysis of the gamma-ray spectra of the samples, the specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were calculated by solving a system of three linear equations that included detector sensitivity factors (K_1, K_2, K_3) and stripping ratios (α, β, γ), which correct for spectral interference by overlapping gamma-ray peaks.

Accordingly, the equations used to determine the activity concentrations of eTh, eU, and K (in Bq kg^{-1}) in a sample are given below (Erzin and Yaprak, 2022):

$$eTh\ (Bqkg^{-1}) = C(^{232}Th)/K_1 \qquad (2)$$

$$eU\ (Bqkg^{-1}) = \left[C\ (^{238}U) - \alpha C(^{232}Th)\right]/K_2 \qquad (3)$$

$$K\ (Bqkg^{-1}) = \left[C(^{40}K) - \gamma\left[C(^{238}U) - \alpha C(^{232}Th)\right] - \beta C(^{232}Th)\right]/K_3 \qquad (4)$$

here, eTh, eU, K represent the activity concentrations of equivalent thorium, uranium, and potassium in the sample, respectively. $C(^{232}Th)$, $C\ (^{238}U)$, $C(^{40}K)$ denote the net count rates in the selected energy windows corresponding to ^{232}Th (e.g., 2614 keV), ^{238}U (e.g., 1765 keV), and ^{40}K (1460 keV), respectively. K_1, K_2 and K_3 are the sensitivity factors of the detector for thorium, uranium, and potassium, respectively. α, β, and γ are the stripping coefficients representing the contribution of thorium to the uranium and potassium windows, and uranium to the potassium window, respectively. The detector sensitivity factors were determined as follows: K_1 = 5.46 counts per 10,000 s per Bq·kg^{-1} for ^{232}Th, K_2 = 7.15 counts per 10,000 s per Bqkg^{-1} for ^{238}U, and K_3 = 2.62 counts per 10,000 s per Bqkg^{-1} for ^{40}K. The stripping ratios α, β, and γ were found to be 0.63, 0.58, and 0.67, respectively. ^{226}Ra activity was used as an indicator of ^{238}U in the present study.

Equation 5 was used to calculate the uncertainty with the measurement of activity concentrations (Asaduzzaman et al., 2016):

$$\sigma_C = A.\sqrt{\left(\frac{\Delta N}{N}\right)^2 + \left(\frac{\Delta \varepsilon_\gamma}{\varepsilon_\gamma}\right)^2 + \left(\frac{\Delta P_\gamma}{P_\gamma}\right)^2 + \left(\frac{\Delta M}{M}\right)^2} \qquad (5)$$

here, ΔN refers to the uncertainty in the net count rate of the sample, $\Delta \varepsilon_\gamma$ represents the uncertainty in the detector efficiency, ΔP_γ denotes the uncertainty in the gamma-ray emission probability and ΔM is the uncertainty in the sample mass.

The minimum detectable activity (MDA) for the gamma-ray measurements was calculated using the following equation (Kurnaz et al., 2016):

$$MDA = \frac{4.66\sqrt{B}}{\varepsilon_\gamma . P_\gamma . t. M} \qquad (6)$$

where B is the background counts and t refers is the counting time (s). The minimum detectable activity (MDA) for each radionuclide was determined from the background radiation spectrum using the same counting time as for the samples (80.000s). The MDAs were estimated as 5.6 Bq/kg for ^{226}Ra, 3.8 Bq/kg for ^{232}Th, and 34 Bq/kg for ^{40}K, respectively.

2.3. Radiation risk calculations

2.3.1. Radium equivalent activity (Ra_{eq})

There is a non-homogeneous distribution of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides in construction materials and in order to determine the actual activity level in terms of radiation exposure, depending on these radionuclides, the radium equivalent activity (Ra_{eq}) has been defined. To obtain the specific activity of materials containing different amounts of ^{226}Ra, ^{232}Th and ^{40}K, the following formula is used (Beretka & Mathew, 1985):

$$Ra_{eq}(Bq\ kg^{-1}) = C_{Ra} + 1.43C_{Th} + 0.077C_K \qquad (7)$$

where C_{Ra}, C_{Th}, and C_K are the radionuclide activity concentrations of the ^{226}Ra, ^{232}Th and ^{40}K respectively.

2.3.2. Absorbed dose rate (D_{in})

The absorbed dose rate (D_{in}) in indoor air depending on the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in building materials is calculated by the following formula using the dose conversion coefficients determined by UNSCEAR (2000) and the European Commission (EC, 2000) for the centre of a standard room:

$$D_{in}(nGy\ h^{-1}) = 0.92C_{Ra} + 1.1C_{Th} + 0.08C_K \qquad (8)$$

2.3.3. Annual effective dose ($AEDE_{in}$)

The annual effective dose ($AEDE_{in}$) is calculated by the following equation using a value of 0.7 Sv Gy^{-1} for the conversion factor from the absorbed gamma dose rate in air to the effective dose received by adults and a value of 0.8 for the indoor exposure factor (UNSCEAR, 2000):

$$AEDE_{in}(mSv\ y^{-1}) = D_{in}\ x\ 8760(h\ y^{-1})\ x\ 0.8\ x\ 0.7\ (Sv\ Gy^{-1})\ x\ 10^{-6} \quad (9)$$

2.3.4. Internal and external hazard index (H_{in} and H_{ex})

Beretka and Mathew (1985) defined the internal and external hazard index with the following equation:

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \quad (10)$$

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \quad (11)$$

2.3.5. Gamma index (I_γ)

The gamma activity concentration index (I_γ), which helps to estimate the radiation hazard level of materials and depends on the natural radioactivity in construction component, is given by the European Commission with the following equation (EC, 2000):

$$I_\gamma = \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} + \frac{C_K}{3000} \quad (12)$$

3. Results and Discussion

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in building materials in Bursa province were calculated and the results are presented in Table 1. For cement samples, ^{226}Ra values ranged from BDL (Cement 5) to 73.14 ± 8.78 Bq kg^{-1} (Cement 4). In sand , the range was 6.88 ± 4.46 Bq kg^{-1} (Sand 5) to 32.82 ± 5.36 Bq kg^{-1} (Sand 3). For bricks, values varied slightly, between 31.26 ± 5.28 Bq kg^{-1} and 32.44 ± 5.28 Bq kg^{-1} . Joint fillers showed lower activities, ranging from 14.38 ± 6.84 Bq kg^{-1} and 15.48 ± 6.84 Bq kg^{-1}. Among the remaining materials, plaster 2 had 5.58 ± 4.46 Bq kg^{-1}, the Marble had 5.78 ± 4.46 Bq kg^{-1} and Tile exhibited a relatively high value of 56.92 ± 6.86 Bq kg^{-1}.

As shown in Table 1, the highest ^{232}Th activity was measured in a cement sample (94.22 ± 7.38 Bq kg^{-1}), followed by tile (43.48 ± 3.56 Bq kg^{-1}), sand (42.14 ± 3.56 Bq kg^{-1}), brick (32.06 ± 4.06 Bq kg^{-1}), plaster (5.78 ± 3.56 Bq kg^{-1}) , and joint filler (4.26 ± 3.56 Bq kg^{-1}).

Similarly, the highest ^{40}K activity was found in a brick sample (781.26 ± 60.92 Bq kg^{-1}), followed by sand (761.42 ± 60.92 Bq kg^{-1}), cement (621.36 ± 49.72 Bq kg^{-1}), tile (534.68 ± 42.32 Bq kg^{-1}), plaster (118.84 ± 21.16 Bq kg^{-1}), and joint filler (47.54 ± 21.16 Bq kg^{-1}). The average distribution of radionuclide activity for each material type is illustrated in Figure 1.

According to UNSCEAR (2000), the global average activation concentrations are 35 Bq kg^{-1} for ^{226}Ra, 30 Bq kg^{-1} for ^{232}Th and 400 Bq kg^{-1} for ^{40}K (Table 1). In this study, average activities of ^{226}Ra and ^{232}Th in all materials –except for tiles- were either below or close to these global values. For ^{40}K, average levels remained below the global average in all samples, except for sand and brick.

Turhan et al. (2008) reported the average activity concentrations in red bricks from Ankara as of 31.2 ± 7.6 (^{226}Ra), 37.2 ± 7.8 (^{232}Th) , and 775.8 ± 149.6 Bq kg^{-1} (^{40}K). In sand samples, the activity concentrations were found to be 22.9 ± 12.9, 26.4 ± 16.2 and 527.2 ± 129.2 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. For tile samples, they found 70.3 ± 23.7, 62.1 ± 7.4, and 476.9 ± 132.3 Bq kg^{-1} respectively (Table 2). These values were found to be very close to the results obtained in this study.

Table 1. Radionuclide activity concentrations and calculated Ra_{eq} values of building materials commanly used in Bursa province

Material	C_{Ra} Bq kg^{-1}	C_{Th} Bq kg^{-1}	C_K Bq kg^{-1}	Ra_{eq} Bq kg^{-1}
Cement (1)	11.62 ± 4.46	26.42 ± 4.76	441.94 ± 42.32	83.43
Cement (2)	81.16 ± 8.78	85.64 ± 7.12	621.36 ± 49.72	251.47
Cement (3)	5.66 ± 4.46	BDL	37.18 ± 21.16	8.52
Cement (4)	73.14 ± 8.78	81.82 ± 7.12	574.54 ± 45.98	234.38
Cement (5)	BDL	4.68 ± 3.56	50.96 ± 21.16	10.62
Cement (6)	9.34 ± 4.46	22.34 ± 4.76	410.64 ± 42.32	72.91
Cement (7)	72.44 ± 8.78	94.22 ± 7.38	474.78 ± 37.98	243.73
Cement (8)	15.68 ± 5.48	30.86± 4.76	397.94 ± 42.32	90.45
Cement mean value	**33.63**	**43.25**	**376.17**	**124.44**
Sand (1)	22.96 ± 4.46	39.84 ± 3.98	761.42 ± 60.92	138.56
Sand (2)	12.34 ± 4.46	18.36 ± 5.26	337.78 ± 42.32	64.60
Sand (3)	32.82 ± 5.36	38.54 ± 3.56	743.76 ± 59.52	145.20
Sand (4)	11.88 ± 4.46	28.96 ± 4.76	615.94 ± 73.92	100.72
Sand (5)	6.88 ± 4.46	42.14 ± 3.56	646.84 ± 73.92	116.95
Sand (6)	17.46 ± 6.12	25.72 ± 4.76	456.28 ± 42.32	89.37
Sand (7)	14.58 ± 5.08	29.16 ± 4.76	643.46 ± 73.92	105.83
Sand (8)	24.76 ± 4.82	34.92 ± 4.06	601.64 ± 73.92	121.02
Sand mean value	**17.96**	**32.21**	**600.89**	**110.28**
Gypsum (1)	BDL	BDL	45.74 ± 21.16	3.52
Gypsum (2)	5.58 ± 4.46	5.78 ± 3.56	24.18 ± 21.16	15.71
Gypsum (3)	BDL	BDL	27.56 ± 21.16	2.12
Gypsum (4)	BDL	BDL	118.84 ± 21.16	9.15
Gypsum (5)	BDL	BDL	68.16 ± 21.16	5.25
Gypsum mean value	**1.12**	**1.16**	**56.90**	**7.15**
Brick (1)	31.26 ± 5.28	32.06 ± 4.06	781,26 ± 60.92	137.26
Brick (2)	32.44 ± 5.28	31.42 ± 4.06	761.34 ± 60.92	135.99
Brick mean value	**31.85**	**31.74**	**771.3**	**136.63**
Marble	5.78 ± 4.46	BDL	BDL	5.78
Ceramic Tiles	56.92 ± 6.86	43.48 ± 3.56	534.68 ± 42.32	160.27
Joint Filler (1)	15.48 ± 6.84	BDL	43.16 ± 21.16	18.80
Joint Filler (2)	14.38 ± 6.84	4.26 ± 3.56	47.54 ± 21.16	24.13
Joint Filler mean value	**14.93**	**2.13**	**45.35**	**21.47**
UNSCEAR (2000), EC (2000)	**35**	**30**	**400**	**≤370**

BDL: Below Dedection Limit

Table 2, the data obtained in this study are compared with the activity concentrations and radium equivalents in building materials in different areas of the world.

The calculated Ra_{eq} values for the building materials are presented in Table 1. The lowest Ra_{eq} value (2.12 Bq kg^{-1}) was recorded for Gypsum 3, while the highest (251.47 Bq kg^{-1}) was observed in Cement 2. Since all values are below the recommended safety limit of 370 Bq kg^{-1} for building materials (Nuclear Energy Agency [NEA], 1979), they are considered radiologically safe for residential applications (Figure 1).

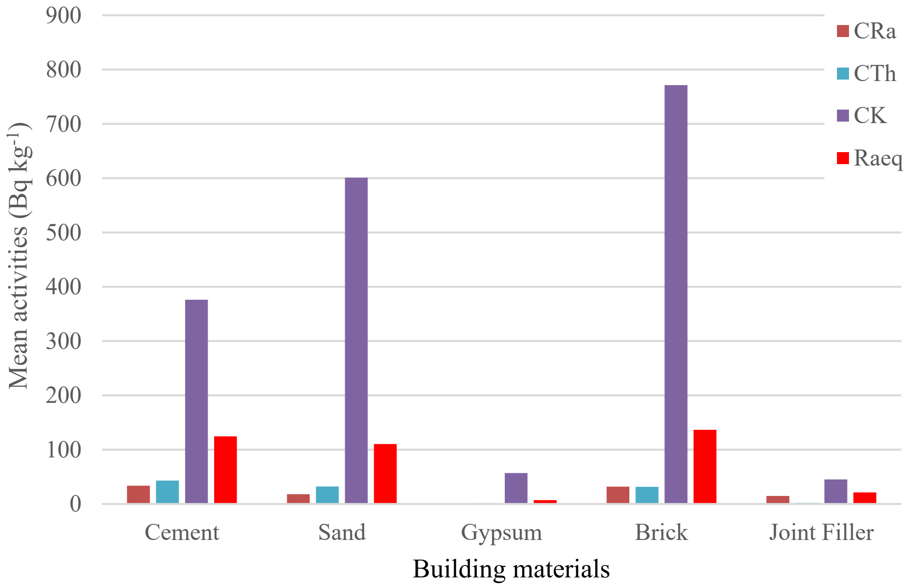

Figure 1. Mean activity concentrations of radionuclides and average radium equivalent (Raeq) values in building materials.

Table 2. Comparison of radionuclide activity concentrations and calculated Raeq values in building materials from different countries

Material	Country	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	Reference
Cement	China (Xianyang)	51.7	32.0	207.7	113.5	Lu et al., 2012
	China (Xi)	68.3 ± 3.6	51.7 ± 5.4	173.8 ± 8.6	162.8 ± 6.3	Xinwei, 2005
	Cuba	23 ±7	11 ±3	467± 85	74± 12	Brígido Flores et al., 2008
	Poland	48 ± 19	29 ± 13	283 ± 89	127 ± 36	Lewicka et al., 2022
	Saudi Arabia (Qassim)	38.4 ±3.8	45.3±1.2	86±4	108.23	El-Taher, 2012
	Saudi Arabia (Tabuk)	42.66	52.90	97.73	125.83	Issa and Alaseri, 2015
	Türkiye (Ankara)	39.9 ± 18.0	26.4 ± 9.8	316.5 ± 88.1	101.9 ± 31.1	Turhan et al., 2008
	Türkiye (Isparta)	26.1	10.4	129.7	51.03	Mavi and Akkurt, 2010
	Yemen (Aden)	40.39 ± 9.8	24.57 ± 5.5	428.48 ± 20.2	108.5 ± 19.2	El-Mageed et al., 2014
	This study	**33.63**	**43.25**	**376.17**	**124.44**	

Table 2. Comparison of radionuclide activity concentrations and calculated Raeq values in building materials from different countries (continued)

Material	Country	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	Reference
Sand	China (Xianyang)	25.8	26.8	553.6	106.7	Lu et al., 2012
	China (Xi)	40.7 ± 4.3	21.5 ± 5.6	302.6 ± 3.4	96.4 ± 2.3	Xinwei, 2005
	Cuba	17 ±4	16± 6	208± 104	55± 14	Brígido Flores et al., 2008
	Türkiye (Ankara)	22.9 ± 12.9	26.4 ± 16.2	527.2 ± 129.2	101.2 ± 50.6	Turhan et al., 2008
	Türkiye (Samsun)	17	19	152	55	Tufan and Dişçi, 2013
	This study	**17.96**	**32.21**	**600.89**	**110.28**	
Red Brick	China (Xi)	58.6 ± 4.7	50.4 ± 3.5	713.9 ± 8.2	178.3 ± 6.2	Xinwei, 2005
	China (Xianyang)	19.9	22.5	413.0	84.0	Lu et al., 2012
	Cuba	57 ±16	12± 10	857 ±759	140 ±68	Brígido Flores et al., 2008
	Türkiye (Ankara)	31.2 ± 7.6	37.2 ± 7.8	775.8 ± 149.6	144.0 ± 28.2	Turhan et al., 2008
	Türkiye (Samsun)	21+4	29+12	534+34	104	Tufan and Dişçi, 2013
	This study	**31.85**	**31.74**	**771.3**	**136.63**	
Gypsum	Saudi Arabia (Qassim)	33.28±4.7	47.2±2.8	88±4.4	107	El-Taher, 2012
	Türkiye	7.2	3.4	40.7	15.1+2.4	Turhan, 2010
	This study	**1.12**	**1.16**	**56.89**	**7.15**	
Ceramic Tiles	Egypt	38.23	42.54	439.33	132.61	Sidique et al., 2022
	Türkiye (Akdeniz bölgesi)	43.5	37.9	310.9		Turhan et al., 2022
	Türkiye (Ankara)	70.3 ± 23.7	62.1 ± 7.4	476.9 ± 132.3	195.8 ± 41.3	Turhan et al., 2008
	This study	**56.92**	**43.48**	**534.68**	**160.27**	

The indoor absorbed dose rate (D_{in}) and the corresponding annual effective dose ($AEDE_{in}$) values in indoor air from gamma-ray emission of ^{226}Ra, ^{232}Th and ^{40}K in building materials are given in Table 3. According to the table, D_{in} values range from 2.2 (Gypsum 3) to 218.58 (Cement 2) nGy h^{-1}. According to UNSCEAR (2000), the global average indoor dose rate is between 20 - 200 nGy h^{-1}. Three cement samples –cement2, cement 4, and cement 7- slightly exceed this limit. The relatively high radioactivity levels in these samples are likely related to the raw materials used in their production. Some industrial by products or natural additives such as fly ash, volcanic tuff, phosphogypsum, or bentonite may contain higher concentrations of uranium-238, thorium-232, and potassium-40. These elevated levels are generally linked to the geological and mineralogical origin of the source materials (Lu et al., 2012). Therefore, the presence of such materials in the cement mixture can lead to increased the overall radioactivity as seen in the aforementioned samples. Although the D_{in} values slightly exceed the recommended limits, they do not indicate a significant health hazard. However, according to radiation safety guidelines, it is advisable to use such materials with care- especially in enclosed or residential setting. They can be diluted with low radioactivity materials or used ventilated or outdoor structures to minimize exposure.

Table 3. Calculated values H_{in}, H_{ex}, I_{γ}, D_{in} and $AEDE_{in}$ for building materials used in Bursa province

Material	H_{in}	H_{ex}	I_{γ}	**D_{in} (nGy h^{-1})**	**$AEDE_{in}$ (mSv y^{-1})**
Cement (1)	0.26	0.23	0.32	75	0.37
Cement (2)	0.90	0.68	0.91	**218.4**	**1.07**
Cement (3)	0.04	0.02	0.03	8.2	0.04
Cement (4)	0.83	0.63	0.84	**203.2**	1.00
Cement (5)	0.03	0.03	0.04	9.1	0.04
Cement (6)	0.22	0.20	0.28	65.9	0.32
Cement (7)	0.85	0.66	0.87	**208.2**	**1.02**
Cement (8)	0.29	0.24	0.34	80.1	0.39
Sand (1)	0.44	0.37	0.53	125.8	0.62
Sand (2)	0.21	0.17	0.25	58.5	0.29
Sand (3)	0.48	0.39	0.55	132	0.65
Sand (4)	0.30	0.27	0.39	91.9	0.45
Sand (5)	0.33	0.32	0.45	104.3	0.51
Sand (6)	0.29	0.24	0.34	80.8	0.40
Sand (7)	0.32	0.29	0.41	96.8	0.47
Sand (8)	0.39	0.33	0.46	109.2	0.54
Gypsum (1)	0.01	0.01	0.02	3.7	0.02
Gypsum (2)	0.06	0.04	0.05	13.3	0.07
Gypsum (3)	0.01	0.01	0.01	2.2	0.01
Gypsum (4)	0.02	0.02	0.04	9.5	0.05
Gypsum (5)	0.01	0.01	0.02	5.4	0.03
Brick (1)	0.45	0.37	0.52	126.3	0.62
Brick (2)	0.45	0.37	0.52	125.3	0.61
Marble	0.03	0.02	0.02	5.3	0.03
Ceramic Tiles	0.59	0.43	0.02	142.9	0.70
Joint Filler (1)	0.09	0.05	0.07	17.7	0.09
Joint Filler (2)	0.10	0.07	0.09	21.7	0.11
UNSCEAR (2000), EC (2000)	**≤1**	**≤1**	**≤1**	**20-200**	**≤1**

When the $AEDE_{in}$ results were compared with the European Commission (EC, 2000) reference values, it was found that only, cement 2 and cement 7 exceed the limit (Figure 2).

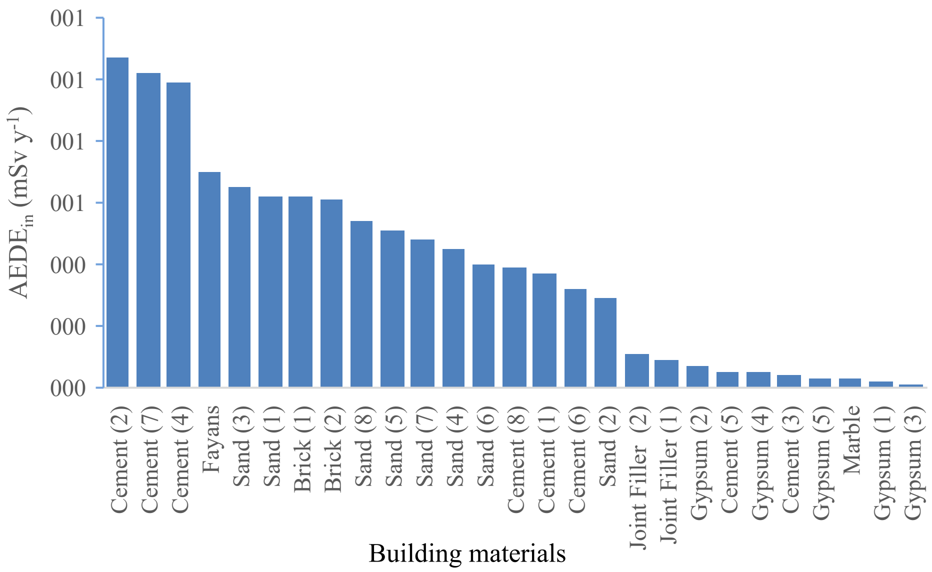

Figure 2. The AEDE$_{in}$ values of the samples.

The H$_{in}$ values obtained in the study varied between 0.006 (Gypsum 3) and 0.899 (Cement 2). Similarly, H$_{ex}$ values were calculated to range from 0.006 (Gypsum 3) to 0.679 (Cement 2) (Table 3). As all H$_{in}$ and H$_{ex}$ values of all samples were below 1, these materials do not pose a radiological risk (Figure 3).

The accepted limit value for the I_γ in building materials is ≤ 1 (EC, 2000). A value of $I_\gamma \leq 0.5$ indicates a negligible radiation risk, contributing up to 0.3 mSv/year. Such materials can generally be used without any restrictions. Values between $0.5 \leq I_\gamma \leq 1.0$ represent a low radiation risk and contribute up to 1 mSv/year to the annual effective dose.

Table 3 shows that the I_γ values for cement 2 (0.91), cement 4 (0.84) and cement 7 (0.87) samples are close to upper limit. In addition, sand 1 (0.53), sand 3 (0.55), brick 1 (0.52), brick 2 (0.52) and, tile (0.59) fall into low risk range. All other materials have I_γ values below 0.5, indicating negligible radiolological risk.

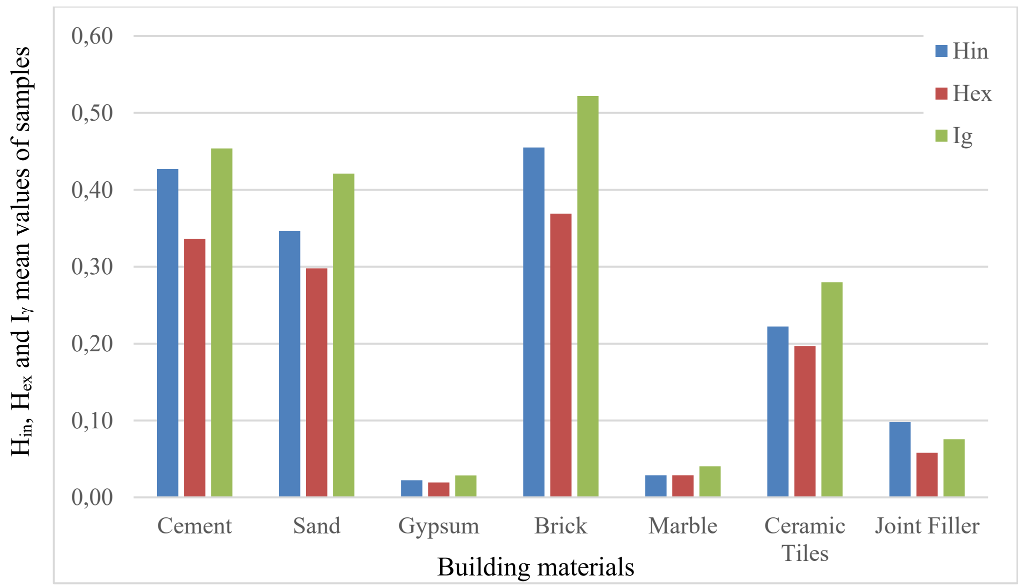

Figure 3. H$_{in}$, H$_{ex}$ and I_γ mean values of the samples.

4. Conclusion

In this study, activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in selected construction materials from Bursa province were measured using gamma spectrometry. Based on these results, key radiological risk indicators were calculated, including radium equivalent activity, external and internal hazard index, indoor absorbed dose rate, annual effective dose rate, and gamma index.

The findings were assessed using the recommended limits set by UNSCEAR (2000) and EC (2000) reports. Apart from the ^{40}K content in sand and brick samples, the average radionuclide activities were generally lower than the reference values. The Ra_{eq} values remained under global safety limit of 370 Bq kg^{-1}.

Except for cement 2, cement 4 and cement 7 samples, the absorbed dose rates were within acceptable limits. The annual effective dose rate values were also below 1mSv/year guideline. All calculated external and internal hazard indeks values were less than one, indicating no significant external and internal hazard. Similarly, I_γ values for all samples were under the threshold of 1, suggesting these materials pose no radiological risk when used in construction.

References

Asaduzzaman, K., Khandaker, M. U., Amin, Y. M., & Bradley, D. A. (2016). Natural radioactivity levels and radiological assessment of decorative building materials in Bangladesh. *Indoor and Built Environment*, *25*(3), 541-550. https://doi.org/10.1177/1420326X14562048

Baker, M. B. (2017). The application of marble and granite as building materials in Jordan. *Jordan Journal of Civil Engineering*, *11*(2), 2017-2234.

Barbosa da Silva, L., Faria da Silva, L., Omar P. Orejuela, C., Junior, V. B., & da Silva, A. X. (2024). Assessment and estimation of the effective dose due to external exposure from natural radioactivity of sands used in civil construction in the state of Rio de Janeiro, Brazil. *Applied Radiation and Isotopes*, *205*, 111157. https://doi.org/10.1016/J.APRADISO.2023.111157

Baykara, O., Karatepe, Ş., & Doğru, M. (2011). Assessments of natural radioactivity and radiological hazards in construction materials used in Elazig, Turkey. *Radiation Measurements*, *46*(1), 153-158. https://doi.org/10.1016/J.RADMEAS.2010.08.010

Beretka, J., & Mathew, P. J. (1985). Natural radioactivity of Australian building materials, industrial wastes and by-products. *Health Physics*, *48*(1), 87-95. https://doi.org/10.1097/00004032-198501000-00007

Brígido Flores, O., Montalván Estrada, A., Rosa Suárez, R., Tomás Zerquera, J., & Hernández Pérez, A. (2008). Natural radionuclide content in building materials and gamma dose rate in dwellings in Cuba. *Journal of Environmental Radioactivity*, *99*(12), 1834-1837. https://doi.org/10.1016/J.JENVRAD.2008.08.001

Chandrasekaran, A., Senthil Kumar, C. K., Sathish, V., Manigandan, S., & Tamilarasi, A. (2021). Effect of minerals and heavy metals in sand samples of Ponnai river, Tamil Nadu, India. *Scientific Reports 2021*, *11*(1), 1-14. https://doi.org/10.1038/s41598-021-02717-x

Ding, X., Lu, X., Zhao, C., Yang, G., & Li, N. (2013). Measurement of natural radioactivity in building materials used in Urumqi, China. *Radiation Protection Dosimetry*, *155*(3), 374–379. https://doi.org/10.1093/RPD/NCT002

EC (European Commission). (2000). *Radiological protection principles concerning the natural radioactivity of building materials.* Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/988f3243-5259-43a5-b621-fbff662deeb0/language-en

El-Mageed, A. I. A., Farid, M. E. A., Saleh, E. E., Mansour, M., & Mohammed, A. K. (2014). Natural radioactivity and radiological hazards of some building materials of Aden, Yemen. *Journal of Geochemical Exploration*, *140*, 41–45. https://doi.org/10.1016/J.GEXPLO.2014.01.015

El-Taher, A. (2012). Assessment of natural radioactivity levels and radiation hazards for building materials used in Qassim Area, Saudi Arabia. *Romanian Journal of Physics*, *57*, 726-735.

Erkan, A. (2007). An investigation on the natural radioactivity of building materials, raw materials and interior coatings in Central Turkey. *Turkish Journal of Medical Sciences*, *37*(4), 199-203.

Erzin, S., & Yaprak, G. (2022). Prediction of the activity concentrations of 232Th, 238U and 40K in geological materials using radial basis function neural network. *Journal of Radioanalytical and Nuclear Chemistry*, *331*(9), 3525-3533. https://doi.org/10.1007/s10967-022-08438-3

Eštoková, A., & Palaščáková, L. (2013). Assessment of natural radioactivity levels of cements and cement composites in the Slovak Republic. *International Journal of Environmental Research and Public Health, 10*(12), 7165-7179. https://doi.org/10.3390/IJERPH10127165

Issa, S. A. M., & Alaseri, S. M. (2015). Determination of natural radioactivity and associated radiological risk in building materials used in Tabuk Area, Saudi Arabia. *International Journal of Advanced Science and Technology*, *82*, 45-62. https://doi.org/10.14257/ijast.2015.82.05

Kayakökü, H. (2024). Experimental investigation of gamma radiation shielding ability of some building materials in Bitlis (Turkey). *Radiation Physics and Chemistry*, *214*, 111297. https://doi.org/10.1016/J.RADPHYSCHEM.2023.111297

Kurnaz, A., Gezelge, M., Hançerlioğulları, A., Çetiner, M. A., & Turhan, Ş. (2016). Radionuclides content in grape molasses soil samples from Central Black Sea region of Turkey. *Human and Ecological Risk Assessment: An International Journal*, *22*(6), 1375-1385. https://doi.org/10.1080/10807039.2016.1185356

Lewicka, S., Piotrowska, B., Łukaszek-Chmielewska, A., & Drzymała, T. (2022). Assessment of natural radioactivity in cements used as building materials in Poland. *International Journal of Environmental Research and Public Health*, *19*(18), 11695. https://doi.org/10.3390/IJERPH191811695

Lu, X., Yang, G., & Ren, C. (2012). Natural radioactivity and radiological hazards of building materials in Xianyang, China. *Radiation Physics and Chemistry*, *81*(7), 780-784. https://doi.org/10.1016/J.RADPHYSCHEM.2012.02.043

Mavi, B., & Akkurt, I. (2010). Natural radioactivity and radiation hazards in some building materials used in Isparta, Turkey. *Radiation Physics and Chemistry*, *79*(9), 933-937. https://doi.org/10.1016/J.RADPHYSCHEM.2010.03.019

Melià, P., Ruggieri, G., Sabbadini, S., & Dotelli, G. (2014). Environmental impacts of natural and conventional building materials: a case study on earth plasters. *Journal of Cleaner Production*, *80*, 179-186. https://doi.org/10.1016/J.JCLEPRO.2014.05.073

NEA (Nuclear Energy Agency). (1979). *Exposure to radiation from the natural radioactivity in building materials*. OECD publishing, Paris

Ramadhan, R. A., & Abdullah, K. M. (2018). Background reduction by Cu/Pb shielding and efficiency study of NaI (TI) detector. *Nuclear Engineering and Technology*, *50*(3), 462-469. https://doi.org/10.1016/j.net.2017.12.016

Rizaoğlu, T., Karataş, M. Z., & Çoşkun, C. (2022). The effect of the main component ratios in the joint filling on the product quality. *Mining Machines, 40*, 180-190. https://doi.org/10.32056/KOMAG2022.4.1

Salim, K., Houssam, A., Belaid, A., & Brahim, H. (2019). Reinforcement of building plaster by waste plastic and glass. *Procedia Structural Integrity*, *17*, 170-176. https://doi.org/10.1016/J.PROSTR.2019.08.023

Sidique, E., Hassan, S. H. A., & Dawoud, M. M. (2022). Natural radioactivity measurements and radiological hazards evaluation for some Egyptian granites and ceramic tiles. *Sustainability, 14*(21), 14611. https://doi.org/10.3390/SU142114611

Tarhan, M., Tarhan, B., & Aydin, T. (2016). The effects of fine fire clay sanitaryware wastes on ceramic wall tiles. *Ceramics International*, *42*(15), 17110-17115. https://doi.org/10.1016/J.CERAMINT.2016.07.222

Tufan, M. Ç., & Dişci, T. (2013). Natural radioactivity measurements in building materials used in Samsun, Turkey. *Radiation Protection Dosimetry*, *156*(1), 87-92. https://doi.org/10.1093/RPD/NCT047

Tuo, F., Peng, X., Zhou, Q., & Zhang, J. (2020). Assessment of natural radioactivity levels and radiological hazards in building materials. *Radiation Protection Dosimetry*, *188*(3), 316-321. https://doi.org/10.1093/rpd/ncz289

Turhan, Ş., Baykan, U. N., & Şen, K. (2008). Measurement of the natural radioactivity in building materials used in Ankara andassessment of external doses. *Journal of Radiological Protection*, *28*(1), 83. https://doi.org/10.1088/0952-4746/28/1/005

Turhan, Ş. (2010). Radioactivity levels of limestone and gypsum used as building raw materials in Turkey and estimation of exposure doses. *Radiation Protection Dosimetry*, *140*(4), 402-407. https://doi.org/10.1093/RPD/NCQ132

Turhan, Ş., Demir, K., & Karataşlı, M. (2018). Radiological evaluation of the use of clay brick and pumice brick as a structural building material. *Applied Radiation and Isotopes*, *141*, 95-100. https://doi.org/10.1016/J.APRADISO.2018.08.022

Turhan, Ş., Kurnaz, A., & Karataşlı, M. (2022). Evaluation of natural radioactivity levels and potential radiological hazards of common building materials utilized in Mediterranean region, Turkey. *Environmental Science and Pollution Research*, *29*(7), 10575-10584. https://doi.org/10.1007/S11356-021-16505-7/METRICS

Tzortzis, M., Tsertos, H., Christofides, S., & Christodoulides, G. (2003). Gamma radiation measurements and dose rates in commercially-used natural tiling rocks (granites). *Journal of Environmental Radioactivity*, *70*(3), 223-235. https://doi.org/10.1016/S0265-931X(03)00106-1

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). (2000). *Sources and effects of ionizing radiation UNSCEAR 2000 report to the general assembly, with scientific annexes volume ı: sources: Vol. I*.

Xinwei, L. (2005). Natural radioactivity in some building materials of Xi'an, China. *Radiation Measurements*, *40*(1), 94-97. https://doi.org/10.1016/J.RADMEAS.2005.01.003

Yang, G., Lu, X., Zhao, C., & Li, N. (2013). Natural radioactivity in building materials used in Changzhi, China. *Radiation Protection Dosimetry*, *155*(4), 512-516. https://doi.org/10.1093/RPD/NCT018

Zhang, L. (2013). Production of bricks from waste materials – A review. *Construction and Building Materials*, *47*, 643-655. https://doi.org/10.1016/J.CONBUILDMAT.2013.05.043