Radiological Effects of Fly Ash as Concrete Additive: A Study in Vietnam

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Research Article

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Title page

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Radiological effects of fly ash as concrete additive:

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Abstract

Nowadays, fly ash is recycled to make more eco-friendly building materials and reduce landfill area of coal-fired power plant. However, the high amount of natural radionuclides contained in fly ash could potentially pose radiological risks to people living in buildings made from these materials. The results revealed that the ^{226}Ra, ^{232}Th and ^{40}K activities for the commonly used building material were in the range from 10.1 to 254.9 Bq kg^{-1}, from 16.6 to 176.9 Bq kg^{-1} and from 21.2 to 1240.3 Bq kg^{-1} and 569.1 Bq kg^{-1}, respectively: High gamma activity concentration for fly ash is due to the origin of fly ash and coal enrichment process of coal-fired power plant, in contrast, sand and stone samples which contain high radon concentration. Additional fly ash in concrete can increase or decrease the radioactivity of building materials, in which its variation depends on the percentage of the fly ash and matrix composition of the mixture. Even though the average indoor annual effective doses were lower than the upper limit, the total annual effective doses were slightly higher than the recommended dose of 2.4 mSv^{-1} due to the exposure of natural sources by UNSCEAR. From this study, radiological effects of fly ash samples as concrete additive in Viet Nam could be evaluated for any practical circumstances before they are used.

Keywords: Natural radioactivity; radiation exposure; concrete; fly ash; raw building material; coal-fired power plant; annual effective dose.

Introduction

All materials in the environment contain natural radionuclides with their various isotopes. Human is exposed by ionizing radiation about 2.4 mSv y^{-1} from these natural sources, in which, approximately about 1.0 mSv y^{-1} is due to the exposure of radon (UNSCEAR, 2000). Materials contain mainly natural radionuclides from the primary sources of ^{238}U series, ^{232}Th series and ^{40}K. The activity concentration of radionuclides in raw building materials greatly affect the annual effective dose due to the ionizing radiation. In ^{238}U series, ^{222}Rn is considered as the main factor of exposure. Radon atoms located within solid grains are unlikely to release into the atmosphere, owing to their very low diffusion coefficients in solids. However, if they are located in the interstitial space between grains, they may diffuse into the surface. Therefore, the release of radon from a residue repository to the atmosphere takes place by the following series of processes:

emanation, transport and exhalation (Ishimori et al., 2013). Due to its short half-life, indoor radon inhalation could potentially damage lung cells and consequently, cause lung cancer. Because of this radiological hazard, radon concentration needs to be monitored from building materials.

Nowadays, significant efforts are made for environmental protection in the field of construction. Higher buildings with closed rooms are built with ventilation and cooling for air circulation. Lighter, more eco-friendly fly ash recycled materials are utilized in construction. Economy, environment and technology could benefit from this utilization. However, these materials contain natural radionuclides to a certain extent that can release an amount of radiation and radon to the environment. Consequently, human's health could be affected due to the radiological effects of radiation and radon (Kobeissi et al., 2013; Hoffmann, 2018). Therefore, building materials made from industrial waste such as fly ash and brick and their practical application should be investigated, evaluated and subjected to different documents provided by IAEA – 474 (Ishimori et al., 2013 and ICRP, 2017). Many authors have developed different methods and techniques to determine the radioactivity released from raw building materials (Ali et al., 1996; Vanasundari et al. 2012; Solak et al., 2014; Asaduzzaman et al., 2015; Tuo et al., 2020). Radon concentration from building materials made from rock, fly ash were evaluated (Bossew, 2003; Kobeissi et al., 2011; Hoffmann, 2018). Furthermore, the annual effective doses due to the indoor radon exposure from building materials were calculated in different studies (Bruzzi et al., 1992; Le et al., 2011; Asaduzzaman et. al., 2015;

Hoffmann, 2018). Moreover, fly ash and bottom ash from coal-fired power plants are often used as a filler component in building materials as well as productions of ceramic and glass-ceramic, zeolite synthesis, therefore the radiological impacts on human due to fly ash and products from fly ash should be evaluated (Zacco et al., 2014; Asaduzzaman et al., 2015).

Now adays, the supplement of fly ash in concrete is a simple replacement approach with significant advantages: (i) Reducing heat of hydration, thus reducing thermal cracks and improving soundness of concrete; (ii) Improving impermeability and resistance of concrete against ingress of moisture and harmful gases, consequently increasing durability; (iii) Reducing weight-to-strength ratio of cement in concrete, hence reducing concrete cost (Temuujin et. al., 2019). Economy, environment and technology could benefit from building material, more eco-friendly and fly ash recycled materials, but the macroenvironment can create in such living area complex radioactivity surroundings, which human’s health could be affected due to the radiological effects. The careful choice of raw building material in construction should be noted to reduce risk of radiation exposure. Radioactivity in raw building material depends mainly on the origin of the material itself and consequently affects the effective dose to human. Therefore, safety assessment of building materials must be carried out before application in construction. Ho Chi Minh City, one of the major cities in Vietnam is currently thriving in many aspects of industrialization. Thus, a large number of building materials need to be supplied from nearby areas. However, there are problems in the management of building materials, especially in the control of radioactive content in the building materials, the lack of regular and consecutive assessments of radiation safety in the field of construction. Thus, raw building materials contain high radioactivity concentration could enter the market and cause radiological effects on human. In this study, we evaluated gamma radioactivity concentration, radon concentration and annual effective dose due to gamma and radon exposure from currently used building materials. The raw materials as soil, cement, sand, stone samples which were commonly used in the Viet Nam and their mixtures with fly ash of different percentage for concrete production were studied. Their potential radiological hazards to indoor workers in the standard room (CEN room) (CEN, 2017) made by the concrete samples which were made by these raw materials were then calculated. These are the absorbed dose, the annual effective dose from gamma and radon exposure. The data collected in this study could contribute to the international database of natural radionuclides in building materials.

Material and method

Description and processing of the sample

A total of 85 samples of raw building materials and soil have been studied. Soil samples were collected in different areas of Ho Chi Minh City. Cement, sand and stone samples were taken from local manufacturers and suppliers in Vietnam. Fly ash samples were taken from the landfill of thermal power plants, Vinh Tan, Vietnam. About 2 kg of each sample was collected. All samples were placed in polythene bags, labelled and transported to the laboratory for sample preparation and analysis.

The samples were then transported to the laboratory, dried at room temperature, crushed with a particle size less than 0.2 mm. Following that, samples were dried at 105^0C for 8 hours and packed into a cylinder beaker. Samples were sealed within 30 days to reach radioactive equilibrium between ^{226}Ra radionuclide and its daughters in uranium series. After this period, the samples were measured by a gamma spectrometry system using HPGe detector for 24 hours.

Activity analysis

The gamma spectrometer with the p-type HPGe detector GC3520 was used in this work. It has the nominal relative efficiency of 35% at 1332.5 keV and the energy resolution of 1.8 keV FWHM at 1332.5 keV energy peak of ^{60}Co. Its germanium crystal has a 62.2 mm diameter, a 50.1 mm height, a 7.5 mm diameter of core hole, a 23 mm depth, and a 1.5 mm thickness of aluminum window. Lead shield chamber is covered outside with a 100 mm layer of lead and 10 mm of steel. Inside, the 1 mm tin and 1.6 mm copper graded liner prevent interference by lead X rays. The system is operated by Lynx 32k MCA based on digital signal processor (DSP). The Lynx is controlled by Genie 2000 program of Canberra Industries. The ^{226}Ra activity concentration of the sample was determined by gamma-ray spectra from ^{214}Pb (295.2 keV and 351.9 keV) and ^{214}Bi (609.3 keV). The ^{232}Th activity concentration can be determined through ^{228}Ac (338.3 keV and 911.2 keV), ^{212}Pb (238.6 keV) and ^{208}Tl (583.2 keV and 2614.3 keV). The activity concentration of ^{40}K was determined directly by their own gamma-ray 1460.83

keV (ISO, 2007). Details of activity concentration calculation method can be found in Loan et al. (2018) and Ba et al. (2019).

Indoor dose due to radiation exposure for standard room

Indoor dose rate (D) (nGy h^{-1}) due to gamma radiation emitted from six surfaces of CEN model room (4 × 3 × 2.5) m^3 (CEN, 2017) was calculated using Eq. (1) (Ali et al., 1996):

$$D(\text{nGy h}^{-1}) = 0.922A_{Ra} + 1.096A_{Th} + 0.0806A_{K} \qquad (1)$$

Indoor annual effective dose (D_γ) (mSv.y^{-1}) due to gamma radiation was calculated using Eq. (2). with the dose conversion factor of 0.7 Sv Gy^{-1} for workers and indoor occupancy factor of 0.8 (Siotis et al. 1984; Sahu et al. 2016)

$$D_\gamma(\text{mSv y}^{-1}) = D\,(\text{nGy h}^{-1}) \times 8760\,(\text{h}) \times 0.8 \times 0.7\,(\text{Sv Gy}^{-1}) \times 10^{-6} \qquad (2)$$

The amount of radon available for transport to the surface was calculated using Eq. (3) (Siotis et al., 1984; Ishimori et al., 2013; Taylor - Lange et al., 2014; Sahu et al., 2016):

$$J = Q\,\lambda\,\rho\,f\,L_o \tanh\left(\frac{d}{L_o}\right) \qquad (3)$$

where, J is the radon exhalation rate (Bq m^{-2} s^{-1}), Q is the radium specific activity (Bq kg^{-1}), λ is the radon decay constant (2.1×10^{-6} s^{-1}), ρ is the construction density (assumed to be 2000 kg m^{-3}), f is the radon emanation coefficient (0.14) (Ishimori et al., 2013), d and L_o are the half-thickness of the building material (assumed to be 0.09) and the diffusion length in the concrete (assumed to be 0.2), respectively (Siotis et al., 1984; Taylor - Lange et al., 2014; Sahu et al., 2016).

The radon concentration in air is given by Eq. (4) (Siotis et al., 1984; Ishimori et al., 2013; Taylor - Lange et al., 2014; Sahu et al., 2016; Ba et. al. 2020).

$$C = \frac{J\,A}{V\,\mu} \tag{4}$$

where, C is the steady-state indoor radon concentration (Bq m^{-3}); A, V, and μ are the surface area of the concrete floor slab (m^2), house volume (m^3), and the air exchange rate (s^{-1}) (assumed 3600 s), respectively (Siotis et al., 1984). In this study, the CEN room with a dimension of (4 × 3 × 2.5) m^3 (CEN, 2017) was made of the same building material with a thickness of 20 cm and a density of 2350 kg cm^{-3} for all structures (Pepin, 2018).

The annual effective dose due to radon exposure was calculated using Eq. (5) (ICRP, 2014; ICRP, 2017).

$$E_{radon} = (C \times 0.4 \times K \times H) / (3700 \text{ Bq m}^{-3} \times 170 \text{ h}) \tag{5}$$

where E_{radon} is annual effective dose (mSv y^{-1}), C is radon concentration (Bq m^{-3}), K is dose conversion factor from Bq m^{-3} to mSv (10 mSv per working level month for occupational workers), 0.4 is exposure parameter, H is annual occupancy for workers (7000 hours),170 h is the exposure hours taken for working level month.

Results and discussion

Activity concentrations

The activity concentrations of naturally occurring radionuclides ^{226}Ra, ^{232}Th and ^{40}K in different samples of raw building materials were determined by gamma spectrometer using HPGe detector as shown in Table 1. The results revealed that the average representative ^{226}Ra activity was 48.8 Bq kg^{-1} in the range from 10.1 Bq kg^{-1} for *sand* to 254.9 Bq kg^{-1} for *stone*. The average activity of ^{232}Th was found to be 49.8 Bq kg^{-1} in the range from 16.6 Bq kg^{-1} for *soil* to 176.9 Bq kg^{-1} for *stone*. For ^{40}K, the radioactivity ranged from 21.2 Bq kg^{-1} for *soil* to 1240.3 Bq kg^{-1} for *stone* with an average activity of 569.1 Bq kg^{-1}. The radioactive mineral content in the building materials, as well as the geological, geochemical and geographical origins of the raw materials, could be taken into account for the variation of radioactivity among the building materials (Kobeissi et al., 2013). The average values of ^{226}Ra, ^{232}Th and ^{40}K activity in the studied samples were comparable with the world average values in UNSCEAR (50, 50 and 500 Bq kg^{-1}, respectively) (UNSCEAR, 1993).

On the other hand, for fly ash samples, the average activity concentrations of 77.4 Bq kg^{-1}, 91.7 Bq kg^{-1} and 956.2 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K were 1.5, 1.8 and 2.4 times higher, respectively than the world average values for building material. High value of concentration in fly ash sample could be considered as a potential radiological risk if fly ash is mixed with a high proportion in building materials. For this reason, an appropriate proportion of fly ash in concrete mixture needs to be calculated. Furthermore, the average activity concentrations of ^{226}Ra, ^{232}Th were still lower than the world average activity concentrations (200 Bq kg^{-1} and 200 Bq kg^{-1}, respectively) for fly ash. However, the average activity concentration of ^{40}K was higher two times than the world average of 500 Bq kg^{-1} for fly ash (UNSCEAR, 1982). The variation of radionuclide activity concentration is explained that radionuclide concentration in fly ash were related to the radionuclide concentration of the coal, the power station boiler conditions during the coal combustion and temperature of combustion (Temuujin et al., 2019). The results of activity concentration were found in good agreement with other studies (Asaduzzaman et al., 2015).

The average activity concentrations of ^{40}K in raw materials observed to be higher than those of ^{226}Ra and ^{232}Th, the average fraction values are 11.7 and 11.4. The highest average value of the ^{226}Ra and ^{232}Th activity concentrations were found to be in the fly ash (77.4 and 91.7 Bq kg^{-1}, respectively). Because, (i) fly ash is produced by coal with origins from fossilized organisms (mostly plants); (ii) fly ash were enriched due to the enrichment process of coal-fire power plant (Bhattacharyya et al., 2009). The highest of ^{40}K was found 1240.3 Bq kg^{-1} in stone sample.

Table 1: Activity concentrations of natural radionuclides in raw building materials

Source	**Samples (N)**	**Activity (Bq kg^{-1})**		
		^{226}Ra	**^{232}Th**	**^{40}K**
Fly ash	16	68.2 - 90.6(77.4)	58.1 - 128.5(91.7)	840.2 - 1124.3(956.2)
Soil	39	15.1 - 47.8(22.8)	16.6 - 64.6(28.6)	21.2 - 485.6(208.4)
Cement	10	33.54 - 77.5 (40.1)	26.3 - 36.2 (27.4)	93.6 - 328.9(253.3)

Sand	12	10.5 - 142.5 (46.7)	17.9 - 167.5 (49.9)	65.5 - 902.8 (607.0)
Stone	8	24.6 - 254.9(57.2)	30.1 - 176.9(51.5)	72.2 - 1240.3 (820.6)
Average	**-**	**10.5 - 254.9(48.8)**	**16.3 - 176.9(49.8)**	**21.2 - 1240.3 (269.1)**

Note: The symbol of 68.2 - 90.6 (77. 4) means Min - Max (Average).

For raw building material samples, the average activity of ^{226}Ra, ^{232}Th and ^{40}K radioactivity in this study are in the range of the obtained values from other studies (in see Fig 1) (UNSCEAR, 1993, Le et al.; 2011; Asaduzzaman et al., 2015; Raghu et al., 2017; Tuo et al., 2020). In details, Le et al. (2011) reported the average activity of 213 samples of different types of building materials collected in Vietnam market were 52.1, 55.7 and 593.5 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. In the study of Asaduzzaman et al. (2015), ^{226}Ra activity concentration of cement, red sand and fly ash were 60.5, 49.4 and 117.8 Bq kg^{-1}, respectively at Bangladeshi dwellings. The values of ^{226}Ra, ^{232}Th and ^{40}K activity concentration were 69.9, 53.2 and 318.6 Bq kg^{-1} for samples collected in India (Raghu et al., 2017) and 74, 72 and 495 Bq kg^{-1} for building materials available in NorthEastern Poland (Zalewski et al., 2001); The average activity of raw materials in this research were lower than Tuo et al. (2020) (127.8, 114.8 and 701.5 Bq kg^{-1}, respectively). The differences in activity in research works are due to the differences between the origins and number of investigated raw building materials samples.

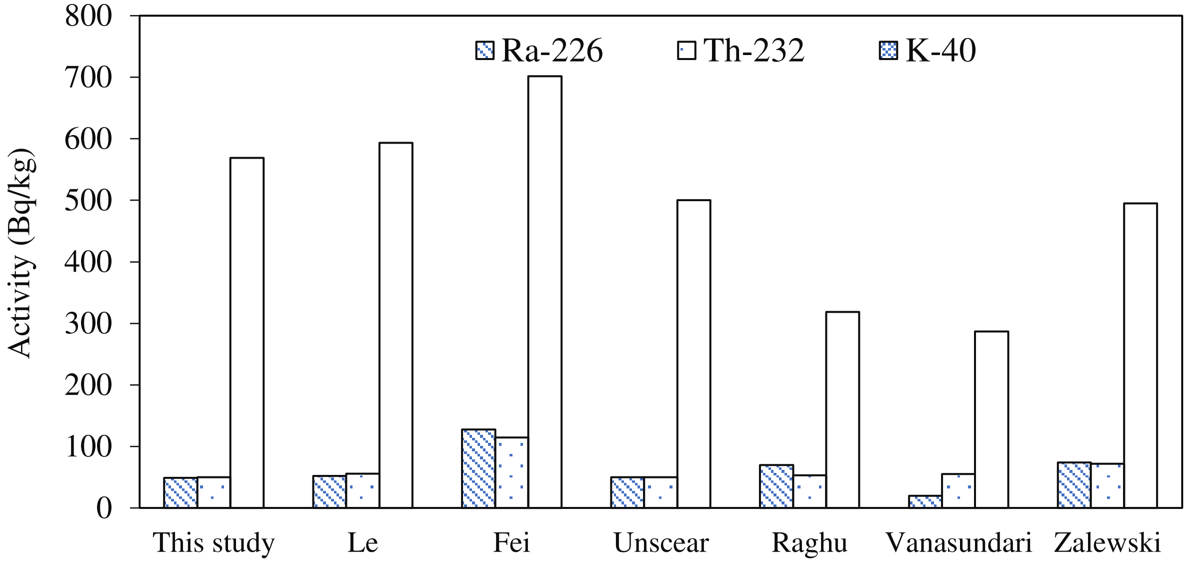

Fig 1. Comparison of activity concentrations for raw building materials in different studies.

Indoor annual effective doses for raw building materials

Possible radiological hazards to human health due to radiation exposure from the raw building material samples were assessed and shown in Table 2. The estimated gamma absorbed dose rates ranged from 69.2 nGy h^{-1} for soil to 248.9 nGy h^{-1} for fly ash with an average value of 145.5 nGy h^{-1}. The results were found to be similar to the work of Vanasundari et al. (2012) and Tuo et al. (2020) and 2.5 times higher than the value of 84 nGy h^{-1} provided by UNSCEAR (2000). Similarly, the indoor annual effective dose due to gamma exposure from the studied raw building material samples ranged from 0.34 to 1.22 mSv y^{-1} with an average value of 0.71 mSv y^{-1}. This average value was found to be higher than 0.41 mSv y^{-1} for indoor radiation sources of terrestrial radionuclides evaluated by UNSCEAR (2000).

In the case of internal exposure by radon, the results indicated that the radon exhalation rate and radon concentration for all raw building material samples were in the range from 0.7 to 8.0 Bq m^{-2} h^{-1} with the average value of 4.2 Bq m^{-2} h^{-1} and from 0.3 to 3.2 Bq m^{-3} with the average value of 1.7 Bq m^{-3}, respectively. The highest radon concentrations were found in soil and stone samples. Because the radon emanation fraction of soil and stone samples in raw material were higher than the other samples (see Table 3). The radon concentrations were in good agreement with previous studies of Siotis et al. (1984) (1.2 Bq m^{-3}) and Taylor - Lange et al. (2014) (1.2 - 5 Bq m^{-3}). The radon concentration contributions in the observed samples were lower than the maximum value of 20 Bq m^{-3} for indoor radon from raw building material (Hoffmann, 2018).

Table 2 also summarizes the annual radon effective doses for the raw building materials. The dose values varied from 0.01 to 0.14 mSv y^{-1}, with the average value of 0.07 mSv y^{-1}. This average value is lower than the worldwide average of 1.15 mSv y^{-1} (UNSCEAR, 2000).

Living or working in a room, people will be exposed to gamma, alpha and radon radiation exposure. Therefore, the total annual effective dose (D_γ, E_{radon}) needs to be calculated. The results indicated the total annual effective dose for CEN room made of the studied raw building material samples was in the range from 0.69 mSv y^{-1} (for cement) to 2.21 mSv y^{-1} (for stone) with an average value of 1.44 mSv y^{-1}.

Table 2: The average indoor annual effective dose for the raw building materials.

Source	$E_{manation}$	D (nGy h^{-1})	D_γ (mSv y^{-1})	J (Bq m^{-2} h^{-1})	C (Bq m^{-3})	E_{radon} (mSv y^{-1})
Fly ash	0.03[a]	248.9	0.31	3.0	1.2	0.05
Soil	0.2[b]	69.2	0.08	5.8	2.3	0.10
Cement	0.013[c]	87.4	0.11	0.7	0.3	0.01
Sand	0.059[c]	146.7	0.18	3.5	1.4	0.06
Stone	0.11[c]	175.3	0.22	8.0	3.2	0.14
Min	**-**	**69.2**	**0.08**	**0.7**	**0.3**	0.01
Max	**-**	**248.9**	**0.31**	**8.0**	**3.2**	0.14
Average	**-**	**145.5**	**0.18**	**4.2**	**1.7**	0.07

[a]Ba et al., 2020,[b]Kovler et al., 2017;[c] Bossew, 2003.

The indoor annual effective doses for concrete containing fly ash

Fly ash is coal combustion products from coal-fired power plants. It is used often for building purposes. It may be used to be an addition to concrete or raw component in cement production. Generally, fly ash in the cement can be used either as cement replacement or sand replacement with proportion depending on chemical and physical properties of fly ash. The proportion is from 6% to 55% in the European Union according to EN197-1:2011 standard (Labrincha et al., 2017). In this study, the high-quality concrete was used, the composition is 23.1 % cement, 27.4 % sand and 49.5%

stone. It was assumed that concrete was made with different combinations of fly ash and other material (% fly ash + % material of the raw building material (cement, sand and stone) = constant)). The percentage of fly ash in the raw building materials was varied from 0 to 20% in this work.

Table 3 indicated that the gamma absorbed dose rate ranged from 147.2 (for concrete with 0% fly ash) to 179.5 nGy h^{-1} (for concrete with 20% fly ash replacement material of cement). When fly ash was added to the concrete sample from 0 to 20%, the average gamma absorbed dose rate increased by 22%. However, the absorbed dose rate was reduced in the concrete samples with fly ash replacement material of sand and stone. Because the radioactivities in the fly ash material were higher than those in the cement and lower than those in the sand and stone samples (see Table 1). Similarly, the average indoor annual effective doses for all types of the studied concrete samples ranged from 0.72 to 0.88 mSv y^{-1}. The maximum value of indoor annual effective doses estimated of all type concrete samples in this study were found to be higher than the recommended limit of 0.3 mSv y^{-1} for building material but still lower than the dose limit of 1 mSv y^{-1} (according to EC, 1999).

The lowest radon concentration of 2.3 Bq m^{-3} was found for the concrete with 0% fly ash, whereas the maximum value of 19.0 Bq m^{-3} for the concrete sample using 20% fly ash as replacement material of cement increased by 8.2 times. The maximum radon concentration was lower than the maximum indoor radon concentration of 20 Bq m^{-3} from raw building material in the study of Hoffmann (2018). In addition, the average annual effective dose by radon exposure for all types of studied concrete samples ranged from 0.12 to 1.01 mSv y^{-1} which are lower than the worldwide average value of 1.15 mSv y^{-1} (UNSCEAR, 2000). The results show that the increase of the annual effective dose due to radon for concrete mixture containing from 0 to 20% fly ash replacement material of the raw building material is negligible.

The total annual effective dose due to gamma, alpha and radon exposure during time of living in the CEN room made by these concrete samples ranged from 1.59 to 9.69 mSv y^{-1}. The high value of the total annual effective dose for each mixture is related to the high percentage of fly ash in the mixture. They depend on type of material which is replaced by fly ash in concrete mixture as follows: cement > sand > stone. The highest average of 2.88 mSv y^{-1} for the concrete containing 20% fly ash as replacement material of cement increases 12% compared with the average value of 2.56 mSv y^{-1} for concrete containing 0% of fly ash. The results showed that the exposure dose from concrete increased with the addition of fly ash into the sample. Noted that the average annual effective doses for all types of observed concrete samples were higher than the worldwide average value of 2.4 mSv y^{-1}for the natural sources (UNSCEAR, 2000).

Table 3: The indoor annual effective doses for fly ash containing concrete samples

Fly ash	**0.0%**	**5.0%**	**10.0%**	**15.0%**	**20.0%**
Cement	**23.1%**	**18.1%**	**13.1%**	**8.1%**	**3.1%**
D (nGy h^{-1})	(55.5-399.)147.2	(61.8-408.7)155.2	(68.1-417.5)163	(74.55-426.4)171.4	(80.8-435.3)179.5

Dγ (mSv y-1)	(0.27-1.96)0.72	(0.30-2.00)0.76	(0.33-2.05)0.80	(0.37-2.09)0.84	(0.40-2.14)0.88
J (Bq m^{-2} h^{-1})	(5.8-46.7)12.9	(6.3-46.9)13.3	(6.7-47.1)13.8	(7.2-47.2)14.3	(7.6-47.4)14.8
C (Bq m^{-3})	(2.3-18.7)5.14	(2.5-18.7)5.33	(2.7-18.8)5.52	(2.9-18.9)5.71	(3.0-19.0)5.90
E_{radon} (mSv y^{-1})	(0.12-1.00)0.27	(0.13-1.00)0.28	(0.14-1.01)0.29	(0.15-1.01)0.31	(0.16-1.01)0.32
Sand	**27.4%**	**22.4%**	**17.4%**	**12.4%**	**7.4%**
D (nGy h^{-1})	(55.5-399)147.2	(63.4-398.1)152.3	(71.4-392.5)157.4	(79.4-388.9)162.5	(87.4-385.2)167.6
Dγ (mSv y^{-1})	(0.27-1.96)0.72	(0.30-1.94)0.75	(0.34-1.93)0.77	(0.37-1.91)0.80	(0.40-1.89)0.82
J (Bq m^{-2} h^{-1})	(5.8-46.7)12.9	(6.6-46.1)13.2	(7.3-45.4)13.6	(8.0-0.44.7)14.0	(8.7-44.1)14.4
C (Bq m^{-3})	(2.3-18.7)5.14	(2.3-18.4)5.30	(2.9-18.2)5.45	(3.2-17.9)5.61	(3.5-17.6)5.77
E_{radon} (mSv y^{-1})	(0.12-1.00)0.27	(0.14-0.98)0.28	(0.16-0.97)0.29	(0.17-0.96)0.30	(0.19-0.94)0.31
Stone	**49.5%**	**44.5%**	**39.5%**	**34.5%**	**29.5%**
D (nGy h^{-1})	(55.5-399.8)147.2	(62.1-389.1)150.8	(68.7-379.4)154.5	(75.4-367.7)158.2	(82.0-357.0)161.9
Dγ (mSv y^{-1})	(0.27-1.96)0.72	(0.30-1.91)0.74	(0.34-1.86)0.76	(0.37-1.80)0.78	(0.40-1.75)0.79
J (Bq m^{-2} h^{-1})	(5.8-46.7)12.9	(6.4-44.6)13.1	(6.9-42.3)13.4	(7.5-40.4)13.6	(8.0-38.3)13.9
C (Bq m^{-3})	(2.3-18.7)5.14	(2.6-17.9)5.24	(2.8-17.0)5.35	(3.0-16.2)5.45	(3.2-15.3)5.55
E_{radon} (mSv y^{-1})	(0.12-1.00)0.27	(0.14-0.95)0.28	(0.15-0.91)0.28	(0.16-0.86)0.29	(0.17-0.82)0.30

In general, the radioactivity in concrete depends on the composition of the raw building material in concrete products. Some raw building materials used in construction contain high concentrations of ^{226}Ra, ^{40}K and ^{232}Th depending on the nature of the material origin and composition. People might be exposed from gamma, radon and alpha rays by living in a room containing high concentration of radionuclides. Not only the annual effective dose for each radiation exposure from gamma, alpha, radon needs to be estimated, but also the total annual effective dose due to summing impacts from them should also be calculated to evaluate accurately radiological impacts to human.

Conclusion

In this study, the average activity concentration of radionuclides were found to be highest in fly ash sample. The radioactivity in fly ash were also higher than the corresponding values of building materials about 1.5, 1.8 and 2.4 times for ^{226}Ra, ^{232}Th and ^{40}K, respectively. Consequently, people could be exposed to the highest absorbed dose rate of 248.9 nGy h^{-1} and indoor annual effective dose of 0.31 mSv $^{-1}$ in a room made from fly ash. However, due to the high radon emanation coefficient of stone, radon is a radiological hazard to people living in a room made from stone. More specifically, the radon exhalation rate, radon concentration, annual effective dose and equivalent effective dose due to radon exposure by stone are the highest among other materials, 8.0 Bq m^{-2} h^{-1}, 3.2 Bq m^{-3}, 0.07 mSv y^{-1} and 1.58 mSv y^{-1}, respectively. Hence, appropriate proportion between fly ash and other raw building materials in the concrete mixture need to be evaluated. The results indicated that the indoor annual effective doses were in the range from 0.72 to 0.88 mSv y^{-}1, below the limitation of 1 mSv^{-1}for all combinations of fly ash and other raw materials. However, the total effective doses were slightly higher than the recommended dose of 2.4 mSv $^{-1}$ for natural sources by UNSCEAR, from 2.56 to 2.88 mSv $^{-1}$. Therefore, the utilization of the studied building materials needs to be cautiously monitored in practical circumstances to ensure radiation safety for residents.

Close investigations are needed shortly to study the relationship between material structure and radioactivity in raw building material for maintaining high health standards.

Declarations

Authors Contributions:

Vu Ngoc Ba, Bui Ngoc Thien, Truong Thi Hong Loan designed the ideas for the study, planned for the experiment, derived the models and analysed the data, wrote the manuscript. The others participated for sampling, did a prepation of samples for analysis. All authors provided critical feedback, discussion and helped shape the research, analysis for the manuscript. All authors read and approved the final manuscript.

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