Open Access
Original paper

Budownictwo i Architektura / Civil and Architectural Engineering 25(2) (2026) 26029
https://doi.org/10.35784/bud-arch.8916

Radioactivity of multicomponent concrete, radon exhalation and dose assessment aspects

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Received: 28.12.2025; Revised: 16.03.2026; Accepted: 07.04.2026; Available online: 25.06.2026

Abstract:
The aim of this research is to study the radioactive properties of multicomponent concrete and calculate human radiation doses when it is used in the construction of residential buildings. Research objectives were the experimental determination of the specific activities of natural radionuclides in multicomponent concrete; calculation of the gamma radiation dose from natural radionuclides in concrete and the effective equivalent radiation dose to people living in modern masonry buildings; calculation of the indoor volumetric concentration of radon at its emanation from concrete structures. The specific activities of ^{226}Ra, ^{232}Th and ^{40}K in concrete were determined by using gamma spectrometric analysis. According to the value of the effective specific activity C_{ef} < 370 Bq/kg, the concrete samples can be used in construction without restrictions. The effective equivalent dose of radiation for people living in concrete premises for 50 years is smaller than the public dose limit (1 mSv/year). The calculated effective doses of gamma radiation in premises made of the studied concrete, and the volumetric concentrations of radon isotopes comply with the radiation safety standards, so concrete can be used in civil engineering.

Keywords:
concrete, radiation safety, natural radionuclides, radon emission, radiological indicators

1. Introduction

1.1. Basic concepts

Natural radiation originates from four primary natural sources present in the environment: cosmic radiation, terrestrial radiation from the natural radionuclides (NRN) in the Earth's crust, radioactive radon gas in the air, and radionuclides naturally present in food and water that are ingested or inhaled.

External exposure consists of cosmic rays and γ-radiation from NRN scattered in the environment (except for heavy radioactive elements - α-emitters). An important component of this is gamma radiation from building materials.

Internal exposure is due to α- and β-active NRN, which most often enter the body when inhaling contaminated air, with contaminated water or food. The main component of internal radiation is the irradiation of lung tissue by radon isotopes ^{222}Rn and ^{220}Rn.

Naturally occurring radioactive material (NORMs) are materials containing NRN: ^{238}U, ^{232}Th, ^{40}K, the concentration of which has been increased due to human activity. NORMs are the main component of man-made background radiation, resulting from the redistribution and concentration of naturally occurring radionuclides. The safety of NORMs must be strictly monitored.

The effective equivalent dose of γ-radiation for people living in modern stone buildings considers the impact of cosmic radiation and gamma radiation from the NRF of building materials at a given point in time, taking into account the body's ability to repair radiation damage.

1.2. Analysis of scientific publications

Building materials made from various raw materials are classified by the specific activity of NRN [1]. People spend over 80% of their time indoors and therefore are exposed to radioactive NRN in building materials [2]. The level of external and internal human exposure in buildings can be reduced by optimizing radiation protection methods, complying with building codes, reducing radon emissions from building materials, and raising public awareness. [3].

Portland cement is produced from several raw materials: limestone, clay, gypsum, and iron ore. Iron ore provides ^{232}Th in cement, coal and fly ash provide ^{226}Ra, and clays provide ^{40}K [4,5]. When producing slag Portland cement using industrial waste, its radiological properties are rarely examined [6]. The specific activities of NRN in cement samples of various compositions were determined using gamma spectrometry [4,5,7–15]. A comparative analysis of the radiological properties of cements is presented in Table 1. The last column presents the evaluation criterion for building materials, namely the effective specific activity C_{ef}, Bq/kg. C_{ef}, is calculated from the average values of specific activities C_i of NRN using Eq. 1 [19]

$$C_{ef} = C_{Ra} + 1{,}31 C_{Th} + 0{,}09 C_{K} \quad (1)$$

where C_{Ra}, C_{Th}, C_{K} are the specific activities respectively ^{226}Ra, ^{232}Th and ^{40}K; 1.0; 1.31; 0.09 are the coefficients equal to the ratio of dose rates in infinite space created at the same specific activities of ^{232}Th and ^{226}Ra; ^{40}K and ^{226}Ra, respectively. The values of these coefficients depend on the energy and quantum yields of the NRN radiation.

All construction materials listed in Table 1 belong to the first class of radiation hazard (C_{ef} < 370 Bq/kg) and can be used in construction without restrictions [19].

0.09 are the coefficients equal to the ratio of dose rates in infinite space created at the same specific activities of ^{232}Th and ^{226}Ra; ^{40}K and ^{226}Ra, respectively. The values of these coefficients depend on the energy and quantum yields of the NRN radiation.

Cement with blast furnace slag additives has a radioactivity level 1.65 times higher than white cement [15,20]. The experimentally determined effective specific activities of finished concrete and the raw materials used for its production are, Bq/kg: metakaolin (84–116), silica fume (76–108) [18], fly ash (134–285) [18,21,22], blast-furnace slag (197–318) [18] and coal-mining waste products (121−305) [23,24].

Radon radionuclides and their DP determine the risk of exposure due to alpha radiation. With relatively higher radon concentrations in residential buildings and longer periods of human occupancy, indoor radon exposure can reach 90% of the level associated with the risk of radon-induced lung cancer [25]. Rn accounts for approximately 70–75% of the radiation dose received by the population from all sources of natural radiation [26]. Radon concentrations in rooms were determined to be 4.6−583 Bq/m^3 with the rate of radon emission from concrete in the range of 0.23–510 Bq/m^{2}h [27]. To reduce the porosity of concrete products, the number of open pores and the radon emanation, the process of accelerated carbonization is used with the formation of $CaCO_3$ and $CaO{\cdot}SiO_2{\cdot}H_2O$ [28,29]. Reliable methods are needed to standardize the rate of radon emission from building materials and to measure its concentration in indoor air [27].

The aim of the research is to study the radioactive properties of multicomponent concrete and calculate human radiation doses when their using in the construction of residential buildings. Seven concrete samples used by Kharkiv Reinforced Concrete Structures Plant ZhBK PromStroy were studied.

Research objectives are

- experimental determination of the specific activities of NRN in multicomponent concrete;
- calculation of the gamma radiation dose from NRN in concrete and the effective equivalent radiation dose to people living in modern masonry buildings;
- calculation of the indoor volumetric concentration of radon at its emanation from concrete structures.

The research novelty lies in the multiple use of calculation methods for determining the radioactivity of concrete as a multicomponent building material and a comparative assessment of its gamma radiation and radon exhalation, dose loads and risks, which is important for clarifying the conditions of population radiation safety and optimizing human internal radiation.

Table 1. Radioactivity of cement manufactured in different countries

Material (country)	C_i, Bq/kg			Source	C_{ef}, Bq/kg
	^{226}Ra	^{232}Th	^{40}K		
Clinker (Pakistan, Islamabad)	51.1 (32.9–69.3)	23.2 (22.0–24.4)	258.4 (243.1–273.7)	[4]	103.5
	34.2 (22.3–46.1)	29.1 (25.5–32.7)	295.1 (228.2–362)	[4]	97.4
Portland cement (Türkiye)	34.3	58.2	512.0	[5]	154.1
	33.0	16.7	239.5	[7]	75.2
	52.0	40.0	324.0	[8]	131.9
	45.2 (2.1–88.2)	27.3 (1.8–52.7)	457.8 (68.1–847.5)	[9]	84.8
Portland cement (India, Aligarh region)	19.0 (9.0–28.0)	35.0 (21.0–43.0)	406.7 (280.0–554.0)	[11]	99.4
Portland cement (India, Tiruvannamalai district)	54.1	39.3	149.8	[12]	118.3
	28.6	23.5	180.7	[12]	74.7
	31.3	41.2	233.9	[12]	105.2
Portland cement (Nigeria)	66.0	126.0	589.0	[13]	281.1
	43.8	21.5	71.7	[14]	78.1
Portland cement (Egypt)	33.0 (16.0–50.0)	14.0 (11.6–16.4)	45.0 (19.0–71.0)	[15]	55.2
Portland cement (Serbia)	5.0–4938.0	3.0–63.0	10.0–3192.0	[16]	—
Portland cement (Slovakia)	13.8 (8.6–19.1)	18 (9.8–26.3)	645.9 (156.5–489.4)	[17]	92.3
Portland cement (Romania)	23.0–27.3	—	—	[18]	—

2. Materials and methods

Samples of concrete used for the production of purlins and floor slabs in civil engineering were studied. Concrete samples were pre-crushed using a jaw crusher.

The gamma-spectrometry method was used to determine the specific activities of natural radionuclides C_i in concrete. Gamma-spectrometric analysis of the concretes was performed using a SEG-001 scintillation gamma spectrometer with whose range of measured energies of gamma radiation is from 0.2 to 3 MeV, a scintillation detection unit is with a NaI (Tl) crystal (100x150 mm), the number of analyzer channels is 1024. The minimum measurable activity at an external background of 15 μR/h with an exposure of 1 hour in a 1 L Marinelli vessel for various radionuclides is equal to (Bq): ^{226}Ra – 6.0, ^{232}Th – 3.0, ^{40}K – 20. The operating mode establishment time is 30 minutes. The spectrometer is equipped with a passive lead low-background detector shield, 100 mm thick and weighing 980 kg. The samples were placed in a 1-liter Marinelli measuring vessel (Fig. 1). The average NRN activity measurement time was 2 hours. The limit of permissible basic error of activity measurement for Marinelli "1-liter" geometry and confidence level of 0.95 was no more than 25%. AKWin software was used to process the measurement results. It is designed to manage measurements, store obtained results, perform various spectrometer calibrations, document processing results, and ensure measurement quality. AKWin software ensures measurement quality. It also features an express control mode to ensure that permissible levels are not exceeded.

3. Results and discussion

3.1. Activity of concrete samples

Table 2 includes experimental data on the specific activities C_i of radionuclides obtained using the gamma spectrometry method, as well as the calculated effective specific activity C_{ef} of concrete (using Eq. 1). The activities of ^{226}Ra and ^{232}Th are comparable to the data in Table 1. The activity of ^{40}K in samples No. 1–3 is somewhat overestimated, which does not lead to a significant contribution of ^{40}K to the value of C_{ef} due to the lower energy of its gamma quanta (1.46 MeV) compared to ^{226}Ra (>2 MeV) and ^{232}Th (2.6 MeV). This fact is considered by the corresponding coefficients in Eq. 1. Concrete samples No. 1 and 3 have the highest specific activities, while sample No. 6 has the lowest.

Fig. 1. SEG-001 scintillation gamma spectrometer

Table 2. The activity of concrete samples

No. of concrete sample	C_i, Bq/kg			C_{ef}, Bq/kg
1	^{226}Ra	^{232}Th	^{40}K	
2	42.3	59.1	942	200 ± 11
3	42.4	54.8	714	175 ± 13
4	46.4	61.2	920	205 ± 13
5	24.9	46.2	398	119 ± 13
6	31.3	52.8	—	101 ± 10
7	22.2	35.7	416	104 ± 12
8	38.3	34.0	382	200 ± 11

The C_{ef} value exceeds the Ukrainian average value (106 Bq/kg [26]), with the exception of samples No. 6 and 7. However, all concrete samples with C_{ef} < 370 Bq/kg belong to I Class of radiation hazard for building materials used in construction without restrictions [19]. These building materials do not pose a significant radiation hazard to humans.

The effective specific activity of concrete can be calculated according to the principle of additivity, based on the effective specific activities of its components: cement, sand, aggregate, etc., using the Eq. 2

$$C_{ef} = \Sigma C_{comp}\, n_{comp}, \quad (2)$$

where C_{comp} is the effective specific activity of the NRN in a particular concrete component, Bq/kg; $n_{component}$ is the mass fraction of the concrete component.

The studied concrete samples consisted of three components: crushed stone ($C_{crushed\ stone}$ = 141 Bq/kg), sand (C_{sand} = 97 Bq/kg) and cement (C_{cement} = 146 Bq/kg).

3.2. Radiation doses for people living in concrete buildings

The effective equivalent radiation dose for people living in concrete buildings D_{build} was calculated using the Eq. 3 [26]

$$D_{build} = 4.74\, C_{ef},\ \mu\text{Sv/year} \quad (3)$$

The dose received due to gamma radiation from concrete ΔD_{NRN} was determined [26] using the Eq. 4:

$$\Delta D_{\mathrm{NRN}} = D_{build} - 305,\ \mu\text{Sv/year} \quad (4)$$

where 305 μSv/year is the dose that people may receive if they spend the entire year outdoors in mid-latitudes.

Thus, ΔD_{NRN} represents the additional effect of NRN gamma radiation due to living in masonry buildings. The calculation results for the annual effective equivalent dose of radiation to people and the dose received due to NRN gamma radiation from concrete samples are presented in Table 3.

Table 3. Calculated dose values when using concrete samples

No. of concrete sample	D_{build}, mSv/year	ΔD_{NRN}, mSv/year	D_{50}, mSv	D_{70}, mSv
1	0.948	0.643	47	66
2	0.830	0.525	42	59
3	0.972	0.667	49	69
4	0.564	0.259	28	39
5	0.479	0.175	24	34
6	0.493	0.188	25	35
7	0.545	0.240	27	38

The gamma dose from concrete samples No. 1–3 exceeds the total annual gamma dose from building materials and radon isotope emanation from walls (0.35 mSv/year [26]). The calculated value of ΔD_{NRN}, except for concrete samples No. 1–3, is comparable with the following data, mSv/year: 0.326–0.515 − for cements [12], 0.12–0.39 [15], and 0.21–0.31 − for concretes of different compositions [21]. Thus, the highest intensity of gamma radiation NRN is characteristic of concrete samples No. 1–3.

The obtained values were compared with the Radiation safety standards [19]: the effective dose rate for protection against natural irradiation in industrial conditions (2.5 μSv/h) and the requirement that the effective dose rate of gamma radiation indoors should exceed the dose rate in open areas by no more than 0.2 μSv/h at the design and operation stages of residential and public buildings. For example, for concrete sample No. 3, the effective dose rate of gamma radiation indoors is 0.076 μSv/h, and the excess of this value over the dose rate in open areas (0,034 μSv/h) is 0.042 μSv/h, which complies with the standards [19]. For the remaining concrete samples, the effective dose rate values are even lower. The annual effective dose rate standard of 5 mSv for natural irradiation in industrial conditions was not exceeded.

According to IAEA safety standards [30], the annual effective radiation dose from NRN of building materials should be no more than 1 mSv, which is met (see Table 3). The indoor radiation dose (Table 3) for personnel over 50 years will be $D_{50} = D_{build} \cdot 50$ mSv. For the population, the indoor radiation dose is calculated (Table 3) for 70 years, $D_{70} = D_{build} \cdot 70$ mSv. The calculated effective dose values comply with the standards [19]: for the population over 70 years, no more than 70 mSv; for personnel over 50 years, no more than 1 Sv. Note that the calculated radiation doses are less than the total radiation dose to the population due to natural radiation sources and medical procedures (170 mSv [30]).

3.3. Compliance of concrete with international radiological indicators

To quantitatively assess the radiological impact of concrete on humans, radiation hazard indices, radiation doses, and risk are used.

3.3.1. Radiation Hazard Indices

Radium activity equivalent Ra_{eq} is defined by Eq. 5 as the weighted sum of the activities of ^{226}Ra, ^{232}Th and ^{40}K [31]

$$\mathrm{Ra}_{eq} = C_{\mathrm{Ra}} + 1.43\, C_{\mathrm{Th}} + 0.077 C_{\mathrm{K}},\ \text{Bq/kg} \quad (5)$$

It is assumed that the gamma dose rate of 370 Bq/kg for ^{226}Ra, 259 Bq/kg for ^{232}Th, and 4810 Bq/kg for ^{40}K are equivalent.

Gamma index I_γ estimates the potential for exceeding the 1 mSv dose limit due to excess external gamma radiation indoors (Eq. 6). The rounded values of the coefficients for NRN are: 300 Bq/kg for ^{226}Ra, 200 for ^{232}Th, and 3000 for ^{40}K [32]

$$I_\gamma = C_{\mathrm{Ra}}/300 + C_{\mathrm{Th}}/200 + C_{\mathrm{K}}/3000 \quad (6)$$

Alpha index I_α characterizes the inhalation effects of radon isotopes and their DP on the lungs and is calculated using Eq. 7 [33,34]

$$I_\alpha = C_{\mathrm{Ra}}/200 \quad (7)$$

Activities of ^{226}Ra not exceeding 200 Bq/kg.

External hazard index I_{ex} determines the hazard of external irradiation from ^{226}Ra, ^{232}Th and ^{40}K [32,35]. I_{ex} is determined by Eq. 8.

$$I_{ex} = C_{Ra}/370 + C_{Th}/259 + C_K/4810 \quad (8)$$

Internal hazard index I_{in} assess the degree of internal respiratory exposure to radon isotopes and their DP and is calculated using the Eq. 9 [35]

$$I_{in} = C_{Ra}/185 + C_{Th}/259 + C_K/4810 \quad (9)$$

Activity utilization index AUI defines the radiation dose rate in air in the presence of ^{226}Ra, ^{232}Th and ^{40}K in industrial waste or concrete containing them (Eq. 10 [36])

$$AUI = C_{Ra}f_U/50 + C_{Th}f_{Th}/50 + C_Kf_K/500 \quad (10)$$

where the NRN parts in the total dose rate of gamma radiation in the air are f_U=0.462, f_{Th} = 0.604, f_K = 0.041. The average specific activities of ^{40}K, ^{232}Th and ^{226}Ra in soils are 500, 50 and 50 Bq/kg, respectively [33].

3.3.2. Radiation doses

Absorbed dose rate in the open air, D_R due to gamma radiation of the environment NRN is calculated using Eq. 11 [31]

$$D_R = 0.462\ C_{Ra} + 0.604C_{Th} + 0.0417C_K,\ \text{nGy/h} \quad (11)$$

where conversion factors equal 0.462, 0.604 and 0.0417 Bq/kg for ^{226}Ra, ^{232}Th and ^{40}K respectively.

The annual effective dose equivalent AEDE for outdoor exposure is determined by Eq. 12

$$AEDE= 1.21\cdot10^{-3}\cdot D_R,\ \text{mSv/year} \quad (12)$$

Excessive lifetime carcinogenic risk ELCR during exposure is calculated based on the *AEDE* value of Eq. 13 [35]

$$ELCR = AEDE\cdot DL\cdot RF \quad (13)$$

where *DL* is the life expectancy, 70 years; *RF* is the risk factor of 0.05 1/Sv for stochastic effects in any population.

3.3.3. The limitation of Radiation Hazard Indices

All the above radiation hazard indices have limitations.

- The maximum limit value of Ra_{eq} is 370 Bq/kg [34].
- All indexes must not exceed 1: $I\gamma \le 1$, $I_\alpha \le 1$, $I_{ex} \le 1$, $I_{in} \le 1$ [34,35], $AUI \le 1$ [36].
- The AEDE value is limited to 1 mSv/year [34].
- The excessive lifetime carcinogenic risk should not exceed 0.05 [35].

The quantitative values of the presented international radiological indicators are given in Table 4.

The value of Ra_{eq} does not exceed the maximum value of 370 Bq/kg, in this case, the external dose will not exceed 1.5 mSv/year [33]. There is no radiation hazard from a non-uniform distribution of NRN in concrete.

The gamma index determines the radiation safety of building materials used in large quantities, such as concrete. For all concrete, the value $I\gamma \le 1$ (Table 4), which indicates that the annual dose due to excess external gamma radiation in the building does not exceed 1 mSv [31].

The values $I_\alpha \le 1$ show that indoor radon concentration is less than 200 Bq/m^3. This is indicated by the specific activities of ^{226}Ra, which are less than 200 Bq/kg for all concrete samples (Table 2).

All values of the external and internal hazard indexes are within normal limits. I_{ex} is derived from the expression for Ra_{eq} with the assumption that the value of Ra_{eq} corresponds to the maximum, i.e. 370 Bq/kg. For the I_{in} the maximum value for Ra_{eq} is taken to be 185 Bq/kg.

Table 4. Indices of the radiation hazard of concrete

No. of concrete sample	Radiation hazard indices						Doses		Risk
	≤ 370	≤ 1					–	< 1 mSv/year	< 0.05
	Ra_{eq}, Bq /kg	I_γ	I_α	I_{ex}	I_{in}	*AUI*	D_R, nGy/h	*AEDE*, mSv/year	$ELCR\cdot10^{-3}$
1	199.35	0.75	0.21	0.54	0.65	1.18	94.52	0.114	0.40
2	175.74	0.65	0.21	0.33	0.44	1.11	82.46	0.100	0.35
3	204.76	0.77	0.23	0.55	0.68	1.24	96.77	0.117	0.41
4	121.61	0.45	0.12	0.33	0.40	0.82	56.01	0.068	0.24
5	106.80	0.37	0.16	0.29	0.37	0.93	46.35	0.056	0.20
6	105.28	0.39	0.11	0.28	0.34	0.67	49.17	0.059	0.21
7	116.33	0.43	0.19	0.31	0.42	0.80	54.16	0.066	0.23

According to the considered indicators, concrete can be used with no radiological hazard. The exception is activity utilization index *AUI* > 1 for concrete samples No. 1−3. An increased dose rate of radiation in the air can be expected when using this concrete. However, in order to make a final conclusion about the possibility of using concrete (samples No. 1−3) in civil construction, it is necessary to check the compliance of *AEDE* and *ELCR* with the standardized values.

The absorbed dose rate in the open air, D_R at 1 m above a concrete floor, results from NRN gamma radiation. It determines the risk of human exposure to radiation. The highest D_R values are for concrete samples No. 1−3. The annual effective dose equivalent *AEDE* is determined by the risk of human exposure, i.e. the absorbed dose rate. The factor of D_R transformation to the effective dose is 0.7 Sv/Gy; the outdoor exposure coefficient is 0.2 [31]. For concrete samples No. 1−3, the global average values of D_R = 58 nGy/h and *AEDE* = 0.07 mSv [31] were exceeded. However, the calculated *AEDE* values are less than the annual effective dose of 1 mSv/year recommended by the IAEA for the population [34].

The *ELCR* values for concrete samples No. 1−3 exceed the global average value of $0.29{\cdot}10^{-3}$ [31], but are below the limit of 0.05 established by the International Commission on Radiological Protection [35]. Thus, the probability of blastomogenesis in the population due to the use of the studied concrete is generally insignificant. However, assessing the excess lifetime risk of cancer using only dose coefficients and ICRP risk coefficients is inaccurate. This issue requires detailed study.

Determining the radioactive characteristics of various construction, raw materials, and man-made materials is relevant. This approach facilitates the accumulation of experimental data, which can address issues of improving human safety and reducing public radiation doses.

3.4. Human internal irradiation by inhalation of radon isotopes

The process of radon exhalation can be divided into two stages. The first stage is the emanation of atoms into the internal pores of the material. The second stage is associated with diffusion of radon through pores with release from the material. With reduced air exchange and an elevated or moderate exhalation rate, the indoor volumetric radon activity can reach high values. For modern stone buildings with reinforced concrete slabs, the penetration of Rn into indoor air from the soil is difficult. The main source of Rn is its exhalation from building structures. The maximum possible release of ^{222}Rn is determined by the product of the ^{226}Ra concentration in the building material and the radon emanation coefficient (η, %) according to Eq. 14 [26]

$$C_{\text{Rn-222 max}} = C_{\text{Ra}}\rho\eta/P \tag{14}$$

where $C_{\text{Rn-222 max}}$ is the maximum possible volumetric activity of radon-222 in the pores of the material, Bq/l; C_{Ra} is the specific activity of radium in the material, Bq/kg; ρ is the density of the material, kg/l; η is the emanation coefficient; *P* is the porosity of the material, %.

The maximum emission of ^{220}Rn is determined similarly by Eq. 15 [26]

$$C_{\text{Rn-220 max}} = C_{\text{Th}}\rho\eta/P \tag{15}$$

The level of radon emission from concrete was estimated based on the effective activity of radium and thorium $C_{ef\ \text{Ra(Th)}}$ ($C_{\text{Ra(Th)}}\eta$) and the maximum concentration of Rn in the pores of material ($C_{\text{Rn max}}$). The $C_{\text{Rn max}}$ value was calculated using equations (14) and (15) taking into account the following data: ρ = 2.4 kg/l; η = 0.095% [37]; *P* = 8%. The indoor radon concentration C_{Rn} is typically $0.01C_{\text{Rn-222 max}}$, which is due to the stack effect and the presence of waste in building materials in the form of additives. It also depends on the air exchange rate.

The average human tissue dose due to inhalation of air containing radon isotopes can be approximately estimated using the following Eqs 16, 17 [26,37]

$$D_{\text{Rn-222}} = 0.135C_{\text{Rn-222}},\ \text{mSv/year}, \tag{16}$$

$$D_{\text{Rn-220}} = 1.78C_{\text{Rn-220}},\ \text{mSv/year}, \tag{17}$$

where *C* is an emanation concentration, Bq/m^3.

When using these ratios, several assumptions are made: the concentration of ^{222}Rn and ^{220}Rn in inhaled air is constant; ^{222}Rn and ^{220}Rn are in equilibrium with their DP. It is assumed that approximately 60% of aerosol particles carrying radioactive DP of ^{222}Rn and ^{220}Rn are retained in the human lungs. The lung volume is 3000 cm^3, and its mass is 800 g.

For ventilated rooms, the following model is used: the air is completely replaced within 17 minutes, i.e. 0.001 of the air volume is exchanged every second. The following Eqs 18, 19 were found [26,37]:

$$D_{\text{Rn-222}} = 0.037C_{\text{Rn-222}},\ \text{mSv/year} \tag{18}$$

$$D_{\text{Rn-220}} = 0.104C_{\text{Rn-220}},\ \text{mSv/year} \tag{19}$$

The values of $D_{\text{Rn-222}}$ and $D_{\text{Rn-220}}$ in ventilated and non-ventilated buildings are presented in Table 5.

Table 5. Concentrations of radon isotopes in concrete pores and in indoor air and average human tissue doses

No.	C_{Ra}, Bq/kg	$C_{\text{Rn-222 max}}$, Bq/l	$C_{\text{Rn-222}}$, Bq/m^3	$D_{\text{Rn-222}}$, mSv/year		C_{Th}, Bq/kg	$C_{\text{Rn-220 max}}$, Bq/l	$C_{\text{Rn-220}}$, Bq/m^3	$D_{\text{Rn-220}}$, mSv/year	
				vent.	non-vent.				vent.	non-vent.
1	42.3	1.21	12.1	0.45	1.63	59.1	1.68	16.8	1.74	29.9
2	42.4	1.21	12.1	0.45	1.63	54.8	1.56	15.6	1.62	27.8
3	46.4	1.32	13.2	0.49	1.78	61.2	1.74	17.4	1.81	31.0
4	24.9	0.71	7.1	0.26	0.96	46.2	1.32	13.2	1.37	23.5
5	31.3	0.89	8.9	0.33	1.20	52.8	1.50	15.0	1.56	26.7
6	22.2	0.63	6.3	0.23	0.85	35.7	1.02	10.2	1.06	18.2
7	38.3	1.09	10.9	0.40	1.47	34.0	0.97	9.7	1.01	17.3

The concentrations $C_{\text{Rn-222}}$ and $C_{\text{Rn-220}}$ in their physical meaning are similar to equivalent equilibrium volumetric activities (*EEVA*). Radon activity levels in indoor air are always higher than those in the atmosphere. The main factors determining radon activity levels in indoor air are the rate of radon entry (exhalation) and the air exchange rate. The air exchange rate in a room varies depending on the room's design, weather conditions, and the presence of forced ventilation. There is no information in the literature on the rate of radon exhalation from the walls and ceilings of modern buildings. Such data are available for soils and rocks. The maximum rate of radon exhalation from soils is $5.25{\cdot}10^{-2}$ Bq/m^2·s [26]. The minimum value for rocks is $0.17{\cdot}10^{-2}$ Bq/m^2·s [26]. Assuming that the rate of radon exhalation from building materials varies within these limits, then the volumetric activity of radon in indoor air can be estimated by Eq. 20 [26]

$$C_{Rn-222} = \frac{q \cdot S}{\lambda \cdot V}, \quad \text{Bq/m}^3, \tag{20}$$

where q is a radon exhalation rate, Bq/m^2·s; S is the floor area of a room of 20 m^2; V is the volume of the room at a height of 3 m; λ is the air exchange rate, 1/h.

When ventilating rooms with a complete air changeover for 17 minutes, the air exchange rate is λ = 3.5 1/h. Then, the radon volume activity varies within the range of 2.7–30.8 Bq/m³. The $C_{Rn\text{-}222}$ values (Table 5) correspond to this range.

The calculated $C_{Rn\text{-}222}$ values [26] for 1-, 2-, and 3-room apartments are as follows, Bq/m^3: 4.78; 4.86; 5.13, which is lower than $C_{Rn\text{-}222}$ (Table 5).

The sum of equivalent equilibrium volumetric activities ($EEVA_{Rn\text{-}222}$ + 4.6·$EEVA_{Rn\text{-}220}$) should not exceed 100 Bq/m^3 at the design stage of residential and public buildings; < 200 Bq/m^3 − during their operation [19]; < 300 Bq/m^3 according to IAEA safety standards [30]. Sample No. 3 has the highest yield of radon isotopes (Table 4: $C_{Rn\text{-}222}$ = 13.2 Bq/m^3 and $C_{Rn\text{-}220}$ = 17.4 Bq/m^3). The calculated total volumetric activity value for it is 93.2 Bq/m^3, which is below the standard value used in the design of premises. For the remaining concrete samples, the total volumetric activity is even lower. Concrete can also be used in the construction of industrial facilities, since it meets the requirements for protection against natural radiation in industrial conditions: $EEVA_{Rn\text{-}222} \le 310$ Bq/m^3, $EEVA_{Rn\text{-}220} \le 68$ Bq/m^3 [19]. The average annual specific activity of ^{222}Rn is no more than 1000 Bq/m^3 according to IAEA safety standards [30], which corresponds to the values of $C_{Rn\text{-}222}$ and $C_{Rn\text{-}220}$.

Residents of buildings with radon accumulation conditions can receive high individual lung radiation doses, reaching 1 Sv/year. Additional radiation exposure due to emanation from building structures is 0.35 mSv/year, and due to radon influx from the soil beneath the building, 0.69 mSv/year [26]. $D_{Rn\text{-}222}$ values for a person in a ventilated room constructed from concrete samples No. 4−7 are below 0.35 mSv/year (Table 5). The remaining dose values are higher, which requires additional verification when using these concretes.

The main biological effect of radon isotope inhalation occurs in the human respiratory tract. The tracheobronchial part (26.8 mSv/year) and lung parenchyma (4.0 mSv/year) are exposed to the greatest irradiation [26,38]. $D_{Rn\text{-}220}$ is higher than 26.8 mSv/year for concrete samples No. 1−3 and 5 (Table 5). The main consequence of irradiation of lung tissue is the induction of lung cancer.

4. Conclusion

For all concrete samples, the values of effective specific activity are below 370 Bq/kg, which determines their belonging to the first class of radiation hazard. Concrete complies with international and Ukrainian radiation safety standards for γ-radiation. A slight excess of the activity utilization index values for three concrete samples (1.11−1.24 > 1) was registered. However, they can be used in civil engineering, since the annual effective dose of radiation from NRN building materials of 1 mSv (IAEA) and the indoor radiation dose for 70 years (70 mSv) have not been exceeded.

The radon emanation from concrete was estimated according to the calculation model for rooms with different ventilation conditions. It was shown that the calculated total volumetric activity of the concrete sample with the highest yield of radon isotopes (93.2 Bq/m³) is below the standard value 100 Bq/m^3 at the design stage of residential and public buildings; < 200 Bq/m^3 − during their operation; < 300 Bq/m^3 (IAEA safety standards).

Based on γ-radiation intensity and quantitative indicators of radon exhalation, concrete samples do not pose a radiological hazard when used in civil engineering.

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