Indoor air quality in buildings: assessment of exposure to enhanced natural radioactivity

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Abstract. Our study aimed to assess air quality within buildings constructed with coal ash concrete, with a specific focus on radon measurement. Coal ash, a by-product of the TAQA Morocco thermal power plant. In this investigation, two concrete mixtures were prepared. It is possible that concrete produced from coal ash may contain elevated levels of radon, a naturally occurring radioactive gas that could prove detrimental to human health, given that coal ash contains considerable quantities of radioactive elements. To this regard, two nuclear techniques were employed for analysis: high-resolution gamma spectrometry and alpha dosimetry based on the use of LR115 on the two concrete mixes. The equivalent radium activity (Ra_{eq}), internal (H_{in}) and external (H_{ex}) risk indices, absorbed dose rate ($\dot{D}$), annual effective dose ($\dot{E}$) and excess lifetime cancer risk (ELCR) were also calculated. The surface (E_S) and mass (E_M) radon exhalation rates were calculated for the analysed samples in order to assess the radiological risks resulting from the use of coal ash concrete.The results has revealed no evidence of any health risks to the general public, and therefore coal ash concrete can be used in construction projects.

Keywords : concrete ; radon ; indoor air quality ; fly ash ; bottom ash

1. Introduction

The demand for building materials has increased considerably in response to the rapid growth in the world's population. Consequently, the availability of raw materials and natural resources is decreasing, which has led to a rise in the cost of building materials. Concurrently, the minimization of the environmental footprint, energy intensity, and CO_2 emissions of concrete employed in construction is assuming greater importance. Indeed, in the context of dwindling resources and an intensifying awareness of the consequences of greenhouse gas emissions, It is of the utmost importance to re-examine the processes involved in the production and utilization of concrete. For the reasons outlined above, it is evident that the adoption of life-cycle and sustainable engineering methodologies in the design of concrete mixes, with a view towards reducing environmental impacts while optimizing the performance of construction materials, constitutes a logical course of action.

In light of these considerations, the incorporation of industrial waste [1-2] and residues into concrete has become a practice that addresses both environmental concerns and economic constraints. Among the materials employed to replace cement is fly ash from thermal power stations [3-4]. However, although this practice offers benefits in terms of reducing the

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ecological impact and costs [5-6], it can also have implications for occupant comfort, particularly in relation to indoor air quality.

It is widely accepted that building materials constitute a continuous source of natural radiation [7-8], due to the presence of radioactivity in the rocks and soils [9-10] from which they are derived. The levels of radioactivity in these materials vary depending on their geological origin [11-12].

Radioactive exposure can be classified into two categories: internal and external. External exposure is caused by gamma radiation emitted from radionuclides in the three radioactive decay chains (^{238}U, ^{235}U and ^{232}Th) and from ^{40}K. In contrast, internal exposure arises from the inhalation of radon and its progeny. It is currently considered that ^{222}Rn is the primary source of human exposure to natural radiation [13]. This naturally occurring radioactive gas is derived from the decay of radium-226, which is a component of the uranium-238 decay chain [11]. As it decays, radon emits alpha particles and produces solid progeny that are also radioactive (polonium, bismuth, lead, etc.). These descendants continue to decay, emitting radiation, mainly alpha and beta particles. Once inhaled, they dissipate their energy in the surrounding lung tissue, damaging the lung cells and modifying their atomic structure. In 1987, the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) classified radon as a human lung carcinogen.

The natural uranium present in coal is one of the most abundant naturally occurring radioactive elements. Consequently, coal combustion results in the production of coal ash that can contain varying amounts of natural radioactivity. In view of the above, it is imperative to evaluate the suitability of ash-based concrete. The objective of this study is to assess whether the use of coal ash in concrete presents an additional health risk to residents due to radon exhalation. A direct practical way of measuring the rate of radon exhalation from the surface of concrete is through use of an accumulator. Radon gradually piles up in this device and is then analyzed by passive techniques employing solid-state nuclear trace detectors (SSNTD). The detectors offer a high level of precision when quantifying the amount of radon emitted. Concrete samples which were subjected to examination in this study contained different proportions of coal ash that was supplied by TAQA Morocco, the country's biggest electricity generator. Altering the percentage compositions of coal ash in concrete enables one to gauge how it affects radon emission levels. From this point forth, it is anticipated that results will be used to determine if there are any potential health hazards with usage of coal ash in concrete and provide guidelines on its use during construction activities.

This study aimed to quantify the specific activities of the radioelements ^{226}Ra, ^{232}Th and ^{40}K, in addition to the surface and mass exhalation rates of ^{222}Rn, for two concrete mixtures based on coal ashes. To evaluate the radiological influence of concrete on the public and the environment, several radiological risk indices, namely the equivalent radium Ra_{eq}, the internal risk H_{in} and external risk H_{ex}, the annual effective dose and the excess lifetime cancer risk ELCR were calculated.

2. Materials and Methods

2.1. Materials

In the present study, coal fly ash and bottom ash collected form TAQA Morocco thermal power plant were used as cementitious materials to produce concrete mixtures.

Two concrete mixtures were developed. The first mixture is based on fly ash (CF_i), which was used as a cement substitute at four different percentages: 10%, 20%, 30% and 40%. The second mixture (CB_i) has the same percentages as the first, but instead of fly ash, ground bottom ash was used. These two types of mixture can be used to assess the impact of different additives on air quality. The details of mixture of concrete (CF_i) and are depicted in Table 1 where i present the percentage of fly ash and ground bottom ash incorporation. The mechanical study of these two concrete mixes has been covered in previous studies [12].

Table 1. Concrete mixture

Concrete						
	Water (Kg/m^3)	Sand (0/4) (Kg/m^3)	Cement (Kg/m^3)	FA (Kg/m^3)	GBA (Kg/m^3)	Aggregate (Kg/m^3)
C_0	187	695	350	0	-	1165
CF_{10}	187	695	315	26	-	1165
CF_{20}	187	695	280	51	-	1165
CF_{30}	187	695	245	77	-	1165
CF_{40}	187	695	210	102	-	1165
CB_{10}	187	695	315	-	31	1165
CB_{20}	187	695	280	-	63	1165
CB_{30}	187	695	245	-	64	1165
CB_{40}	187	695	210	-	126	1165

2.2. Spectroscopic analysis

Gamma spectroscopy analysis was used to estimate ^{226}Ra, ^{232}Th and ^{40}K in studied materials. These measurements were performed by gamma ray spectrometer using the Broad Energy Germanium detector (BEGe). Its energy measurement range was 30 to 3000keV with a resolution of 0.633 keV to 122 keV and from 1.934 keV to 133 keV [13]. The treatment of the amplitude spectra is carried out using an automatic analysis software Genie 2000 [13] allowing directly to give the mass activity of each radioelement present in the sample. In order to assess the radiological impact of studied materials. Different parameters were calculated based on the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K like radium equivalent activity (Ra_{eq}), Alpha hazard index (I_α), and Gamma hazard index ($I\gamma$) following the recommendations of the European Commission (1999) and UNSCEAR (2000) [14].

2.2.1 Radium equivalent

Radium equivalent (Ra_{eq}) is the most widely used index for radiological risk assessment. It is calculated using the following equation [15].

$$Ra_{eq} = A_{226Ra} + 1{,}43A_{232Th} + 0{,}077A_{40K} \tag{1}$$

Where A_{222Ra}, A_{232Th} , and A_{40k} are the specific activities in (Bq/kg) of ^{226}Ra, ^{232}Th, and ^{40}K in the samples analyzed.

2.2.2 Internal and external hazard indices

The measurement of the total activity of radionuclides in concrete samples was insufficient for the assessment of the radiological impact of gamma radiation. In order to gain a more comprehensive understanding of the radiological impact, other parameters were also taken into account, including the external hazard index (H_{ex}) [14] and the internal hazard index (H_{in}) [16], which provide insight into external and internal exposure, respectively. The H_{ex} and H_{in} should not be exceeded to 1 for safe building materials. The indices are quantified by the following equations (2) and (3):

$$H_{ex} = \frac{A_{226Ra}}{370} + \frac{A_{232Th}}{259} + \frac{A_{40K}}{4810} \tag{2}$$

$$H_{in} = \frac{A_{226Ra}}{185} + \frac{A_{232Th}}{259} + \frac{A_{40K}}{4810} \tag{3}$$

2.2.3 *Absorbed dose rate and annual effective dose*

The absorbed dose rate $\dot{D}$ (nGy/h) due to the specific activity of natural radionuclides from construction materials in air at 1m height is defined by the following equation (4) [17]:

$$\dot{D}(nGy/h) = 0.462A_{226Ra} + 0.604A_{232Th} + 0.0417A_{40K} \quad (4)$$

The annual effective dose received by the population was estimated taking into account the coefficient of conversion of dose rate absorbed in air in effective dose (0.7 Sv/Gy) and external occupancy factor (0.2) [18-19]. The annual effective doses are estimated as follows (see equation (5) and (6)):

$$\dot{E}_{ex}(mSv/y) = \dot{D}(nGy/h)x\ 8760\ (h)x\ 0.2\ x\ 0.7\ (Sv/Gy)10^{-6} \quad (5)$$

$$\dot{E}_{in}(mSv/y) = \dot{D}(nGy/h)x\ 8760\ (h)x\ 0.8\ x\ 0.7\ (Sv/Gy)10^{-6} \quad (6)$$

2.2.4 *Internal (α radioactivity) level index Iα*

In order to evaluate risks associated with radon released by building materials in the air of dwellings, the specific activity concentration of Ra (A_{Ra}) was employed to estimate the alpha index Iα. It should be noted that the value should not exceed 0.5, as per the relevant guidelines [20]. The alpha index Iα is calculated by the following equation (7):

$$I_\alpha = \frac{A_{Ra}}{200Bq\ kg^{-1}} \quad (7)$$

2.2.5 *Life time Cancer Risk (LCR) index*

To estimate the cancer risk, lifetime Cancer Risk (LCR) index is used. It is calculated as follows:

$$LCR = EAED \times DL \times R_F \quad (8)$$

where $EAED$ is the annual effective dose equivalent, DL is the duration of life (70 years), and RF is the risk factor, 0.05 Sv −1 [21].

2.2.6 *Gamma activity index (Iγ)*

The gamma activity index (Iγ) that is described in order to evaluate gamma-ray radiation from construction materials is calculated by using the mean activities of these radionuclides and the obtained values should be less than unity [14].

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \quad (9)$$

2.3. Measurements of activity concentration of radon

Measurements of the radon exhalation rate were conducted using the SSNTD LR115 type II. For granular materials, including fly ash, bottom ash, cement, sand and coarse aggregates. A quantity of 50g of each sample was placed in the cylindrical can (with a diameter of 5.5 cm and a height of 9.5 cm) to a level that ensured the remaining space was sufficient to allow for the necessary sensitivity. In the case of concrete specimens, dimensions of 5*10 cm^2 were employed. The specimens were then dried in an oven at 105 °C for 24 hours to ensure that all moisture was removed. Each specimen was then placed in the cylindrical can, which had dimensions of 10 cm in diameter and 22 cm in height. Each can was equipped with a detector piece (2*2 cm^2) fixed on the upper part of the can. The LR115 detectors had the capacity to detect alpha particles of all energies emitted from radon. Alpha particles leave tracks in the detector and the number of tracks is proportional to the average radon concentration.
Following a 75 day irradiation period, the detectors were developed in NaOH solution 2.5N at 60°C for 100 minutes. After chemical etching, the LR-115 detectors were washed in

distilled water and dried in air. Alpha particle track densities were counted using an optical microscope. The radon concentration A_V^{Rn} in Bq/m^3 was determined by the following equation (10) [22].

$$D_{LR} = \varepsilon_{LR}(\theta_c . E_\alpha) . A_V^{Rn} \tag{10}$$

Where D$_{LR}$ is the net track density (Tr.cm^{-2}). $\varepsilon_{LR}(\theta_c . E_\alpha$) is the efficiency of detection in a function of the critical angle of recording $\theta_c$and the energy of the alpha particle E_α. This efficiency is equal to 0.0258 (traces·cm^{-2}·d^{-1})/(Bq·m^{-3}).
The activity of each sample was determined using measured track density (MTD) subtracted from the background track (BTD) density to obtain the net track density (See Equation 11) [22].

$$D_{LR} = MTD - BTD \tag{11}$$

The background and lower limit detection of LR115 detector are equal to 4 tr/cm^2 and 4.33 kBq.m^3.h respectively.

2.3.1 Radon exhalation rates

After calculating the density of traces per unit area and per unit time in the LR115. the volume activities of the radon A_V^{Rn} were calculated using the detection efficiency equal to 0.0258 (traces.cm^{-2}.j^{-1})/(Bq.m^{-3}) [23]. The surface exhalation rates (E$_S$ in Bq.m^{-2}.h^{-1}) and mass (E$_M$ in Bq.kg^{-1}.h^{-1}) of ^{222}Rn were determined by the following equation (12) and (13) [24]:

$$E_S = \frac{A_V^{Rn} V \lambda_{Rn}}{S_e\left[t+\left(\frac{1}{\lambda_{Rn}}\right)\left(e^{-\lambda_{Rn} t}-1\right)\right]} \tag{12}$$

$$E_M = \frac{A_V^{Rn} V \lambda_{Rn}}{M\left[t+\left(\frac{1}{\lambda_{Rn}}\right)\left(e^{-\lambda_{Rn} t}-1\right)\right]} \tag{13}$$

With $A_V^{Rn}$is the volume activity of radon (Bq.m^{-3}.h); V is the volume of the enclosure (m^3); λ_{Rn} is the radon decay constant (h^{-1}); S$_e$ is the area of the sample (m^2); M is the mass of the sample in kg and t is the exposure time (h).

2.3.2 Radon emanation factor

In order to examine the radiological impact of the studied materials. emanation factor (EF) were calculated. It can be defined as the fraction [25].

$$EF = \frac{A_{out}^{Rn}}{A_{in}^{Ra}} * \% \tag{14}$$

Were A_{out}^{Rn} is the radon activity in the can after accumulation (in Bq) and A_{in}^{Ra} is the ^{226}Ra activity content in the material (in Bq). As reported by previous investigations. The emanation factor depends on the porosity of materials [26]. Thus, it is necessary to calculate the porosity of concrete mixtures based on coal ash.

2.4. Porosity of specimens concrete

In order to determinate the porosity of the hardened concrete. Firstly, samples were dried at 105 C for 24h. Then, the dry weight was measured. The Samples were submerged underwater for 24h and the weight under water was measured. After obtaining the dry weight and weight under water of each sample. The porosity of hardened concrete is calculated using the following equation Eq. (16). Porosity of concrete samples was measured at 7 days, 28 days and 90 days.
Where P=porosity (%), w$_1$=weight under water, w$_2$=oven dry weight. vol.=volume of sample. ρ =density of water.

$$P = \left[1 - \left(\frac{W1 - W2}{V * \rho}\right)\right] * 100 \tag{16}$$

3. Results and discussion

3.1. Porosity of concrete samples

The obtained results of porosity of different concrete made with fly ashes and bottom ashes are depicted in Table 2. At the age of 7 days, the porosities of concrete containing fly ash and ground bottom ash are lower than those of control concrete. This result can be attributed to the fact that the pozzolanic reaction is weak at an early age. The porosity of concrete mixtures based on fly ash and ground bottom ash decreases with increasing age. This phenomenon can be attributed to the enhanced hydration of the cementitious materials. Following a period of 90 days, the porosity of concrete incorporating fly ash and ground bottom ash decreases to values comparable to those observed in the control concrete. At this point in time, the porosity of the CF10, CF20, CF30 and CF40 mixtures was recorded at 10.4%, 10%, 10.5% and 10.2%, respectively, in comparison to the porosity of control concrete, which was 10.6% at the same age. As regard, the porosity of the CB10, CB20, CB30 and CB40 mixtures was recorded at 10%, 10.6%, 10.5% and 10.7%, respectively, similar to the porosity of control concrete, which was 10.6% at age of 90 days.

Table 2. Porosity of different concrete samples

Mix concrete	Porosity %		
	7 days	28 days	90 days
C0	15.6	11.7	10.6
CF10	14.5	10.6	10.4
CF20	17.6	11.3	10
CF30	20.1	11.7	10.5
CF40	21	12	10.2
CB10	14.6	10.2	10
CB20	16.8	11.8	10.6
CB30	19.8	12.5	10.5
CB40	20.8	12.6	10.7

3.2. Radon release and ^{226}Ra, ^{232}Th and ^{40}K concentrations in raw materials

Before measured the radon activity concentrations of concrete based on fly ashes and bottom ashes. It was important to assess radon activity concentrations of all components of concrete. The results of radon release and ^{226}Ra, ^{232}Th and ^{40}K concentrations in raw materials are depicted in Table 3.

Table 3. Activity of ^{226}Rn, ^{232}Th, ^{40}K and ^{222}Rn of materials used in concrete

Sample	**^{226}Rn (Bq.kg^{-1})**	**^{232}Th (Bq.kg^{-1})**	**^{40}K (Bq.kg^{-1})**	**^{222}Rn (Bq.m^{-3})**
Cement	33 ± 1	21 ± 2	245 ± 10	230±11
Sand	19 ± 3	18 ± 1	520 ± 5	200±10
Aggregate	22 ± 2	25± 3	330 ± 3	360± 34
CFA	122	96	316	286 ± 29.5
CBA	77	70	158	405 ± 34

The recorded values of radon release from cement, Sand and aggregates were 230 Bq/m^3, 200 Bq/m^3 and 360 Bq/m^3, respectively. As regard fly ashes and bottom ashes collected from TAQA Morocco thermal power plant. It was measured in previous study. The obtained results showed that the average value of radon release from fly ashes and bottom ashes were 286 Bq/m^3 and 405 Bq/m^3 respectively. The average values of activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in fly ashes were 122 Bq.kg^{-1}, 96 Bq.kg^{-1} and 316 Bq.kg^{-1} while the average values of activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in bottom ashes were 77 Bq.kg^{-1}, 70 Bq.kg^{-1} and 158 Bq.kg^{-1}.

3.3. Effect of fly ashes and bottom ashes incorporation in concrete on the release amount of radon

The results of radon release from concrete samples are listed in Table 4. It can be seen that radon release from concrete samples based on fly ashes ranged from 831.6 ± 16.5 Bq.m^{-3} to 885.4 ± 18.1 Bq.m^{-3}. While concrete samples containing bottom ashes. Values of radon release varied from 770.6 ± 12.8 Bq.m^{-3} to 710.3 ± 14.7 Bq.m^{-3}. However, radon release of control concrete was 808.4 ± 15.1 Bq.m^{-3}. In order to quantify the radiological impact of incorporation of exhalation rate of radon in different concrete were calculated. From Table 3. it can be observed that radon release from concrete CF-10, CF-20, CF-30 and CF-40 where higher than control concrete. The values of radon exhalation rate increased with the increase of fly ash level in concrete mixture. This finding can be attributed to the high radium-226 concentration of fly ash comparing to that of cement (See Table 4).

Table 4. Radon release, radon exhalation and radon emanation coefficient in concrete samples

Sample	**^{222}Rn (Bq/m^3)**	**Es (mBq/m^3)**	**E_M (mBq/m^3)**	**EF (%)**
C-0	808.4 ± 15.1	489.9 ± 9.4	23.3 ±1.1	5.4
CF-10	831.6 ± 16.5	504.0 ± 10.3	24 ±1.2	5.4
CF-20	860.4 ± 16.8	521.5 ± 10.5	24.8 ±2.1	6.0
CF-30	870.2 ± 17.4	536.6 ± 10.9	25.2 ±2.3	6.4
CF-40	885.4 ± 18.1	467.0 ± 11.3	25.6 ±2.3	6.7
CB-10	770.6 ± 12.8	467.0 ± 8	22.2 ±1.1	4.2
CB-20	756.1 ± 13.1	458.2 ± 8.2	21.8 ±1.3	3.8
CB-30	737.1 ± 13.8	446.7 ± 8.6	21.3 ±1.1	3.6
CB-40	710.3 ± 14.7	430.5 ± 9.2	20.5 ±1.1	3.4

As regard concrete samples containing bottom ashes. values of radon release were lower than radon release from control sample. From the obtained data. radon exhalation rate of concrete based on bottom ashes varied from 467.0 ± 11.3 to 430.5 ± 9.2 mBq/m^3. These values were lower than radon exhalation of control concrete which recorded a value of 489.9 ± 9.4 mBq/m^3. It can be observed that bottom ashes incorporation in concrete reduced the radon exhalation compared to radon exhalation of control concrete. This decreasing of radon exhalation from concrete with the increasing of bottom ashes level can be explained by the fact that bottom ashes used in concrete mixture was finer than fly ashes, which contributes to decrease porosity of concrete.

Table 5. The activity concentrations of ^{226}Ra. ^{232}Th and ^{40}K measured in concrete samples

Sample	Activity concentration (Bq kg^{-1})			Ra$_{eq}$
	^{226}Ra	^{232}Th	^{40}K	
C-0	25.9±14	21.1±10	236.9±34	74.32
CF-10	46.6±14	21.9±10	236.6±34	76.06

CF-20	48.8±15	20.5±13	204.4±36	69.89
CF-30	53.6±17	18.7±11	165.9±36	63.17
CF-40	58.1±12	20.1±13	184.8±35	66.10
CB-10	32.2±12	29.0±12	368.7±37	102.03
CB-20	36.7±13	35.0±10	412.0±34	116.52
CB-30	37.1±13	22.4±11	210.7±37	83.37
CB-40	40.6±13	20.0±11	182.4±36	79.28

The obtained data for radon emanation coefficient ranged from 5.4% for CF-10 to 6.7 for CF-40. It can be seen that radon emanation coefficient in concrete samples based on fly ashes increased with the increasing of fly ash content. While radon emanation coefficient of concrete samples containing bottom ashes ranged from 4.2 for CB-10 to 3.4 for CB-40. It seems that the increasing of bottom ashes content in concrete mixture decreased radon emanation coefficient

Since radon emanation in hardened concrete depends on different parameters like porosity and radium content. For this reason, the determination of activities radionuclides in hardened concrete was conducted. The obtained results of ^{226}Ra, ^{232}Th and ^{40}K concentrations are depicted in Table 5. It can be observed that ^{226}Ra concentration in both of concrete containing fly ashes and bottom ashes were higher compared to ^{226}Ra concentration in control concrete. However. values of ^{226}Ra concentration in concrete based on fly ashes were higher than ^{226}Ra concentration in concrete based on bottom ashes. This finding can be explained that ^{226}Ra concentration in fly ashes was 1.6 times higher than ^{226}Ra concentration in bottom ashes. The Ra_{eq} values in studied samples are well below the internationally accepted value 370 Bq.kg−1 set in the UNSCEAR report.

The recorded values of the radon emanation coefficient varied from 5.4% to 6.7 % for concrete samples containing fly ashes. Contrary results were obtained for concrete samples containing bottom ashes. It seems that radon emanation coefficient decreased with the increase of bottom ashes level.

Table 6. Radiological parameters calculated of concrete samples

	IA	IDR (nGyh^{-1})	H_{ex}	H_{in}	$\dot{D}$ (nGy/h)	$\dot{E_x}$	$\dot{E_{in}}$	IAED	EAED	LCR
C-0	0.13	66.00	0.20	0.27	34.59	0.04	0.17	20.37	0.3	$1.13*10^{-3}$
CF-10	0.13	67.43	0.21	0.28	35.35	0.04	0.17	20.96	0.3	$1.16*10^{-3}$
CF-20	0.12	61.74	0.19	0.26	32.38	0.04	0.16	21.68	0.3	$1.06*10^{-3}$
CF-30	0.12	55.60	0.17	0.23	29.14	0.04	0.14	21.93	0.3	$0.96*10^{-3}$
CF-40	0.12	58.17	0.18	0.24	30.53	0.04	0.15	22.31	0.3	$1.00*10^{-3}$
CB-10	0.16	91.00	0.28	0.36	47.75	0.06	0.23	19.42	0.4	$1.56*10^{-3}$
CB-20	0.17	103.42	0.31	0.41	54.37	0.07	0.27	19.05	0.5	$1.78*10^{-3}$
CB-30	0.18	73.80	0.23	0.32	38.54	0.05	0.19	18.57	0.4	$1.27*10^{-3}$
CB-40	0.18	70.29	0.21	0.31	36.61	0.04	0.18	17.90	0.3	$1.21*10^{-3}$

The results of radiological parameters estimated form concrete samples are listed in Table 6. It can be seemed that IA values estimated for concrete samples containing fly ashes were close to IA value of control sample. Whereas, for CB-10 CB-20 CB-30 and CB-40 concrete samples varied from 0.16 to 0.18. The obtained data of IA values were below the criterion of 1 corresponding to the activity concentration of 200 Bqm^{-3}.

As regard IDR values, it can be seen that estimated values of the concrete samples with fly ashes ranged from 58 to 67.43 nGy h^{-1}. For concrete samples made with bottom ashes, the IDR values ranged from 70.29 to 103.42 nGy h^{-1}. The IDR values are below the worldwide average indoor absorbed dose rate in air of 84 nGy h^{-1} given in the UNSEAR (2008) Report except of CB-10 and CB-20. The EAED values of concrete samples made with fly ashes and bottom ashes were closed to EAED value of control concrete. The EAED values of the samples ranged from 0.7 to 2.0 mSv with an average of 1.1 mSv. All samples meet the annual effective dose limit of 1 mSv according to the dose criteria for building materials recently recommended by the EU.

The LCR values for the concrete samples made with fly ashes varied from 0.96×10^{-4} to 1.16×10^{-3} while The LCR values for concrete samples made with bottom ashes varied from 1.21×10^{-3} to 1.78×10^{-3}.

Conclusion

The indoor air quality of buildings constructed with coal ash concrete was rigorously evaluated using a number of key radiological parameters, including radium equivalent activity, external and internal risk indices, indoor absorbed gamma dose rate and corresponding annual effective dose. The findings for these parameters demonstrated values that were consistent with the international recommendations on radiological safety.

In particular, the radium equivalent activity measured was found to be well below the established hazard thresholds, indicating a low contribution from the radionuclides present in the coal ash. The external and internal risk indices were both determined to be below 1, which indicates that there is no significant radiological risk to the occupants of the buildings. Furthermore, the indoor absorbed gamma dose rate and the annual effective dose were calculated and found to comply with established safety standards, thus ensuring minimum exposure to radiation.

Accordingly, this research indicates that there are no serious radiological hazards posed by using coal ash in concretes. The utilization of such concrete type during construction ensures safety for occupants against naturally occurring radionuclides.

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