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ARTICLE

Assessment of natural radioactivity levels and the associated radiological hazards in some building materials from Mayo-Kebbi region, Chad

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Abstract – In order to assess the levels of natural radioactivity and the associated radiological hazards in some building materials of the Mayo-Kebbi region (Chad), a total of nineteen samples were collected on the field. Using a high resolution γ-ray spectrometry system, the activity concentrations of radium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K) in these samples have been determined. The measured average activity concentrations range from $0.56 \pm 0.37\,\mathrm{Bq\,kg^{-1}}$ to $435 \pm 7\,\mathrm{Bq\,kg^{-1}}$, $1.3 \pm 0.6\,\mathrm{Bq\,kg^{-1}}$ to $50.6 \pm 1.1\,\mathrm{Bq\,kg^{-1}}$ and $4.3 \pm 2.0\,\mathrm{Bq\,kg^{-1}}$ to $840 \pm 9\,\mathrm{Bq\,kg^{-1}}$, for ^{226}Ra, ^{232}Th and ^{40}K, respectively. The highest ^{226}Ra average activities is found in soil brick samples of Zabili. The highest mean value of ^{232}Th and ^{40}K concentrations are found in soil brick samples of Madajang. The activity concentration and the radium equivalent activity (Ra_{eq}) have been compared to other studies done elsewhere in the world. Their average values are lower than most of those of countries with which the comparison has been made. Were also evaluated, the external radiation hazard index, the internal radiation hazard index, the indoor air absorbed dose rate, the outdoor air absorbed dose rate, the activity utilization index, the annual effective dose, the annual gonadal dose equivalent, the representative level index, as well as, the excess lifetime cancer risk. In accordance with the criterion of the Organization for Economic Cooperation and Development, our results show that soil brick samples of Zabili and Madajang increases the risk of radiation exposure, thereby the possibility of developing cancer by people living in this environment. Based on these findings, brick samples from Zabili and Madajang are not recommended for construction purposes. All other sample materials have properties that are acceptable for use as building materials in terms of radiation hazard.

Keywords: building materials / gamma-ray spectrometry / natural radioactivity / radiation hazards / excess lifetime cancer risk

1 Introduction

All building materials contain radionuclides of natural origin and are considered to be the main sources for the radiation exposures of individuals living in dwellings. The use of materials with elevated radioactivity in building construction can increase the indoor exposure to ionizing radiation. In recent years, the study of radioactivity has attracted increasing interest in various building materials in European American, Asian, Indian and some African countries. Results are available online (Ackers *et al.*, 1984; Aders *et al.*, 1985;

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Beretka and Mathew, 1985; Ettenhuber and Lehmann, 1986; Pinnock, 1991; Tufail *et al.*, 1992; Malanca *et al.*, 1993; Hayumbu *et al.*, 1995; Bou-Rabee and Bem, 1996; Ahmad *et al.*, 1997; Khatibeh *et al.*, 1997; Ahmed and Hussein, 1998; Mantazul *et al.*, 1998; Alam *et al.*, 1999; Ibrahim, 1999; Amrani and Tahtat, 2001; Rizzo *et al.*, 2001; Stoulos *et al.*, 2003; Ademola and Farai, 2005; Dabayneh, 2007; Ngachin *et al.*, 2007; Brigido Flores *et al.*, 2008; Faheem and Mujahid, 2008; Turhan *et al.*, 2008; Cosma *et al.*, 2009; Mavi and Akkurt, 2010; Baykara and Karatepe, 2011; El-Taher, 2012; Ravisankar *et al.*, 2012; Xinwei *et al.*, 2012; El-Mageed *et al.*, 2014; Raghu *et al.*, 2015; Li *et al.*, 2016). Unfortunately, no studies have been conducted to assess the level of radioactivity in building materials in Chad. Thus, Chad does not have standards or guidelines for the maximum level of radioactivity in building materials. However, a study carried out in 1970 and funded by the United Nations Development Programme (UNDP) with the support of experts from the International Atomic Energy Agency (IAEA) revealed the existence of radioactive and toxic heavy metals in Mayo-Kebbi region (Oyamta *et al.*, 2013). Boreholes carried out in the soil and subsoil have proven the existence of uranium (U), chromium (Cr), nickel (Ni) and copper (Cu). A cement plant was built in the studied area, gold mining is still done by craftsmen, the prospecting of uranium and oil was intensified. Small-scale mining of lime by craftsmen, gravel and laterite is sustained. Thus, naturally occurring radioactive materials (NORM) measurements in construction materials in Chad have become an imperative. They will contribute to the development of safety standards for the health protection of the population and workers, and will allow the development of national guidelines used for providing recommendations, for the use and management of raw building materials.

As reported by the United Nations Scientific Committee on the effects of atomic radiation (UNSCEAR) (UNSCEAR, 2000), the worldwide average value for outdoor gamma absorbed dose rate in air due to terrestrial sources is 54 $nGy\,h^{-1}$ and absorbed dose rate in air inside homes is usually higher than outside (~20% on average, but sometimes much more) due to the contribution of construction materials. Natural radionuclides in building materials contribute to radiation exposure in two ways; external and internal exposure. External exposure comes mostly from direct gamma radiation emitted from the decay of radionuclides, of the uranium ^{238}U series, thorium ^{232}Th series and potassium ^{40}K. In the ^{238}U series, the decay chain segment starting from radium ^{226}Ra is radiologically the most important and, therefore, reference is often made to ^{226}Ra instead of ^{238}U. The internal exposure is due to alpha particles resulting from the decay of radon ^{222}Rn and its progeny. Radon is a chemically inert gas which is colorless, odorless, and highly radioactive. When radon is inhaled, the alpha particles dose is delivered directly to the bronchial tissue, creating a potential for radiogenic lung cancer. Taking in account that people spend more than 80% of their time indoors, the duration of exposure to internal and external radiation from building materials is extended.

In this work, a high purity germanium detector (HPGe) was used to measure the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in various building materials (cement, sand, gravel, and soil bricks) collected in the Mayo-Kebbi region (Fig. 1). The results were used to assess the potential radiological risk associated with the building materials by evaluating the radium equivalent activity (Ra_{eq}), the external radiation hazard index (H_{ex}), the internal radiation hazard index (H_{in}), the indoor air absorbed dose rate (D_{in}), the outdoor air absorbed dose rate (D_{out}), the activity utilization index (AUI), the annual effective dose E, the annual gonadal dose equivalent (AGDE), the representative level index (RLI), as well as, the excess lifetime cancer risk (ELCR). The activity concentrations and radium equivalent activity were compared to other studies done elsewhere in the world. Other results were compared to the global average value established by the United Nations Scientific Committee on the effects of atomic radiation (UNSCEAR, 1977, 1988, 1993, 2000, 2010). We also checked whether some results meet the criteria of the Organization for Economic Cooperation and Development (OECD).

For the first time, data will be available on the levels of radioactivity in samples of building materials collected in Chad. These data will be stored in the national database of the Chadian Radiation Protection and Nuclear Safety Agency, and will serve as the baseline level for natural radionuclides in the study area and will contribute to the establishment of a radiological map of the whole country. The recommendations mentioned in the conclusion will allow the Chadian government to regulate the use of construction materials in the study area.

2 Materials and methods

2.1 Study area

The region of Mayo-Kebbi Ouest is one of the 23 regions of Chad, and its capital is Pala (09°21′ 50.721″N, 14°54′34.864″E). It covers an area of 12,479 km^2 and had 564,470 inhabitants in 2009 (INSEED, 2009). This region has a long history of mineral prospecting and mining. A cement plant was built there, the exploitation of gold is artisanal, and the prospection of uranium and oil has been intensified. Artisanal mining of lime, gravel and laterite is supported. These mining activities are performed in a disordered way, and without respecting the international standards (ISO/TC 82/SC 7) that can help minimize the potential long-term damage from mining activities, thus enhancing the quality of life of residents living in a mining area. Our research covers the three departments of the region.

2.2 Sampling and conditioning

According to the June 2013 final report of the Third Survey of Consumption and the Informal Sector in Chad (ECOSIT3, 2013), 82.4% Chadian households lives in dwellings whose walls are made of traditional materials or unsustainable. 57.7% of households lives in dwellings with soil bricks, made of mud kneaded with straw and water and called “banco”. 24.7% of households lives in dwellings with straw walls. These proportions are even higher, in areas such as Mayo-Kebbi which are very far from the capital of the country. Only 9.3% of households occupy housing, with walls in semi hard. Households living in dwellings with hard walls construction (stone / blockwork or concrete / cement) are rare and represent only 2.5%. A wealthy family will add cement to the exterior of a finished wall, protecting it from erosion and ensuring its

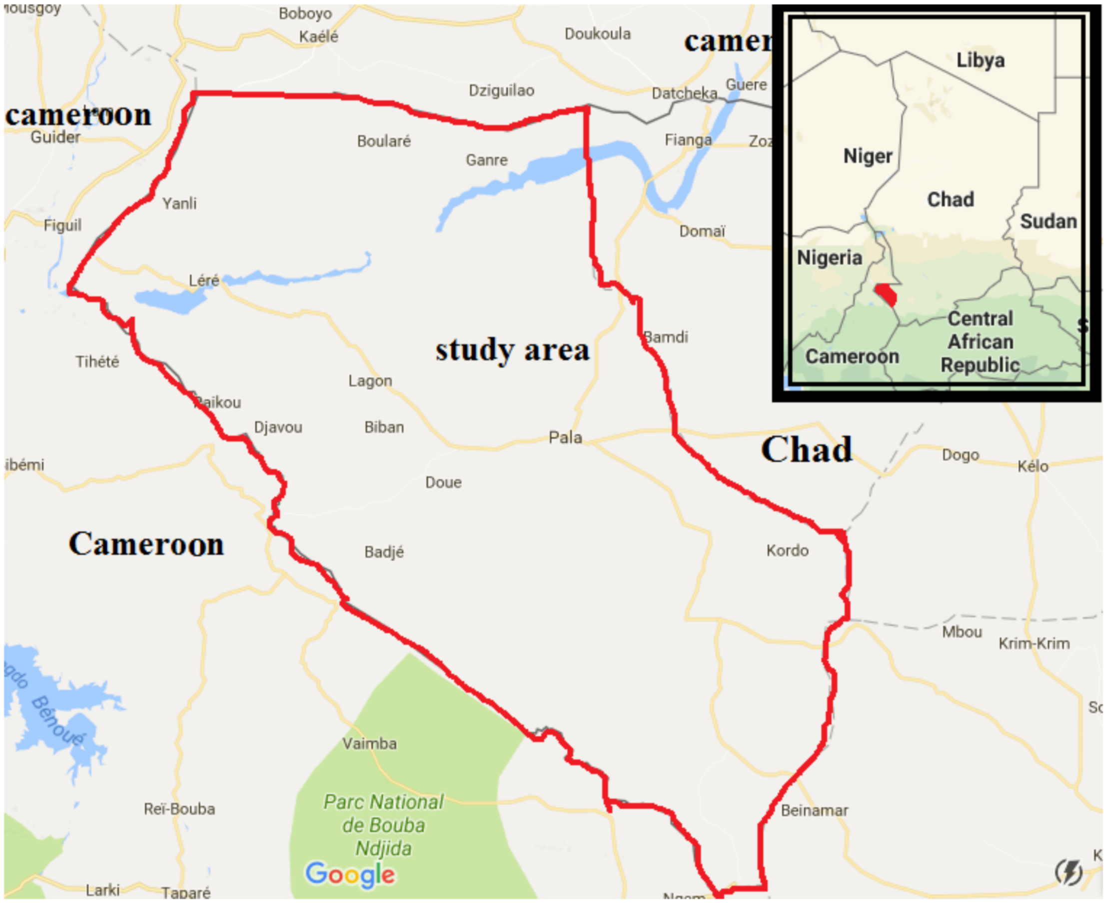

Figure 1. Map showing the location of Mayo-Kebbi Ouest region (provided by Google Map).

Table 1. Sampling sites.

Site	Zabili	Madajang	Gamboké	Bamdi	Rong	Yapala	Tagobo-foulbe	Pala	Léré	Binder	Cement plant
Number of samples collected	1	2	2	1	1	2	1	2	4	1	2
Type of sample taken	Soil bricks	Soil bricks	Soil bricks	Soil bricks	Soil bricks	Soil bricks	Soil bricks	Gravel and sand	Gravel and Sand	Soil bricks	Cement
Sampling place	Houses near mining sites	Houses near mining sites	Houses near mining sites	Houses near mining sites	Houses near mining sites	Houses near mining sites	Houses near mining sites	Pala pond	Léré lake	Houses near mining sites	Cement plant

strength. 91.8% of dwellings occupied by households have clay floors. Few households occupy dwellings whose floor is concrete, cement or tile (6.6%). These data from ECOSIT3 show that the most commonly used building materials in Chad in general and in Mayo-Kebbi in particular, classified in descending order of their use are: soil bricks (banco), gravel, sand, straw and cement.

A total of 19 samples from four types of building materials (soil bricks, gravel, sand, and cement), which are representative of the building materials of the region were collected to measure activity concentrations of ^{238}U, ^{232}Th and ^{40}K. These sites are displayed in Table 1.

Soil bricks samples were taken from inhabited houses. What we call one soil bricks sample, is in fact a mixture of soil taken from five different houses separated from one another by a distance of at least 300 m. Thus, the 11 samples of studied soil bricks, were collected in 55 different houses, covering the entire research area. In each house, the procedure was as follows: soil was taken from the floor and from the four walls of the house. For the floor, a square of 1 meter of side was drawn on the ground. At the middle of a square, as at each corner, was dug a vertical hole of about 5 cm deep and at the bottom of each hole, a handful of soil was taken. For the walls, a brick was randomly located on each side of the wall about 1 meter above the ground, in the middle of the brick, a horizontal hole about 5 cm deep was dug and a handful of earth was taken from the bottom of the hole. Then, we closed the holes with the mud collected in the vicinity of the house.

Samples of sand and gravel were taken from large heaps of sand and gravel stock for sale, near the pond of Pala, and Lake of Léré, from where they were extracted. These two sites provide the largest quantity of sand and gravel used in the study area for the construction of houses. The cement was taken directly from the manufacturing plant at the bagging point.The cement plant is the only plant in Chad. It provides most of the cement used in the area for building construction.

Samples were packed on-site, in polythene bags and correctly catalogued, tagged and coded according to the type of sample and the location of the sampling site. The samples were brought to the sample preparation Unit of the Nuclear Technology Section, Institute of Geological and Mining Research in Yaoundé, Cameroon, where they were dried at 90 °C in an oven during 24 hours, and then they were crushed and sieved to obtain a fine powder with grain size less than 1 mm. The cement did not undergo this treatment, because it was already in the form of a powder at the moment of collection. The powders thus obtained were sealed in plastic bags and transported to iThemba LABS, in South Africa, where they were placed again in an oven heated at 105 °C for 48 hours to completely remove moisture. Then they were cooled in a moisture-free atmosphere, weighed and stored in 100 mL plastic polyethylene cylindrical containers. The containers were hermetically sealed for 4 weeks to prevent the escape of ^{222}Rn gas and ^{220}Rn. This allows ^{226}Ra and ^{232}Th and their short-lived daughters to reach secular equilibrium.

2.3 Gamma spectrometry detection system and efficiency calibration

The measurements described in this study were carried out using a High Purity Germanium (HPGe) detector in a low-background setup located at the Environmental radioactivity laboratory (ERL) of iThemba LABS in South Africa. The detector is basically a p-type GC4520 Canberra coaxial detector. It has a relative efficiency of 45% and a nominal resolution of 2.2 keV FWHM at 1332 keV, and a Peak to Compton Ratio (P/C) of 54. Its endcap diameter is 83 mm. A digital electronic card (DSA) was used to couple the detection system to a PC equipped with Genie 2000 analysis software, covering the range of gamma energy emitted between 50 and 3000 keV. The detector is housed in a 10-cm thick cylindrical lead shield to reduce as much as possible background radiation. The internal interface of the main lead shield is covered with a 2-mm copper liner in order to absorb X-rays generated in the lead.

Energy and efficiency calibrations of gamma-ray spectrometry systems were performed using the radionuclide specific efficiency method to reduce the uncertainty in gamma-ray intensities and the influence of the summation of coincidence and self-absorption effects of emitting gamma photons (Ingersoll, 1983). The energy calibration was done using a standard IAEA-RGTh-1 (3250 Bq kg^{-1} thorium ore) standard reference source prepared in a 1-liter filled Marinelli beaker. Three samples of U (RGU-1), Th (RGTh-1) and K (KCl) were prepared in a 100-mL pill bottle and used as standard sources for efficiency calibration. The detection efficiency of the pill bottle of the samples was determined by first calculating the absolute efficiency while using ^{226}Ra, ^{232}Th and ^{40}K spectrum lines. Absolute photo-peak efficiency was calculated for gamma-ray spectrum lines for the ^{226}Ra, ^{232}Th and ^{40}K using the following equation:

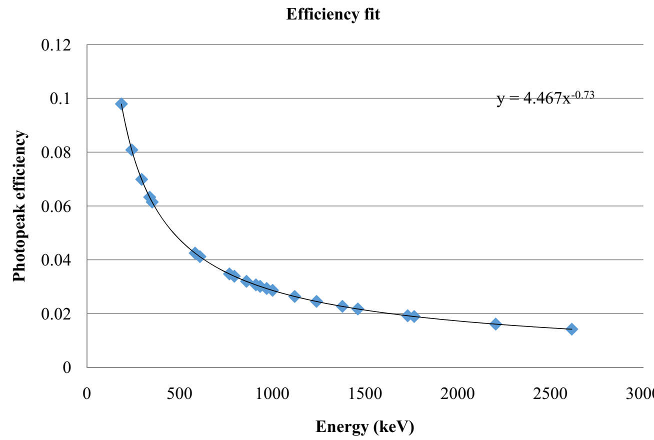

Figure 2. Efficiency calibration curve for pill-bottle geometry.

$$\varepsilon = a E^{-b}, \tag{1}$$

where E is the gamma-ray energy in keV. The power fit parameters a and b were obtained to be 4.4676 and 0.731, respectively. The absolute efficiency curve is presented in Figure 2.

3 Results and discussion

3.1 Activity concentration

All samples were counted for 12 h (43200 s), using the Genie 2000 data acquisition software provided by Canberra. The activity concentrations of each radionuclide were evaluated using the equation (2) below:

$$A_i\left(\text{Bq kg}^{-1}\right) = \frac{N_i}{\varepsilon(E)\gamma t m}, \tag{2}$$

where N_i is the net gamma count in a photopeak (background corrected), $\varepsilon(E)$ the detector efficiency as function of gamma-ray energy, γ the number of gamma per disintegration of the given nuclide at energy E (the absolute transition probability of gamma-decay), m the sample mass (kg) and t the counting time (s).

For radionuclides with more than one photopeak in the spectrum, the activity concentration was calculated using weighted average method. The activity concentration of parents was calculated using the weighted average of the daughters' activity concentrations being in secular equilibrium. The gamma-ray emissions of ^{214}Pb (295.2, 351.9 keV) and

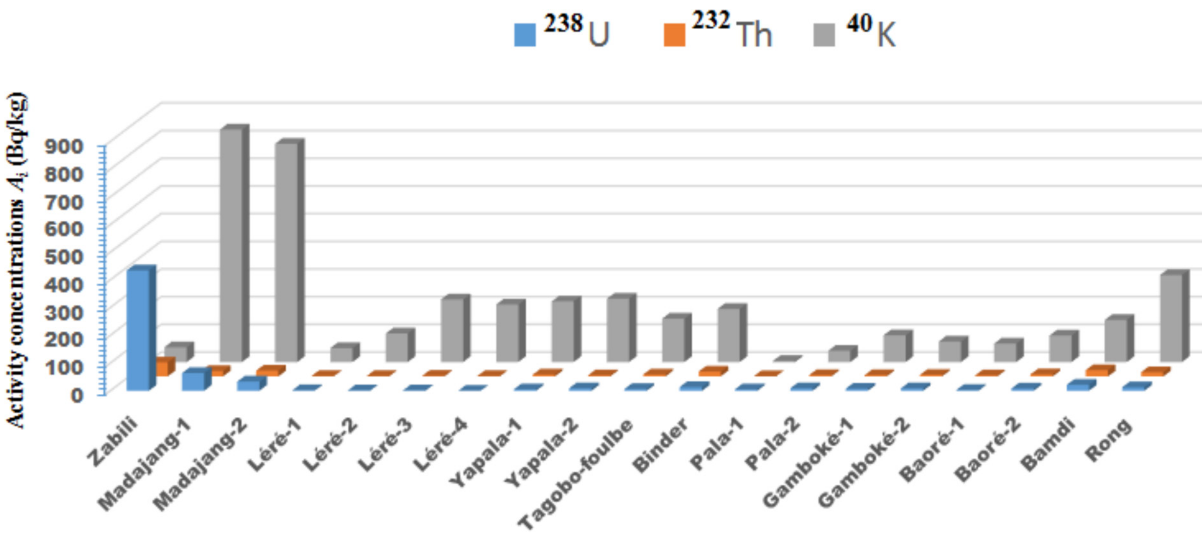

Figure 3. Graphic view of the activity concentrations A_i (Bq kg^{-1}) of the samples.

Table 2. Activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K and radium equivalent activity for various building material samples.

Location	Sample	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}
Zabili	Soil bricks	434.88 ± 7.11	50,61 ± 1.51	53.71 ± 2.53	511.40
Madajang-1	Soil bricks	64.43 ± 3.64	19.45 ± 1.53	839.54 ± 8.98	156.88
Madajang-2	Soil bricks	33.50 ± 3.57	21.06 ± 1.62	788.66 ± 9.25	124.34
Léré-1	Gravel	2.70 ± 0.35	1.58 ± 0.78	50.50 ± 2.75	8.85
Léré-2	Gravel	1.62 ± 0.26	1.66 ± 0.72	103.34 ± 3.57	11.96
Léré-3	Sand	1.99 ± 0.36	2.45 ± 0.63	225.88 ± 4.63	22.88
Léré-4	Sand	0.56 ± 0.37	1.66 ± 0.61	207.86 ± 4.61	18.93
Yapala-1	Soil bricks	5.42 ± 1.77	6.82 ± 0.68	219.08 ± 2.93	32.05
Yapala-2	Soil bricks	9.10 ± 2.44	4.01 ± 0.98	229 ± 4.74	32.46
Tagobo-foulbe	Soil bricks	6.98 ± 2.30	7.17 ± 0.98	156.91 ± 3.99	29.31
Binder	Soil bricks	13.53 ± 2.31	17.49 ± 0.94	192.23 ± 4.22	53.35
Pala-1	Gravel	5.55 ± 2.40	1.30 ± 0.60	4.28 ± 1.96	7.74
Pala-2	Sand	9.42 ± 2.77	5.13 ± 0.83	40.39 ± 2.49	19.86
Gamboké-1	Soil bricks	7.49 ± 2.12	4.60 ± 0.89	96.58 ± 3.38	21.50
Gamboké-2	Soil bricks	9.20 ± 3.23	5.91 ± 0.87	74.20 ± 3.12	23.37
Baoré-1	Cement 32.5	3.23 ± 0.50	3.98 ± 0.66	66.65 ± 2.96	14.06
Baoré-2	Cement 42.5	8.47 ± 2.25	7.49 ± 0.99	95.98 ± 3.48	26.49
Bamdi	Soil bricks	22.12 ± 3.70	22.78 ± 1.29	152.45 ± 4.02	66.44
Rong	Soil bricks	12.77 ± 2.32	15.25 ± 0.88	314.34 ± 5.20	58.78

^{214}Bi (609.3, 1120.2, 1764.5 keV) were assumed to represent the activity concentration of ^{238}U, and the gamma-ray lines of ^{228}Ac (338.4, 911.1, 968.9 keV) and Tl (583.1, 2614.7 keV), were used to represent the activity concentration of ^{232}Th. The activity concentration of ^{40}K was determined using its gamma-ray line at 1460.8 keV.

The potential radiological hazards associated with the building materials samples were assessed by calculating the radium equivalent activity and some radiological hazards index.

Table 2 presents the range and the average values of the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K measured in various types of building materials from Mayo-Kebbi region. Figure 3 is a graphical representation of the results that are in Table 2. It can be observed that ^{40}K contributes more to the specific activity compared to ^{226}Ra and ^{232}Th isotopes. The highest average activity concentration of ^{40}K is 839.54 ± 8.98 Bq kg^{-1} in soil bricks sample from Madajang and the lowest average is 4.28 ± 1.96 in Pala gravel sample. The ^{226}Ra average activity concentration vary from 0.56 ± 0.37 in Léré sand sample to 434.88 ± 7.11 Bq kg^{-1} in soil bricks sample collected from Zabili. For ^{232}Th, the average activity concentrations range from 1.30 ± 0.60 Bq kg^{-1} in Pala gravel sample to 50,61 ± 1.51 Bq kg^{-1} in soil bricks sample collected from Madajang. It is well known that the average worldwide activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K are 40, 40 and 400 Bq kg^{-1}, respectively (UNSCEAR, 2000). Based on these

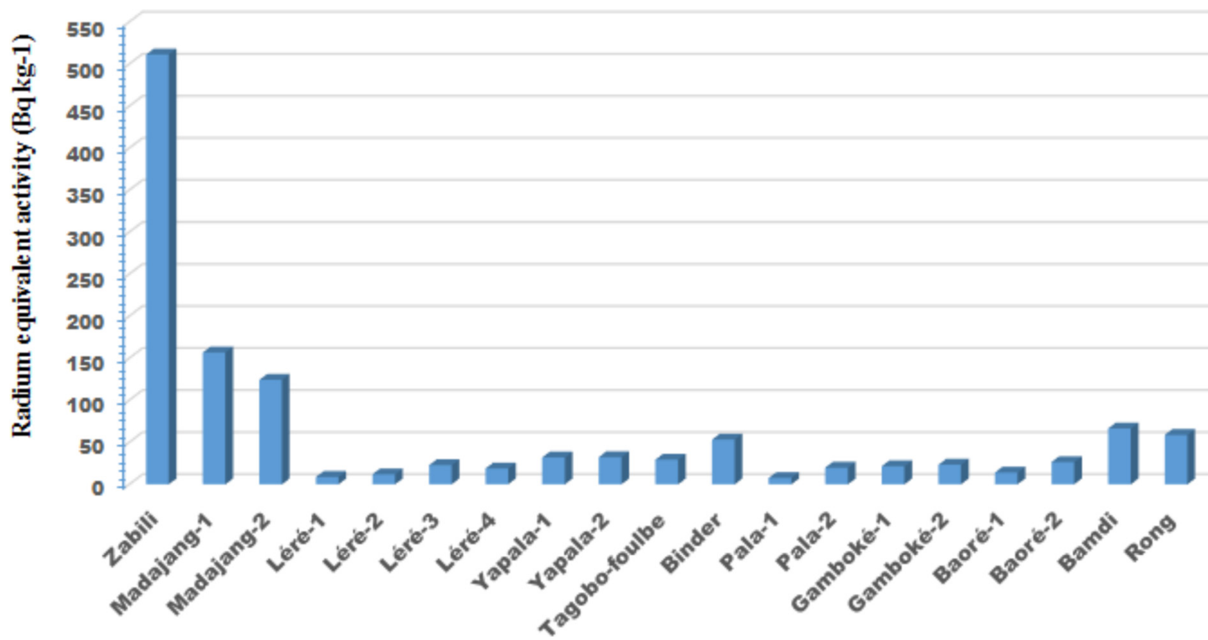

Figure 4. Radium equivalent activity (Bq kg^{-1}) as a function of location of the building material samples analysed.

Table 3. Ra_{eq} variation according to the material and the sample collection area.

	Soil bricks	Sand	Gravel	Cement
Minimum values of Ra_{eq} (Bq kg^{-1})	Gamboké-1: 21.50	Léré-4: 18.93	Pala-1: 7.74	Baoré-1: 14.06
Maximum values of Ra_{eq} (Bq kg^{-1})	Zabili: 511.40	Léré-3: 22.88	Léré-2: 11.96	Baoré-2: 26.49

criteria, high activity concentrations (> 40 Bq kg^{-1}) of ^{226}Ra were found in soil bricks sample. The ^{226}Ra concentration in soil bricks from Zabili is more than 10 times higher than the corresponding worldwide average value and the ^{226}Ra concentration in soil bricks from Madajang is 64.4 Bq kg^{-1}. High activity concentrations of ^{232}Th (51 Bq kg^{-1}) and ^{40}K (789 and 840 Bq kg^{-1}) were respectively found in soil bricks samples from Zabili and Madajang. The ^{40}K activity concentration measured in soil bricks from Madajang is more than twice the corresponding worldwide average value which is 400 Bq kg^{-1}.

3.2 Assessment of the radium equivalent activity (Ra_{eq})

The distribution of ^{226}Ra, ^{232}Th and ^{40}K in building materials is not uniform. Therefore, the complete and real radioactivity levels of ^{226}Ra, ^{232}Th and ^{40}K in building materials can be assessed using a common radiological index called the radium equivalent activity (Ra_{eq}). The radium equivalent activity is a weighted sum of activity concentration of ^{226}Ra, ^{232}Th and ^{40}K radionuclides based on the assumption that 370 Bq kg^{-1} of ^{226}Ra, 259 Bq kg^{-1} of ^{232}Th and 4810 Bq kg^{-1} of ^{40}K produce the same radiation dose rate (Ngachin *et al.*, 2007; Guembou Shouop *et al.*, 2017a, 2017b). The radium equivalent activity was calculated using the following equation (3) (Koblinger, 1984; Ngachin *et al.*, 2007; El-Galy *et al.*, 2008; El-Taher, 2012; Guembou Shouop *et al.*, 2017a, 2017b):

$$Ra_{eq} = A_{Ra} + (1.43 \times A_{Th}) + (0.077 \times A_K), \quad (3)$$

where A_{Th}, A_{Ra} and A_K are the specific activities of ^{232}Th, ^{226}Ra and ^{40}K in Bq kg^{-1}, respectively.

The calculated values of the radium equivalent (Ra_{eq}) of all the samples analyzed are given in Table 2, and the graphical view is shown in Figure 4. These values range from 7.74 Bq kg^{-1} (Pala-1: gravel) to 511.40 Bq kg^{-1} (Zabili: soil bricks). The results summarized in Table 3 show that the values of Ra_{eq} with the exception of the Zabili soil brick samples are below the maximum allowable value of 370 Bq kg^{-1} according to the UNSCEAR (2000) report, which is equivalent to an external dose of 1 mSv/y (NEA-OECD, 1979; EC, 1999). The Zabili soil brick sample presents a significant radiological hazard compared to all other building materials analyzed.

3.3 Comparison of specific activities and Ra_{eq} of samples from Mayo-Kebbi region, with those found in similar studies in other countries of the world

Table 4 compares the reported values of the activity concentrations of radionuclides and their radium equivalent

Table 4. Comparison of radioactivity concentration and radium equivalent activity (Ra_{eq}) in building materials samples from Mayo-Kebbi region (Chad), with that of other countries around the world.

Materials	Countries	Radioactivity concentration ($Bq\,kg^{-1}$)			Ra_{eq} ($Bq\,kg^{-1}$)	References
		^{226}Ra	^{232}Th	^{40}K		
Cement	Algeria	41	27	422	112	(Amrani and Tahtat, 2001)
	Greece	20	13	247	–	(Stoulos et al., 2003)
	Egypt	31.3	11.1	48.6	50.9	(Ahmed and Hussein, 1998)
	China	64.7	38.5	328.7	142.7	(Li et al., 2016)
	Cameroon	27.01	15.24	276.53	70.1	(Ngachin et al., 2007)
	Cuba	45	22	99	83	(Brigido Flores et al., 2008)
	Italy	38	22	218	92	(Rizzo et al., 2001)
	Zambia	23	32	134	79	(Hayumbu et al., 1995)
	Brazil	61.7	58.5	564	188.8	(Malanca et al., 1993)
	Bangladesh	62.3	59.4	329.0	172.8	(Mantazul et al., 1998)
	Bangladesh	29.7	54.3	523	148	(Alam et al., 1999)
	K.S.A	38.4	45.3	86	108	El-Taher, 2012)
	Malaysia	51	23	832	188	(Ibrahim, 1999)
	Chad	5.85	5.73	81.31	20.31	This work
Sand	Algeria	12.0	07.0	74.0	28.0	(Amrani and Tahtat, 2001)
	Australia	3.7	40	44.4	64.32	(Beretka and Mathew, 1985)
	Cameroon	14.23	31.25	586.33	104.06	(Ngachin et al., 2007)
	Douala, Cameroon	40.09	43.24	341.79	128.24	(Guembou Shouop et al., 2017a, 2017b)
	Cuba	17	16	208	55	(Brigido Flores et al., 2008)
	China	22.2	15.4	260.9	55.3	(Li et al., 2016)
	Greece	18	17	367	–	(Stoulos et al., 2003)
	Egypt	9.2	3.3	47.3	17.56	(Ahmed and Hussein, 1998)
	India, Namakkal	2.27	21.72	352.8	59.68	(Ravisankar et al., 2012)
	Pakistan	20	29	383	91	(Faheem and Mujahid, 2008)
	Palestine	20.6	18.8	26.3	–	(Dabayneh, 2007)
	K.S.A	12.3	24.2	195	60.35	(El-Taher, 2012)
	USA	37	33.3	18.5	86	(El-Mageed et al., 2014)
	Xianyang, China	25.8	26.8	553.6	106.7	(Xinwei et al., 2012)
	Yemen	20.78	27.68	1118.36	164.5	(El-Mageed et al., 2014)
	Chad	3.99	3.08	158.04	20.56	This work
Gravel	Brazil	10.3	N.D	933	82.1	(Malanca et al., 1993)
	Cameroon	24.47	138.89	1161.46	312.51	(Ngachin et al., 2007)
	Cuba	20	13	134	49	(Brigido Flores et al., 2008)
	Pakistan	24.8	9.9	51.3	42.9	(Tufail et al., 1992)
	Egypt	13.4	23	193	62.4	(El-Taher, 2010)
	Nederland	9.7	12.6	140	38.5	(Aders et al., 1985)
	K.S.A	14.7	24.2	195	65.7	(El-Taher, 2012)
	Australia	13.9	14.8	171	48.2	(Bou-Rabee and Bem, 1996)
	USA	33.3	33.3	14.8	82	(El-Mageed et al., 2014)
	Chad	3.29	1.51	52.70	9.51	This work
Brick	Cameroon	49.57	91.28	171.96	193.34	(Ngachin et al., 2007)
	Cuba	57	12	857	140	(Brigido Flores et al., 2008)
	Tamil Nadu, India	13.180	101.340	386.380	187.847	(Raghu et al., 2015)
	Malaysia	241	51	7541	895	(Ibrahim, 1999)
	Bangladesh	29.47	52.50	292.25	127.14	(Mantazul et al., 1998)
	Chad	56.31	15.92	283.33	100.89	This work

activity for selected building materials, obtained in other countries in comparison to those determined in this study. As shown from these table, the radioactivity and the radium equivalent activity in building materials varied from one country to another, which can be attributed to differences in the contents of radioactive minerals and in the geological, geochemical and geographical origins of the raw materials, among other factors. Radium, thorium and potassium are not uniformly distributed in soil or rocks, from which building materials are derived, but the activity concentrations vary, often greatly, over a distance of some meters. The measured values of radium, thorium and potassium contents show only the average radioactivity in building materials used in Mayo-Kebbi Ouest region not over the entire Chad. It is also important to point out that the other values are not the representative values for the countries mentioned but for the regions from where the samples were collected. From these comparisons, it can be seen that the construction materials of the Mayo-Kebbi region in Chad, have on average specific activities and radium equivalent activity much lower than most of the countries with which the comparison was made.

3.4 Absorbed gamma dose rate (*D*)

If some building materials have a high activity concentration, they may increase indoor and outdoor radiation exposure as well as the internal and external exposure of inhabitants. The absorbed dose rate measures the energy deposited in a medium by ionizing radiation per unit mass and per time unit. The larger the absorbed dose the higher the hazard.

Outdoor absorbed dose rates (D_{out}): the guidelines provided by the (UNSCEAR, 2000) report allows to assess the outdoor absorbed gamma dose rates in air, due to terrestrial gamma rays, coming from disintegration of the nuclides ^{226}Ra, ^{232}Th and ^{40}K, present in building materials. Those nuclides are supposed to be equally distributed in ground, and the absorbed dose rate measurement is supposed to have been making at 1.0 m above the ground level. The (D_{out}) was calculated using the following equation by (Shams *et al.*, 2015).

$$D_{out}\left(\mathrm{nGy\,h^{-1}}\right) = 0.427A_{Ra} + 0.662A_{Th} + 0.043A_K, \quad (4)$$

where A_{Ra}, A_{Th} and A_K have been defined previously. The dose conversion factors 0.43 nGy h^{-1} Bq^{-1} kg^{-1} for ^{226}Ra, 0.666 nGy h^{-1} Bq^{-1} kg^{-1} for ^{232}Th and 0.047 nGy h^{-1} Bq^{-1} kg^{-1} for ^{40}K are from (Ngachin *et al.*, 2007). In the UNSCEAR and European Commission reports, the dose conversion coefficient was calculated for the centre of the standard room. The dimension of the room is 4 m × 5 m × 2.8 m. The thickness of the walls, floors and the ceiling and density of the structure are 20 cm and 2350 kg m^{-3} (concrete), respectively.

The third column of Table 5 shows that the Outdoor absorbed dose rates range from 3.4 nGy h^{-1} in Gravel from Pala, to 223.2 nGy h^{-1} in soil bricks from Zabili, with mean value of 31.5 nGy h^{-1}. The world average value is 60 nGy h^{-1}, which means that most samples are below this value, except the soil brick sample from Zabili, which is four times higher than the world average value.

Indoor absorbed dose rates: according to UNSCEAR (2000), the building materials act as sources of radiation and also as shields against outdoor radiation. In general, the indoor-outdoor ratio range is relatively narrow and reflects the fact that building materials are usually of local origin and that their radionuclide concentrations are similar to those in local soil. Since essential data on average radon accumulation in the indoor atmosphere of houses, in the study area, are not yet available, we assessed the indoor absorbed dose rates, based on the fact that, the worldwide average gamma dose rate indoors is 1.4 times higher than outdoors (UNSCEAR, 2000; Asaduzzaman *et al.*, 2015).

$$D_{in}\left(\mathrm{nGy.h^{-1}}\right) = 1.4D_{out}. \quad (5)$$

The calculated indoor gamma dose rates for the nineteen (19) samples are presented in Table 5. The fourth column of this table show that the Indoor absorbed dose rates range from 4.834 nGy h^{-1} in Gravel from Pala, to 312.521 nGy h^{-1} in soil bricks from Zabili, with mean value of 44.069 nGy h^{-1}. The population-weighted world average is 84 nGy h^{-1} (UNSCEAR, 2000), which implies that the indoor absorbed dose rate of the soil brick samples from Madajang is 1.34 times higher than the world average value, and that from Zabili, is 3.72 times higher than the world average value (Fig. 5).

3.5 Annual effective dose (*E*)

The annual effective dose is estimated from the dose rate. Using the result of Outdoor and Indoor absorbed dose rates calculated above, annual effective dose was estimated as follow (Mahmoud *et al.*, 2014):

$$E\left(\mathrm{nSv\,y^{-1}}\right) = (D_{out}OF_{out} + D_{in}OF_{in})T.CC, \quad (6)$$

where E (nSv y^{-1}) is annual effective dose, D_{out} (nGy h^{-1}) and D_{in} (nGy h^{-1}) are mean outdoor and indoor absorbed dose rates, T (h) is time to convert from year to hour (8760 hours), OF_{out} and OF_{in} are outdoor and indoor occupancy factors (20% and 80% for outdoor and indoor, respectively) and CC is conversion coefficient (0.7×10^{-6} Sv per Gy for adults) reported by UNSCEAR to convert absorbed dose in air to the effective dose equivalent in human (UNSCEAR, 2000).

The calculated annual effective dose values for nineteen (19) samples are presented in Table 5.

The fifth column of Table 5 shows the annual effective dose values ranging from 0.028 mSv y^{-1} in Gravel from Pala, to 1.807 mSv y^{-1} in soil bricks from Zabili, with mean value of 0,255 mSv y^{-1}. It should be noted that the average value of the annual effective dose is less than the maximum value of 1 mSv y^{-1} recommended by ICRP (ICRP, 1991; EC, 1999). However, Zabili soil brick samples have an annual effective dose greater than this limit, and 7 times higher than the average value calculated for the entire study area.

3.6 Annual gonadal dose equivalent (AGDE)

The annual gonadal dose equivalent (AGDE) is used to evaluate the potential effects of the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K on certain important organs, such as

Table 5. The mean values of radiation dose in the samples from Mayo-Kebbi region.

Location	Sample	Radiation dose D_{out} (nGy h^{-1})	D_{in} (nGy h^{-1})	E (mSv y^{-1})	AGDE (μSv y^{-1})
Zabili	Soil bricks	223.229	312.521	1.807	1 572.194
Madajang-1	Soil bricks	80.117	112.164	0.648	544.005
Madajang-2	Soil bricks	65.498	91.697	0.530	439.185
Léré-1	Gravel	4.587	6.422	0.037	30.804
Léré-2	Gravel	6.659	9.323	0.054	44.393
Léré-3	Sand	13.104	18.346	0.106	87.316
Léré-4	Sand	11.116	15.562	0.090	73.937
Yapala-1	Soil bricks	17.169	24.037	0.139	114.047
Yapala-2	Soil bricks	17.347	24.286	0.140	116.787
Tagobo-foulbe	Soil bricks	15.151	21.211	0.123	100.809
Binder	Soil bricks	26.501	37.101	0.215	175.276
Pala	Gravel1	3.453	4.834	0.028	23.927
Pala	Sand	9.366	13.112	0.076	63.234
Gamboké-1	Soil bricks	10.824	15.154	0.088	72.698
Gamboké-2	Soil bricks	11.379	15.931	0.092	76.431
Baoré-1	Cement 32.5	7.172	10.041	0.058	47.545
Baoré-2	Cement 42.5	13.142	18.399	0.106	87.618
Bamdi	Soil bricks	31.848	44.587	0.258	211.441
Rong	Soil bricks	30.422	42.591	0.246	201.907

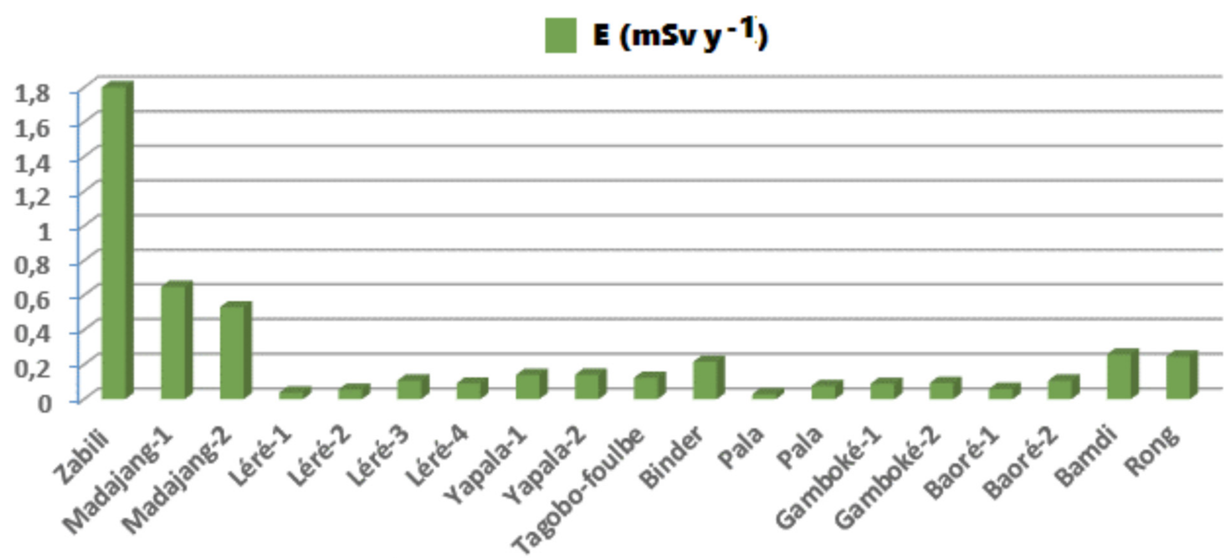

Figure 5. Values of E (mSv y^{-1}) of all the samples.

reproductive organs (gonads), bone marrow and bone cells. In the samples, it was calculated using the following relation (Shams *et al.*, 2015):

$$AGDE\left(\mu\text{Sv y}^{-1}\right) = 3.09A_{Ra} + 4.18A_{Th} + 0.314A_K, \quad (7)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K respectively in Bq kg^{-1}. The numbers 3.09, 4.18 and 0.314 are the respective conversion factors that transform the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K into total dose received by the organs of interest.

From Table 5 and Figure 6, the values of AGDE ranged from 23,927 μSv y^{-1} in Gravel from Pala to 1572,2 μSv y^{-1} in soil bricks from Zabili, with mean value of 214,9 μSv y^{-1}. This mean value is lower than the world worldwide mean value which is between 316.68 and 415.65 μSv y^{-1} (Shams *et al.*, 2015). But we observe that the first three samples of Table 5, collected at Madajang and Zabili exceed the world mean value,

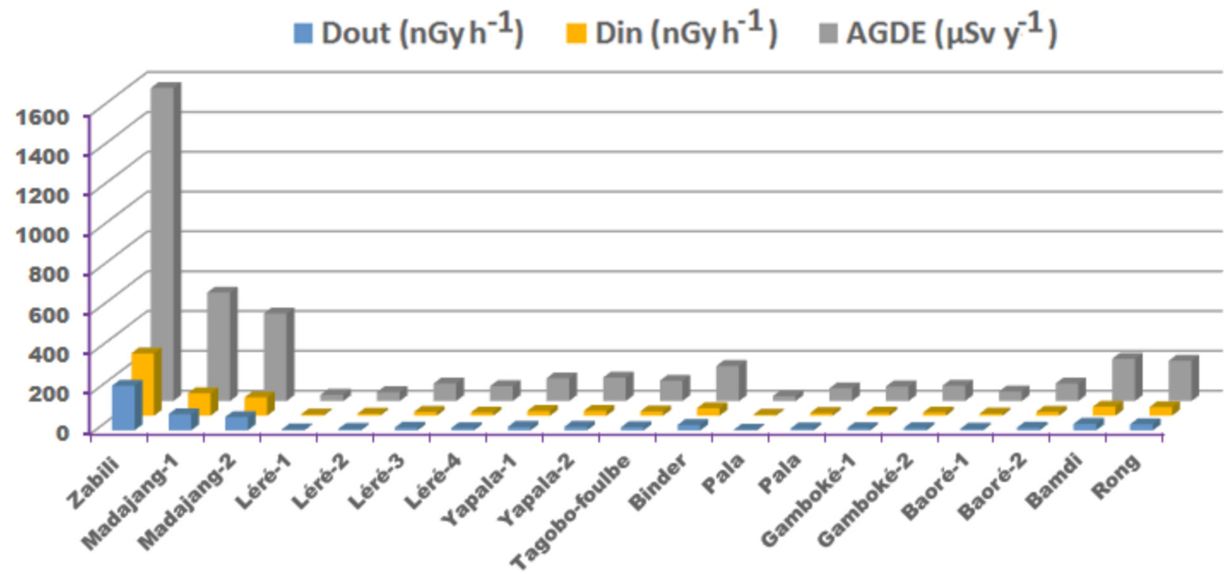

Figure 6. Values of D_{out} (nGy h^{-1}), D_{in} (nGy h^{-1}), and AGDE (µSv y^{-1}), for all samples.

indicating that the hazardous effects of the radiation are not negligible. Special attention should be given to these two areas.

3.7 External and internal radiological hazard index

External hazard indices (H_{ex}): the external radiological risks associated with construction materials are assessed by calculating the External Risk Index (Hex), which is given by the following formula (El-Taher, 2012; El-Mageed *et al.*, 2014):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}, \tag{8}$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bq kg^{-1}. Its numerical value must be less than unity, to consider that the external radiological hazards are negligible. $H_{ex} = 1$ is a corresponding quantity to the upper limit of Ra$_{eq}$ (370 Bq kg^{-1}) (Ngachin *et al.*, 2007; Guembou Shouop *et al.*, 2017a, 2017b).

The calculated external hazard index values are presented below in Table 6 and Figure 7. The values of H_{ex} is ranged from 0.021 for gravel from Pala to 1.382 for soil bricks from Zabili. Except the soil bricks of Zabili, the external hazard indexes of other studied samples are less than unity, and accordingly they can safely be used for construction unlike those from Zabili.

Internal hazard indices (H_{in}): for individuals living in the dwellings, Radon and its short-lived product can be hazardous to their respiratory organs. Internal hazard indices H_{in} is used to quantify the internal exposure to radon and its daughter products. H_{in} is given by the following equation (Brigido Flores *et al.*, 2008):

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \tag{9}$$

For the safe use of a material in the construction of dwellings, H_{in} should also be less than unity (Raghu *et al.*, 2015).

The calculated values of the internal hazard index for the studied samples are given below in Table 6 and Figure 7. Considering that the value of H_{ex} and H_{in} must not exceed the unit limit, it appears that only soil bricks from Zabili which have $H_{in} = 2.56$, do not meet this criterion. For all other samples, the internal hazard indices are lower than the unity. So, soil bricks from Zabili should be handled or used with caution to avoid excessive exposure of the people to radiation. The use of building materials from other localities have no immediate negative health implications on the inhabitants, but it is necessary to observe and study the long-term cumulative effects on the inhabitants of those localities.

3.8 Activity utilization index (*AUI*)

The activity concentrations of natural radionuclides in building materials affect the absorbed dose inside, especially for massive houses made of different materials such as stones, bricks, concretes or granites. This is explained by the fact that, the building materials act as sources of radiation and also as shields against outdoor radiation, thereby radiation emitted by sources outdoors is efficiently absorbed by the walls (UNSCEAR 2000 Report). As a result, indoor air dose rates will be higher than the natural radionuclide concentrations used in building materials. By applying the appropriate conversion factors, an Activity utilization index (*AUI*) is constructed to facilitate the calculation of air dose rates, from different combinations of the three nuclides ^{226}Ra, ^{232}Th and ^{40}K in building materials samples. (*AUI*) is given by the following expression taken from (Shams *et al.*, 2015).

$$AUI = \left[\left(\frac{A_{Ra}}{50}\right) f_{Ra} + \left(\frac{A_{Th}}{50}\right) f_{Th} + \left(\frac{A_K}{500}\right) f_K\right] w_m, \tag{10}$$

where $f_{Ra} = 0.462$, $f_{Th} = 0.604$ and $f_K = 0.041$ are the fractional contributions to the total dose rate in air due to gamma radiation from the actual concentrations of ^{226}Ra, ^{232}Th and ^{40}K respectively. w_m is the fractional use of building materials

Table 6. The mean values of radiation hazard indices in the samples from Mayo-Kebbi region.

Location	Sample	Radiation hazard indices				
		H_{ex}	H_{in}	AUI	RLI	$ELCR$ (x 10^{-3})
Zabili	Soil bricks	1.382	2.557	4.634	3.441	3.7947
Madajang-1	Soil bricks	0.424	0.598	0.899	1.184	1.3608
Madajang-2	Soil bricks	0.336	0.426	0.629	0.960	1.113
Léré-1	Gravel	0.024	0.031	0.048	0.067	0.0777
Léré-2	Gravel	0.032	0.037	0.043	0.096	0.1134
Léré-3	Sand	0.062	0.067	0.067	0.188	0.2226
Léré-4	Sand	0.051	0.053	0.042	0.159	0.189
Yapala-1	Soil bricks	0.087	0.101	0.150	0.250	0.2919
Yapala-2	Soil bricks	0.088	0.112	0.151	0.253	0.294
Tagobo-foulbe	Soil bricks	0.079	0.098	0.164	0.223	0.2583
Binder	Soil bricks	0.144	0.181	0.352	0.393	0.4515
Pala	Gravel1	0.021	0.036	0.067	0.053	0.0588
Pala	Sand	0.054	0.079	0.152	0.141	0.1596
Gamboké-1	Soil bricks	0.058	0.078	0.133	0.160	0.1848
Gamboké-2	Soil bricks	0.063	0.088	0.162	0.170	0.1932
Baoré-1	Cement 32.5	0.038	0.047	0.083	0.106	0.1218
Baoré-2	Cement 42.5	0.072	0.095	0.177	0.195	0.2226
Bamdi	Soil bricks	0.179	0.239	0.492	0.477	0.5418
Rong	Soil bricks	0.159	0.193	0.328	0.447	0.5166

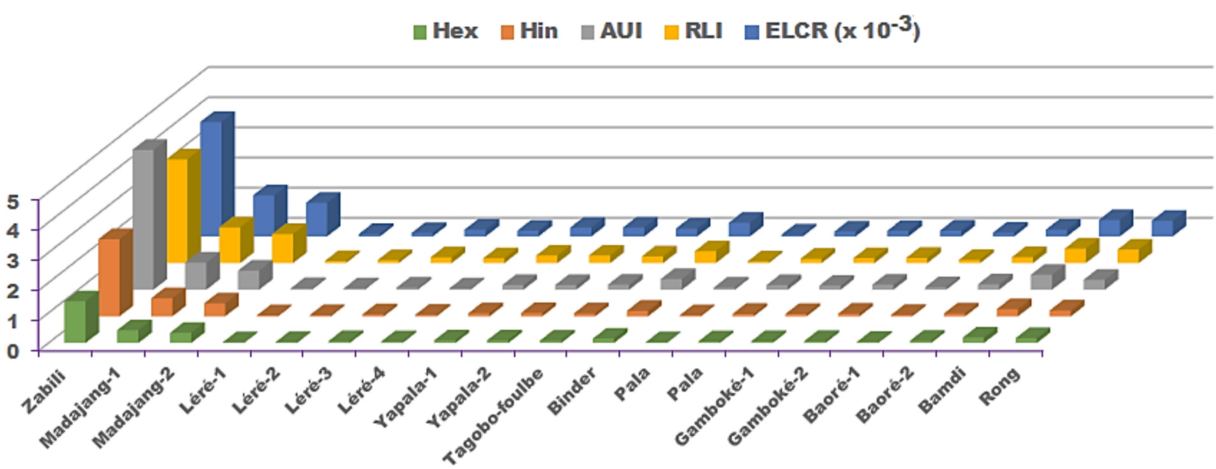

Figure 7. Radiation hazard indices.

in the dwelling with the activity characteristic. In this study, we assume that we are in the case of full utilization of the typical masonry, and we take $w_m = 1$.

The values of the activity utilization index calculated for the studied samples are given in Table 6 and Figure 7. They range from 0.042 for sand from Lere to 4.634 for soil bricks from Zabili, with an average value of 0.461. This average value is less than 2 and corresponds to an annual effective dose less than 0.3 mSv y^{-1}, indicating that building materials from Mayo-Kebbi region (Chad) are safe. But the case of soil bricks from Zabili, with $AUI = 4.634$ are to be avoided. It is advisable not to use them to build houses.

3.9 Representative level index (*RLI*)

The representative level index is used to estimate the level of gamma radiation hazard associated with the natural radionuclides in specific building materials. It is a screening tool for identifying materials that may be hazardous to health when used for the construction of buildings. It is correlated with the annual dose due to the excess external gamma radiation caused by superficial material. Values of $RLI \leq 1$ correspond to dose rate ≤ 0.3 mSv y^{-1} whereas $RLI \leq 3$ correspond to dose rate ≤ 1 mSv y^{-1}. RLI is calculated using equation based on (NEA-OECD, 1979) formula:

$$RLI = \left(\frac{A_{Ra}}{150}\right) + \left(\frac{A_{Th}}{100}\right) + \left(\frac{A_K}{1500}\right). \quad (11)$$

The safety value for this index must be ≤ 1.

The representative level index for building material samples are displayed in Table 6 and Figure 7. The calculated *RLI* varies from 0.053 for gravel from Pala to 3.441 for soil bricks from Zabili, with an average of 0.471. It is clear that this average value does not exceed the upper limit of the *RLI*, which is unity. Therefore, according to the dose criterion above, bricks from Zabili with $RLI = 3.441$ (≥ 3) should not be used as a building materials, since these values correspond to dose rates higher than 1 mSv y^{-1}.

3.10 Excess lifetime cancer risk (*ELCR*)

The Excess lifetime cancer risk (*ELCR*) can be defined as the probability that an individual can develop cancer over his lifetime due to exposure level to radiation. The *ELCR* has been calculated using the following equation (Chandrasekaran *et al.*, 2014).

$$ELCR = E\left(\mathrm{mSv\,y^{-1}}\right)DL(70\,\mathrm{y})RF\left(0.05 \times 10^{-3}\,\mathrm{mSv^{-1}}\right), \quad (12)$$

where E is the annual effective dose equivalent, DL is the duration of life (70 years average) and RF is the risk factor, *i.e.* fatal cancer risk per mSv. For stochastic effects, the ICRP Publication 106 used a value of $RF = 0.05 \times 10^{-3}$ mSv^{-1} in any given population. The worldwide recommended value of *ELCR* is 0.29×10^{-3} (Chandrasekaran *et al.*, 2014; Ugbede and Echeweozo, 2017).

The values of *ELCR* obtained for the studied samples are summarized in the last column of Table 6 and on the graphical representation of Figure 7. *ELCR* values ranged from 0.058×10^{-3} to 3.794×10^{-3} with average value of 0.535×10^{-3}. The average of the excess lifetime cancer risk is 1.84 times greater than the upper recommended value of 0.29×10^{-3}. Building materials with such high *ELCR* values can lead to radiation hazards, and the risk of developing cancer by people living in this environment is very high, so they should be avoided for construction.

4 Conclusion

With high purity γ-ray spectrometry system, the activity concentrations of ^{238}U (^{226}Ra), ^{232}Th and ^{40}K in building materials collected from Mayo-Kebbi region (Chad) were measured. The materials studied in this research show that some of the building materials used in the region are not safe in terms of radiological hazard. All types of cement analysed show low levels of radioactivity, even when compared to levels in other countries around the world. Gravel and sand samples also show low levels of activity and therefore negligible radiological risk. The value of radiation hazard parameters of soil bricks, especially from Zabili presents significant radiological exposure risks. The soil bricks from Zabili exhibit an annual effective dose of 1.807 mSv y^{-1} which is about 2 times higher than the maximum value recommended by ICRP, especially if we considered that it is a single source of radiological exposure. The average of the excess lifetime cancer risk is 1.84 times greater than the upper recommended value of 0.29×10^{-3}, and soil bricks, from Zabili have an excess lifetime cancer risk, 13 times greater than the upper recommended value. Building materials with such high excess lifetime cancer risk values, can lead to radiation hazards. It may be due to the presence of relatively higher activity concentration of ^{238}U in the soil of this location, where prospecting for uranium was already done by an international mining company. Thus, it is recommended that soil bricks in the region, especially from Zabili should not be used as building materials. From a radiation protection point of view, additional regulations will be needed on building materials from the Mayo-Kebbi region in Chad.

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