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REVIEW PAPER

Natural radioactivity in soils around mega coal-fired cement factory in Nigeria and its implications on human health and environment

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Abstract

Cement industry is one of the anthropogenic activities capable of mobilizing and propagating naturally occurring radioactive materials (NORM) in human environment to levels that may become detrimental to human health. A pilot survey of radiological implications of a mega cement factory (AshakaCem), north-eastern Nigeria, on human health and the environment was conducted using high-purity germanium (HPGe) gamma-ray spectrometric technique. Average activity concentrations for ^{226}Ra, ^{232}Th and ^{40}K in the soil samples were found to be 7.41 ± 0.44, 16.27 ± 0.84 and 196.11 ± 9.08 Bq kg^{-1}, respectively. These values were lower than the world mean values documented by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Calculated radiation hazard parameters associated with the studied soil samples showed mean air absorbed dose rate of 21.43 nGy h^{-1}, with attendant annual effective dose of 0.03 mSv y^{-1} and average excess lifetime cancer risk of 0.9×10^{-4}. Statistical analysis revealed strong relationship between calculated hazard parameters and the investigated natural radionuclides in the studied soil samples and confirmed that ^{226}Ra, ^{232}Th and ^{40}K were major contributors to radiation dose. Results obtained from this study fall within acceptable limits provided for human safety and environmental protection. Thus, the operations of AshakaCem did not provide any significant radiological risk to workers nor pose any immediate radiological threat to the environment.

Keywords Natural radioactivity · Gamma dose rate · Excess lifetime cancer risk · Statistical analysis · AshakaCem · North-eastern Nigeria

Introduction

Although natural radiation is an integral part of human environment, anthropogenic activities have over time greatly influenced the dispersion of naturally occurring radioactive materials (NORM) in the environment to such level that could be detrimental to human health. Naturally occurring radioactive nuclides are found in all geological formations including rocks and soils at concentrations that are determined by the prevailing geographical and geological conditions (Isinkaye et al. 2015; Manigandan and Shekar 2014). Gamma emissions from perennial primordial radioactive nuclides of ^{40}K and those of ^{232}Th and ^{238}U decay chains which are inherent components of soil environment, rocks and earth crust (Absar et al. 2014; UNSCEAR 2000) are the primary sources of human exposure to radiation externally. Additionally, significant radioactive contamination of soils may come from human activities that concentrate radionuclides to levels above normal environmental background. Evaluation of soil radioactivity is therefore crucial to assessing any changes in background radiation levels of a given environment due to anthropogenic activities and to evaluating the radiation risk to the surrounding population in the light of international safety guidelines.

Cement manufacturing industry and associated stages of cement production release significant radioactive pollutants into the atmosphere, thereby enhancing human exposure. It is therefore important that the radiological impacts of cement

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industry be continually monitored to detect possible radiological perturbations in the environment in order to provide effective radiation safety measures for humans (Gbadebo and Amos 2010; Senthilkumar et al. 2013).

Several studies have evaluated the radiological impacts of cement industries around the world (Addo et al. 2014; Gbadebo and Amos 2010; Hussain and Ali 2014; Isinkaye et al. 2015). No data has, however, been reported on the radiological implications of Ashaka Cement factory (AshakaCem) in north-eastern Nigeria. This survey is therefore a pilot study to measure specific activities of ^{40}K, ^{232}Th and ^{226}Ra in soil around AshakaCem and to evaluate the external gamma dose delivered to the public as a result of industrial activities. Data from this study will form reference baseline for subsequent radiological monitoring of the factory.

Materials and methods

Sampling and sample packaging

AshakaCem is located at 10° 55′ 49″ N, and 11° 28′ 34″ E in Bajoga, Funakaye local government area, Gombe, north-eastern Nigeria (Fig. 1). It is one of Nigeria's leading cement-producing industries with foreseeable impact on the immediate environment. Twenty representative soil samples of AshakaCem environment were collected at random for analysis using a hand auger. Each sample representing a particular sampling point consists of 4 sub-samples collected within a 50-m radius circle around the sampling point and carefully bulked together thoroughly. The samples, each about 1.00 ± 0.1 kg, were screened of any foreign matters including stones and shrubs. They were then carefully packed in neatly labelled polyethylene bags and transported to the laboratory for analysis. Radiological analysis of the samples was carried out at the radiation laboratory of Physics Department, University of Malaya, Malaysia.

All samples were openly exposed to dry in air for 72 h at room temperature in the laboratory to completely rid them of their moisture content, after which they were crushed into fine powder and sieved using a 0.2-mm mesh in order to obtain accurate sample homogenisation and to bring the samples to the required uniform grain size for radiometric analysis. A total mass of 478 ± 1.0 g of each sample was neatly packaged into each radiation beaker which was carefully labelled and sealed tightly. Sealed samples were stored for 30 days, to allow attainment of secular equilibrium between the long-lived parent, ^{226}Ra from the ^{238}U decay chain with its short-lived radioactive progeny ^{214}Bi ($T_{1/2}$ = 19.9 m), ^{214}Pb ($T_{1/2}$ = 26.8 m) and ^{222}Rn ($T_{1/2}$ = 3.82 days), similarly with ^{228}Ra from the ^{232}Th decay chain with its short-lived progeny (Amin et al. 2013a, b; Asaduzzaman et al. 2014).

Activity concentration measurement

Gamma spectroscopic analysis of ^{40}K, ^{232}Th and ^{226}Ra activities in the samples was carried out by means of a P-type coaxial ORTEC, GEM-25 HPGe gamma ray detector with resolution of 1.67 keV (FWHM) at 1332 keV peak of ^{60}Co. The detector whose relative efficiency is 28.2% is adequately shielded with thick lead to suppress any external gamma-ray background interference (Asaduzzaman et al. 2014; Jibiri et al. 2014; Kolo et al. 2015) was connected to a PC AII multi-channel analyser for data acquisition. Calibration of the detector was done before analysis using a multi-nuclide gamma ray source whose original activity is 5.109 μCi, obtained from the Isotope Products Laboratories, Valencia, CA, 91355, USA. The cylindrical multi-nuclide gamma-ray calibration source with homogenously distributed activity in the same container geometry as the samples contains the following nuclides: ^{109}Cd (88.040 keV), ^{57}Co (122.061 keV), ^{203}Hg (279.195 keV), ^{113}Sn (391.698 keV), ^{85}Sr (514.007 keV), ^{137}Cs (661.657 keV), ^{88}Y (898.042 keV, 1836.063 keV) and ^{60}Co (1173.22 keV, 1332.492 keV). Photo-peak efficiency calibration curve as a function of photon energy used in the present study is shown in Fig. 2.

Minimum detectable activity (MDA) at 95% confidence level for the detector was calculated from the equation (Khandaker et al. 2012):

$$\mathrm{MDA}\left(\mathrm{Bq\ kg^{-1}}\right) = \frac{K_\alpha \sqrt{N_B}}{\eta(E) P_\gamma T_c M} \quad (1)$$

where the background (CPS) is shown as N_B; photo-peak efficiency as $\eta(E)$; probability of gamma emission as P_γ; coverage factor as K_α, given to be 1.645; the counting time(s) as T_c and mass of sample as M (kg).

Energy of the gamma-ray regions from which net activities of nuclides of interest were calculated, together with their individual MDA, is shown in Table 1.

Activity concentrations of primordial radionuclides ^{226}Ra and ^{232}Th were determined indirectly from the activities of their short-lived decay products by assuming secular equilibrium to have been achieved between the parents and progeny within the period of storage. Thus, weighted average gamma peaks of ^{214}Pb (351.93 keV, 35.6%) and ^{214}Bi (609.32 keV, 45.49%) were used to compute the activity concentration of ^{226}Ra (Khandaker et al. 2019a, b), while activity concentration of ^{232}Th was computed from the weighted average gamma peaks of ^{212}Pb (238.63 keV, 46.6%), ^{228}Ac (911.21 keV, 29%) and ^{208}Tl (583.19 keV, 85.0%) as seen in Table 1 (bold gamma lines). The single characteristic gamma line of

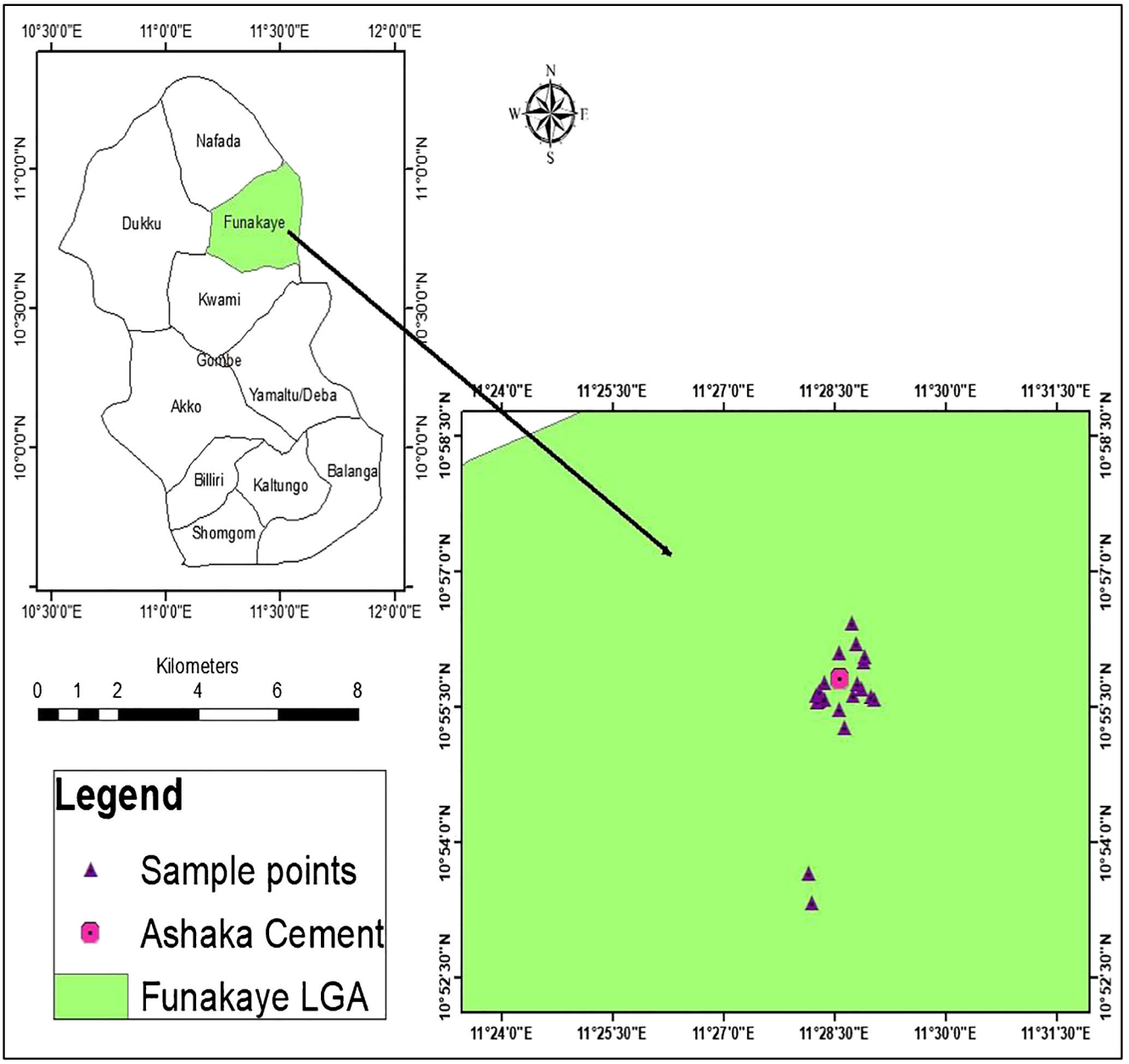

Fig. 1 Location map of Gombe, showing the study area (source: Remote Sensing and GIS Laboratory, FUTMinna, 2019)

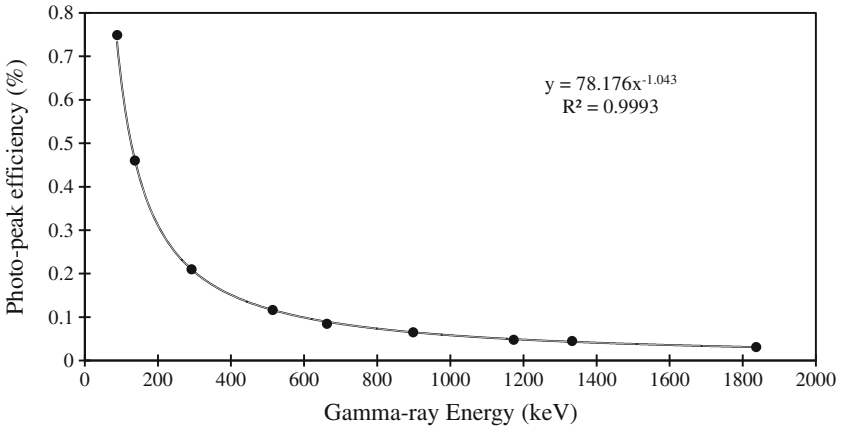

Fig. 2 Efficiency calibration curve of the HPGe gamma-ray detector

Table 1 Decay data for radionuclides with their respective gamma lines and MDA used for activity determination

Nuclides of interest	Detected nuclides	Half-life	Decay mode (%)	γ-ray energy, E_γ (keV)	γ-ray intensity, I_γ (%)	Sources/origin	MDA (Bq kg^{-1})
^{238}U (^{226}Ra)	^{214}Pb	26.80 min	β^- (100)	295.22	18.42	^{238}U (^{226}Ra) series	0.36
				351.93	35.6	^{238}U (^{226}Ra) series	0.55
	^{214}Bi	19.90 min	α (0.02); β^- (99.98)	**609.32**	45.49	^{238}U (^{226}Ra) series	0.99
^{232}Th	^{228}Ac	6.15 h	$\alpha + \beta^-$ (100)	**911.21**	29	^{232}Th series	0.75
				968.97	17.4		0.69
	^{212}Pb	10.64 h	β^- (100)	**238.63**	43.60	^{232}Th (^{228}Ra) series	0.58
	^{208}Tl	3.053 min	β^- (100)	**583.187**	85	^{232}Th (^{228}Ra) series	0.11
^{40}K	^{40}K	1.248×10^9 y	EC (10.72); β^- (89.28)	**1460.822**	10.66	Primordial/terrestrial	9.12

^{40}K (1460.822-keV, 10.66%) was used to assess its activity concentration.

The counting time for each sample was 86,400 s. Obtained net counts less the background were used to compute specific activities, A (Bq kg^{-1}) of ^{40}K, ^{232}Th and ^{226}Ra using the following equation (Khandaker et al. 2012; Kolo et al. 2015):

$$A\left(\text{Bq kg}^{-1}\right) = \frac{\text{CPS} \times 1000}{\varepsilon_\gamma \times I_\gamma \times W} \tag{2}$$

where CPS is net count rate, $\varepsilon_\gamma(E)$ is the energy efficiency of detector at each gamma peak and I_γ is the intensity of gamma rays and sample mass, W in grams.

Radiological parameters

Human exposure to radiation is quantified using some assessment criteria (Jibiri et al. 2014). These include the following.

Radium equivalent activity

Radium equivalent activity (Ra_{eq}) is a radiation index that takes into account the inhomogeneous distribution of natural radionuclides in any environmental sample (Beretka and Mathew 1985; UNSCEAR 2000). It is a weighted activity sum of hazards associated with ^{40}K, ^{232}Th and ^{226}Ra. It is calculated with the presumption that 13, 0.7 and 1 Bq kg^{-1} of ^{40}K, ^{232}Th and ^{226}Ra results in equal external gamma dose rate (Kolo et al. 2015; Ravisankar et al. 2014). Ra_{eq} was calculated from the equation:

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

where A_{Ra}, A_{Th} and A_K, are specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively in becquerels per kilogram.

Absorbed dose rate

External dose rate in air (D_R), 1 m above the ground from primordial radionuclides ^{40}K, ^{232}Th and ^{226}Ra in soils was computed using the formula given by UNSCEAR (2008):

$$D_R\left(\text{nGy h}^{-1}\right) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \tag{4}$$

where A_{Ra}, A_{Th} and A_K assume the same definition as earlier stated.

Annual effective dose equivalent

Annual effective dose equivalent (AEDE) is a measure of exposure risk associated with absorbed dose. To effectively compute AEDE from absorbed dose rate, UNSCEAR (2000) provided two conversion coefficients: 0.70 Sv Gy^{-1} which transforms absorbed dose rate in air to effective dose and outdoor occupancy factor of 0.2, which suggests that almost 80% of individual's time per day is spent indoors. AEDE in millisieverts per year was computed from the equation given by Khandaker et al. (2012) and Ravisankar et al. (2014):

$$\text{AEDE}\left(\text{mSv y}^{-1}\right) = D_R\left(\text{nGy h}^{-1}\right) \times 8760\left(\text{h y}^{-1}\right) \times 0.7 \times 0.2 \times 10^{-6} \tag{5}$$

Annual gonadal dose equivalent

Critical organs in human body which include the reproductive organs, bone marrows, and bone cells receive a measure of dose from radiation exposure (Morsy et al. 2012). Annual gonadal dose equivalent (AGDE) which represents the dose received by the gonads was calculated from the formula (Chandrasekaran et al. 2014; Ravisankar et al. 2014):

$$\text{AGDE}\left(\mu\text{Sv y}^{-1}\right) = 3.09A_{Ra} + 4.18A_{Th} + 0.314A_K \tag{6}$$

where A_{Ra}, A_{Th} and A_K assume their respective definitions as earlier stated.

Activity utilization index

Activity utilization index (AUI) was calculated using the specific activities of ^{40}K, ^{232}Th and ^{226}Ra in the studied soils. AUI was computed from the equation (Ramasamy et al. 2011; Ravisankar et al. 2014):

$$\mathrm{AUI} = \left(\frac{A_{Ra}}{50\mathrm{Bq/kg}}\right) f_U + \left(\frac{A_{Th}}{50\mathrm{Bq/kg}}\right) f_{Th} + \left(\frac{A_K}{500\mathrm{Bq/kg}}\right) f_K \quad (7)$$

where $f_{U,}$ f_{Th} and f_K which have the numerical values of 0.462, 0.604 and 0.041, respectively, represent fragmentary supplements of ^{226}Ra, ^{232}Th and ^{40}K, to the entire gamma dose (Chandrasekaran et al. 2014). Representative specific activities of ^{40}K, ^{232}Th and ^{226}Ra, in soils, are 500, 50 and 50 Bq kg^{-1}, respectively (NEA-OECD 1979).

Hazard indices

External hazard index (H_{ex}) and the internal hazard index (H_{in}) represent radiation hazards incurred from external and internal exposure, respectively, to gamma dose from ^{226}Ra, ^{232}Th and ^{40}K in soils. H_{ex} was computed following the formula (UNSCEAR 2000):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (8)$$

Similarly, the vulnerability of internal organs to radon and its short-lived daughters was measured by the internal hazard index, H_{in} (UNSCEAR 2000):

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (9)$$

UNSCEAR (2000) provides a precautionary safety limit of unity for above indexes.

Representative gamma index

Representative gamma index ($I_{\gamma r}$) defines conformity of environmental samples to dose standards set for building materials (Jibiri et al. 2014). $I_{\gamma r}$ was computed from the equation (Jibiri et al. 2014; NEA-OECD 1979):

$$I_{\gamma r} = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \quad (10)$$

To satisfy the given dose criteria, $I_{\gamma r}$ must be ≤ 1, which corresponds to an annual effective dose of ≤ 1 mSv (Manigandan and Shekar 2014; Ravisankar et al. 2014):

Excess lifetime cancer risk

Excess lifetime cancer risk (ELCR) defines likelihood of cancer occurrence from radiation exposure in the studied soils. It was calculated from the estimated AEDE using the equation (Ravisankar et al. 2014: Taskin et al. 2009):

$$\mathrm{ELCR} = \mathrm{AEDE} \times \mathrm{DL} \times \mathrm{RF} \quad (11)$$

where DL is the lifetime of 70 years, and risk factor, RF, for stochastic effects in any given population is given to be $0.05Sv^{-1}$ (Taskin et al. 2009).

Results and discussion

Activity concentration and radiation hazard indices

Location coordinates of the sampling points together with the measured activities of ^{226}Ra, ^{232}Th and ^{40}K (in Bq kg^{-1}) in investigated soils are presented in Table 2. Specific activity of ^{226}Ra varied from 3.68 ± 0.31 to 11.49 ± 0.61 Bq kg^{-1} with an average value of 7.41 ± 0.44 Bq kg^{-1}. Activity concentrations of ^{232}Th and ^{40}K ranged from 9.15 ± 0.54 to 35.93 ± 1.73 Bq kg^{-1} and 74.77 ± 3.61 to 252.77 ± 11.71 Bq kg^{-1}, respectively, with mean values of 16.27 ± 0.84 and 196.11 ± 9.08 Bq kg^{-1} in sequence. Disparities observed in specific activities may be the result of the chemical compositions, physical characteristics and geochemical properties of the radioactive nuclides along with their individual contents in soils of the study area (El Mamoney and Khater 2004: Ravisankar et al. 2014). Results for specific activities of primordial radionuclides obtained in this study were lower than those of similar studies reported from different countries as seen in Table 3. They were also lower than world mean values reported by UNSCEAR (2000) for soils.

Radiation dose parameters and hazard indices were calculated from Eqs. (3–11) and the results presented in Table 2. Computed Ra_{eq} ranged between 22.52 and 79.94 Bq kg^{-1}, with the mean value of 45.77 Bq kg^{-1} found to be below safety limit of 370 Bq kg^{-1} (UNSCEAR 2000). Furthermore, D_R at 1 m above the ground recorded a mean value of 21.43 nGy h^{-1}, with a complementary AEDE mean value of 0.03 mSv y^{-1} as seen in Table 4. These values are significantly lower than the respective world averages of 57 nGy h^{-1} and 0.07 mSv y^{-1} for external exposure (UNSCEAR 2000).

Table 2 Location coordinates; activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K; dose and radiation hazard indices of soil samples around AshakaCem

Sample ID	Coordinates		Activity concentrations (Bq kg^{-1})				Radiological dose			Radiation hazard indices (≤ 1)				ELCR (× 10^{-3})
	Longitude	Latitude	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	D_R (nGy h^{-1})	AEDE (mSv y^{-1})	AGDE (μSv y^{-1})	AUI	H_{ex}	H_{in}	$I_{\gamma r}$	
ASS 01	10° 56′ 06″	11° 28′ 33″	8.83 ± 0.42	15.63 ± 0.81	216.28 ± 10.01	47.83	22.54	0.03	160.52	0.29	0.13	0.15	0.36	0.10
ASS 02	10° 55′ 46″	11° 28′ 21″	7.02 ± 0.41	15.47 ± 0.80	174.92 ± 8.13	42.62	19.88	0.02	141.31	0.27	0.12	0.13	0.32	0.08
ASS 03	10° 55′ 38″	11° 28′ 44″	7.42 ± 0.41	15.66 ± 0.81	192.34 ± 8.90	44.63	20.91	0.03	148.79	0.27	0.12	0.14	0.33	0.09
ASS 04	10° 55′ 35″	11° 28′ 21″	6.48 ± 0.43	13.89 ± 0.71	222.87 ± 10.30	43.51	20.68	0.03	148.08	0.25	0.12	0.14	0.33	0.09
ASS 05	10° 55′ 37″	11° 28′ 59″	5.68 ± 0.32	11.47 ± 0.62	189.20 ± 8.73	36.64	17.44	0.02	124.88	0.21	0.10	0.11	0.28	0.07
ASS 06	10° 55′ 35″	11° 29′ 01″	7.05 ± 0.42	15.47 ± 0.73	180.71 ± 8.31	43.08	20.13	0.02	143.18	0.27	0.12	0.14	0.32	0.09
ASS 07	10° 55′ 28″	11° 28′ 33″	5.22 ± 0.33	11.74 ± 0.62	95.32 ± 4.42	29.34	13.48	0.02	95.12	0.20	0.08	0.09	0.22	0.06
ASS 08	10° 55′ 16″	11° 28′ 37″	3.68 ± 0.31	9.15 ± 0.54	74.77 ± 3.61	22.52	10.35	0.01	73.10	0.15	0.06	0.07	0.17	0.04
ASS 09	10° 55′ 34″	11° 28′ 17″	6.74 ± 0.41	15.16 ± 0.81	157.76 ± 7.31	40.56	18.85	0.02	133.72	0.26	0.11	0.13	0.30	0.08
ASS 10	10° 55′ 33″	11° 28′ 15″	5.93 ± 0.44	12.68 ± 0.61	168.90 ± 7.80	37.07	17.44	0.02	124.35	0.22	0.10	0.12	0.28	0.07
ASS 11	10° 55′ 38″	11° 28′ 14″	7.38 ± 0.43	16.07 ± 0.80	191.03 ± 8.80	45.07	21.08	0.03	149.96	0.28	0.12	0.14	0.34	0.09
ASS 12	10° 55′ 40″	11° 28′ 17″	9.00 ± 0.51	19.17 ± 1.03	233.31 ± 10.81	54.38	25.47	0.03	181.20	0.33	0.15	0.17	0.41	0.11
ASS 13	10° 55′ 42″	11°^{0} 28′ 51″	8.73 ± 0.50	17.70 ± 0.91	245.57 ± 11.32	52.96	24.97	0.03	178.09	0.31	0.14	0.17	0.40	0.11
ASS 14	10° 55′ 45″	11° 28′ 48″	7.53 ± 0.41	14.63 ± 0.82	193.86 ± 9.01	43.37	20.40	0.02	145.27	0.26	0.12	0.14	0.33	0.09
ASS 15	10° 56′ 00″	11° 28′ 53″	8.35 ± 0.52	18.14 ± 0.92	252.77 ± 11.71	53.77	25.36	0.03	181.03	0.32	0.15	0.17	0.41	0.11
ASS 16	10° 56′ 03″	11° 28′ 54″	11.49 ± 0.61	35.93 ± 1.73	221.74 ± 10.33	79.94	36.26	0.04	255.32	0.56	0.22	0.25	0.58	0.15
ASS 17	10° 56′ 12″	11° 28′ 47″	6.47 ± 0.41	15.36 ± 0.81	203.35 ± 9.42	44.09	20.75	0.03	148.05	0.26	0.12	0.14	0.33	0.09
ASS 18	10° 56′ 26″	11° 28′ 43″	9.57 ± 0.52	19.40 ± 1.01	248.00 ± 11.51	56.40	26.48	0.03	188.52	0.34	0.15	0.18	0.42	0.11
ASS 19	10° 53′ 39″	11° 28′ 08″	8.12 ± 0.52	16.55 ± 0.80	229.91 ± 10.61	49.49	23.33	0.03	166.46	0.29	0.13	0.16	0.37	0.10
ASS 20	10° 53′ 20″	11° 28′ 11″	7.53 ± 0.43	16.09 ± 0.81	229.54 ± 10.60	48.21	22.77	0.03	162.60	0.28	0.13	0.15	0.36	0.10
Min			3.68 ± 0.31	9.15 ± 0.54	74.77 ± 3.61	22.52	10.35	0.01	73.10	0.15	0.06	0.07	0.17	0.04
Max			11.49 ± 0.61	35.93 ± 1.73	252.77 ± 11.71	79.94	36.26	0.04	255.32	0.56	0.22	0.25	0.58	0.15
Mean			7.41 ± 0.44	16.27 ± 0 .84	196.11 ± 9.08	45.77	21.43	0.03	152.48	0.28	0.12	0.14	0.34	0.09

Table 3 Specific activities of natural radionuclides of the present study compared with world average and those from different countries of the world

Location	Activity concentration (Bq kg^{-1})			References
	^{226}Ra	^{232}Th	^{40}K	
South China	225	257	1571	Liu et al. (2015)
Nigeria (North Central)	28.1	31.4	257.6	Isinkaye et al. (2015)
India (east coast, Tamilnadu)	3.67	37.23	387.17	Ravisankar et al. (2014)
Kufa, Najaf city	50.12	39.55	941.25	Hussain and Ali (2014)
Malaysia (Kapar)	86.7	74.3	297.3	Amin et al. (2013a, b)
Spain	39	43	445	Charro and Pena (2013)
Xi'an, China	36.1	51.1	733.9	Lu et al. (2013)
Nigeria (Southwest)	7.92	8.62	17.45	Gbadebo and Amos (2010)
Nigeria (Northeast)	7.41	16.27	196.11	Present work
World average	35	30	400	UNSCEAR (2000)

All computed values for the hazard indices (AUI, H_{ex}, H_{in} and $I_{\gamma r}$) are below unity, which corresponds to an annual effective dose ≤ 1 mSv (Ravisankar et al. 2014). Additionally, calculated average for ELCR was 0.9×10^{-4}, which is lower than the world mean values of 0.29×10^{-3} documented by UNSCEAR (2000) for normal soils. The values were also below safety limit of 0.05 set by the International Commission for Radiological Protection for low-level radiations.

Generally, gamma dose delivered to the public and factory workers in particular due to AshakaCem operations was within the range reported for similar studies around the world (Table 4). The results also indicated a very negligible risk of occurrence of cancer among the population.

Statistical analysis

Statistical analysis for characteristics of the radionuclide was performed using the basic statistical software: the Statistical Program for Social Science (SPSS 22.0). Descriptive statistical data for the assessed radiation parameters in soil samples around AshakaCem showed that data variability of radionuclides in the studied soil samples demonstrates normal distribution sequence according to Anderson-Darling normality test ($p \geq 0.05$), as reflected by the frequency distribution histograms in Fig. 3.

Pearson's correlation analysis

Calculated linear Pearson correlation coefficients at alpha testing level of $p < 0.05$ among radiological parameters for soils around AshakaCem are shown in Table 5. Very strong positive relationship exists between ^{226}Ra and ^{232}Th ($r = +0.87$), which can be attributed to their common origin and natural coexistence (Tanasković et al. 2012). Computed radiological parameters were very strongly correlated with one another ($r \geq +0.79$) and positively correlated ($r \geq +0.60$) with ^{226}Ra, ^{232}Th and ^{40}K. This relationship indicated that ^{40}K, ^{232}Th and ^{226}Ra were principally responsible for gamma emission in the vicinity of AshakaCem.

Cluster analysis (CA)

Different parameters of a particular system can be grouped into clusters on the basis of identical features, using cluster

Table 4 Radiological hazard factors of the present study compared with other reported values around the world

Location	Ra_{eq} (Bq kg^{-1})	D_R (nGy h^{-1})	AEDE (mSv y^{-1})	AGDE (μSv y^{-1})	ELCR (10^{-3})	References
India (east coast, Tamilnadu)	84.57	41.7	0.051	282	0.18	Ravisankar et al. (2014)
Malaysia (Kuantan, Pahang)	24.92	11.16	0.014	77.58	0.05	Kolo et al. (2015)
Saudi Arabia	68.1	35.2	0.043	–	0.09	El-Taher and Al-Zahrani (2014)
India (Western Ghats)	208	91.54		–	0.39	Manigandan and Shekar (2014)
Xi'an, China	165.7	78.9	0.097	–	–	Lu et al. (2013)
Nigeria (Northeast)	45.77	21.43	0.03	152.48	0.09	Present work

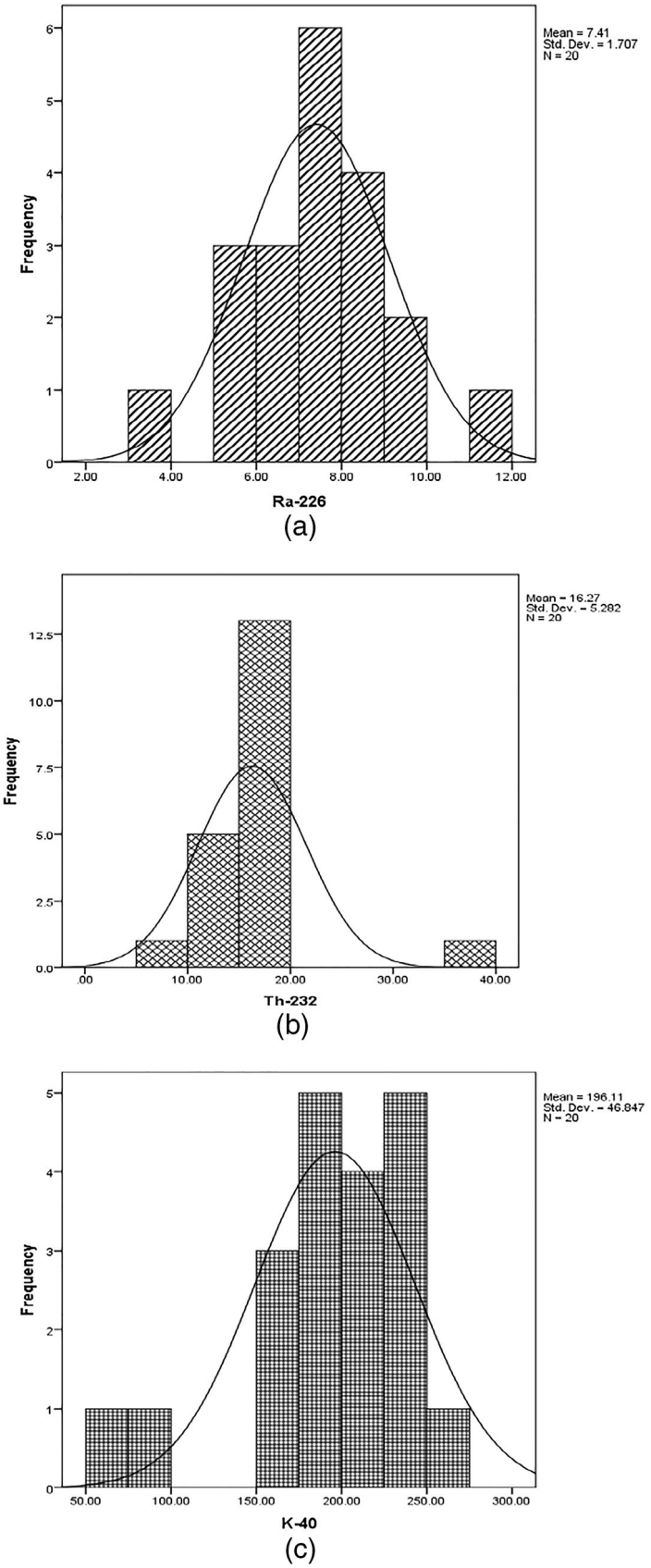

Fig. 3 Frequency distribution histograms of (**a**) ^{226}Ra, (**b**) ^{232}Th and (**c**) ^{40}K

Table 5 Pearson's correlation matrix between radioactive variables of soil samples around AshakaCem

Variables	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	D_R	AEDE	AGDE	AUI	H_{ex}	H_{in}	$I_{\gamma r}$	ELCR
^{226}Ra	1.00											
^{232}Th	0.87	1.00										
^{40}K	0.78	0.51	1.00									
Ra_{eq}	0.96	0.94	0.76	1.00								
D_R	0.96	0.93	0.80	1.00	1.00							
AEDE	0.83	0.75	0.79	0.86	0.87	1.00						
AGDE	0.96	0.92	0.81	1.00	1.00	0.87	1.00					
AUI	0.92	0.99	0.60	0.97	0.96	0.79	0.96	1.00				
H_{ex}	0.95	0.95	0.75	1.00	0.99	0.84	0.99	0.98	1.00			
H_{in}	0.96	0.93	0.78	1.00	1.00	0.86	1.00	0.97	0.99	1.00		
$I_{\gamma r}$	0.96	0.93	0.79	1.00	1.00	0.87	1.00	0.96	1.00	1.00	1.00	
ELCR	0.97	0.89	0.82	0.99	0.99	0.89	0.99	0.94	0.98	0.99	0.99	1.00

analysis technique (Chandrasekaran et al. 2014; Sivakumar et al. 2014). Each cluster is distinctively different from another cluster. Cluster separations with respect to the widest separation between any two identical parameters give the measure of their similarity. Cluster analysis was performed on the radiological parameters for soil samples around AshakaCem in which the Euclidean distance between them was evaluated using average linkage method. The obtained dendrogram is presented in Fig. 2. Primordial radionuclides together with the calculated radiological parameters were grouped into 2 statistically distinct clusters as seen in the dendrogram (Fig. 4). Ra_{eq}, D_R, AEDE, AUI, H_{ex}, H_{in}, $I_{\gamma r}$ and ELCR were grouped in cluster I together with ^{226}Ra and ^{232}Th. Cluster II consists of AGDE linked together with ^{40}K, at high Euclidean distance. Cluster I indicated that all the assessed radiological variables were principally dependent upon ^{226}Ra and ^{232}Th activity concentrations in the studied soils. This result agrees with other results by Chen et al. (2001) and Sivakumar et al. (2014). Annual gonadal dose equivalent on the other hand was primarily due to ^{40}K content in soil samples around AshakaCem as depicted in cluster II.

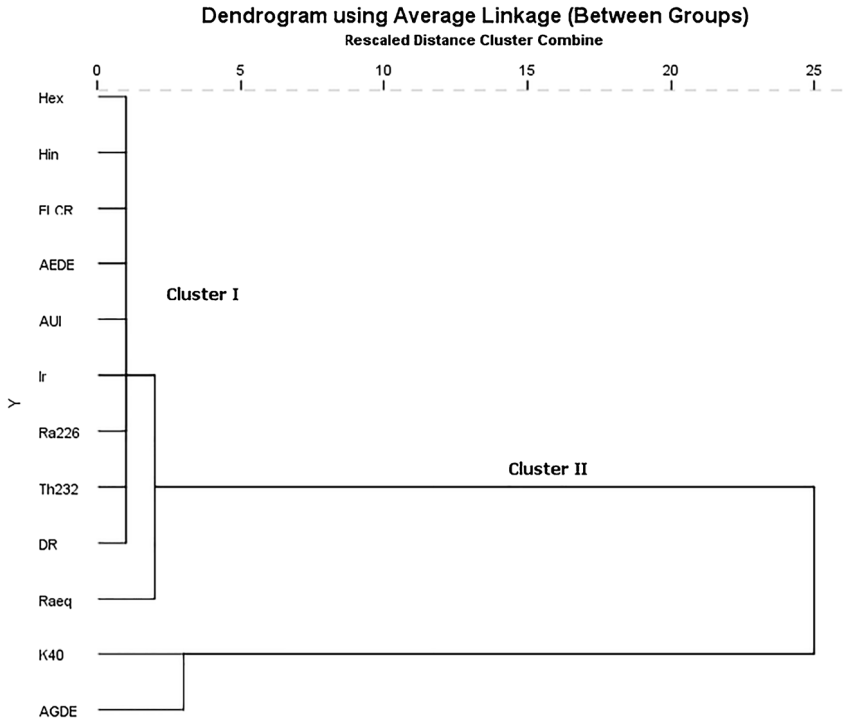

Fig. 4 Dendrogram showing the clustering of radiological parameters

Conclusion

Soil samples around Ashaka Cement Factory, Gombe, north-eastern Nigeria, were investigated for their radionuclide concentrations. Radiological hazard indices were computed from specific activities of ^{40}K, ^{232}Th and ^{226}Ra in the soils in order to evaluate radiological impacts of AshakaCem on the factory workers and the public. The results reflected normal radiation background trend around the factory. Estimated hazard parameters were below safety limits for occupational exposure prescribed by the international safety standards. It is therefore concluded from this study that AshakaCem operations pose insignificant radiation impacts on human health and the environment. There is therefore no serious deleterious exposure that could demand any urgent intervention from the radiation protection perspective. Prevailing administrative policies during this preliminary survey could not permit radiological measurements inside the factory. Measurements of radon-related exposures are, however, recommended as part of the overall environmental impact assessment of industrial sites in future studies. It is also important to note that cement production at AshakaCem is continuous; thus, there is the possibility of accumulation of NORM in the environment after long period of operation. This calls for continuous monitoring of environmental background radiation in the vicinity of AshakaCem and for implementing policies that will keep radiation dose delivered to factory workers and general public as low as reasonably achievable (ALARA).

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