Determination of the natural radionuclide content and associated radiation hazard in soil samples collected from the Ohorongo cement plant and the town of Otavi, Namibia

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ABSTRACT

The activity concentrations and associated radiation hazard of the primordial radionuclides ^{238}U, ^{232}Th, and ^{40}K in soil samples collected from the Ohorongo cement plant and the town of Otavi, Namibia, have been studied by gamma-ray spectrometry. The average activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in the plant are respectively 15.0 ± 4.7 Bq/kg, 25.1 ± 9.9 Bq/kg, and 310.7 ± 97.2 Bq/kg while they are 21.6 ± 7.2 Bq/kg, 20.3 ± 8.5 Bq/kg and 256.4 ± 113.7 Bq/kg in Otavi. All these values are lower than the worldwide average values. In order to determine the associated health hazard, the activity concentrations were used to calculate different radiological parameters. The values of 43 ± 15 μSv/y and 40 ± 15 μSv/y obtained for the mean effective dose rate at the cement plant and town, respectively, are less than the maximum permissible value of 1.0 mSv/y recommended by the International Commission on Radiation Protection (ICRP). Similarly, the values of 74.9 ± 25.6 Bq/kg and 70.4 ± 26.7 Bq/kg obtained respectively for the mean radium equivalent activity (Ra_{eq}) in the cement plant and town as well as the corresponding values obtained for the mean external hazard index are far below the maximum permissible limit. These results imply that radiation hazard is negligible at the Ohorongo Cement plant and town of Otavi.

1 Introduction

Primordial radionuclides such as ^{238}U, ^{232}Th and ^{40}K are present in the soil where they continuously decay and emit ionizing radiation (Oyedele, 2005; Alatise *et al.*, 2008). These radionuclides are the main contributors to the natural background radiation to which human beings are exposed. When the concentrations of the radionuclides in the soil are high, the background radiation will be high and could become a health hazard (UNSCEAR, 2000; Shimboyo *et al.*, 2016). It is for this reason that many scientists in different countries are interested in the determination of the activity concentrations of primordial radionuclides and the corresponding radioactivity levels in the soils of their towns and important places (Hassan and Khoo, 2014; Duggal *et al.*, 2014; Ajithra *et al.*, 2017; Avwiri *et al.*, 2012). In the case of Namibia, there are many mineral resources and therefore the activity concentration of primordial radionuclides in the soils may be high in some locations and towns resulting in high background radiation areas. There is therefore interest in studying the natural radioactivity in the soils of important places and towns in Namibia and thereby obtain a baseline data of environmental radioactivity (Oyedele *et al.*, 2008, 2010; Oyedele and Shimboyo, 2013; Midzi *et al.*, 2019). Such places and towns are the Ohorongo Cement plant and the town of Otavi.

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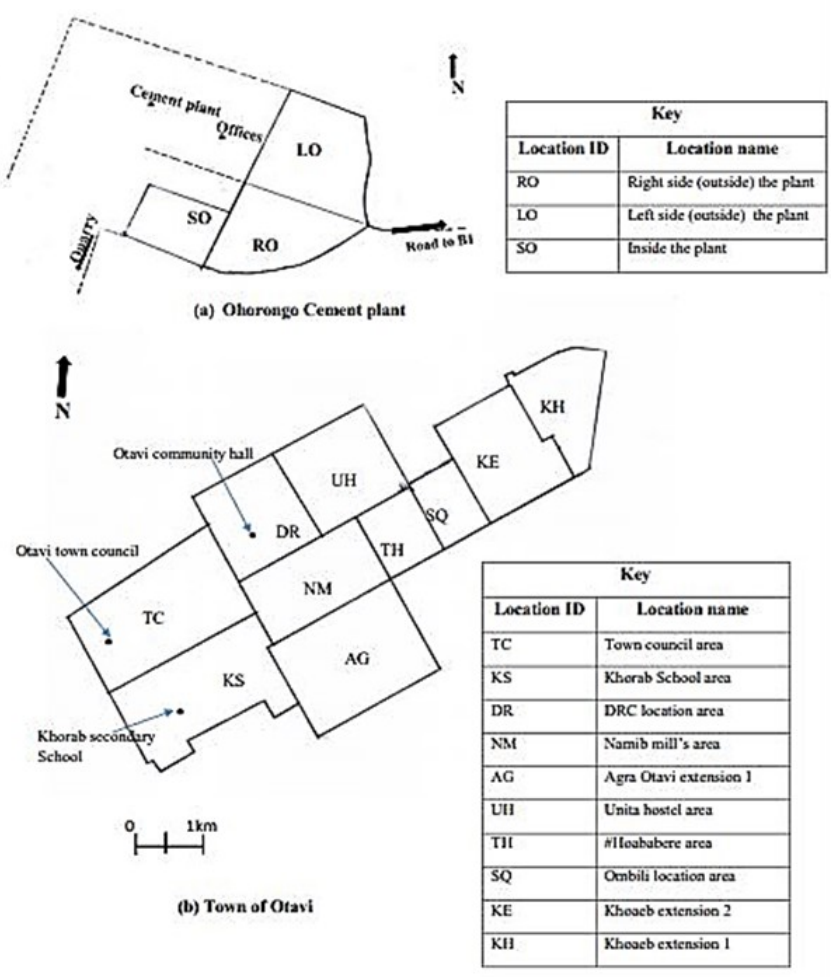
The Ohorongo Cement plant is the largest cement plant in Namibia and it is situated at about 25 km north-west of Otavi on the farm called Sargberg in the Otjozondjupa region. It is at latitude $19°31'68''S$ and longitude $17°27'23''E$ and there are large deposits of limestone, shale and some raw materials near the plant. Many of the plant employees reside in Otavi and the cement plant attracts many visitors from different parts of the world. Otavi is a town between Otjiwarongo and Tsumeb, some 365 km away from the capital city, Windhoek. The town is well known for its farming activities and has a large cereal milling plant. Most tourists and locals travelling from the capital city to the northern part of the country and vice versa, usually stop in this town for refreshments, and a popular meteorite is located 25 km north-east of Otavi. The aim of this project was to determine the activity concentrations and distributions of the radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soils of the Ohorongo cement plant and the town of Otavi and provide information on the levels of background radiation in the plant and town. The study will ascertain whether the levels are within the maximum acceptable limit and will also be useful in establishing a baseline data of activity concentrations for further environmental assessment.



Key	
Location ID	**Location name**
RO	Right side (outside) the plant
LO	Left side (outside) the plant
SO	Inside the plant

Key	
Location ID	**Location name**
TC	Town council area
KS	Khorab School area
DR	DRC location area
NM	Namib mill's area
AG	Agra Otavi extension 1
UH	Unita hostel area
TH	#Hoababere area
SQ	Ombili location area
KE	Khoaeb extension 2
KH	Khoaeb extension 1

Figure 1: The map showing the geographical areas from which the soil samples were collected in (a) the Ohorongo Cement plant and (b) the town of Otavi.

2 Materials and methods

A total of fifty (50) soil samples were collected outside (in front) and inside the cement plant as illustrated in Figure 1(a). Similarly, the town of Otavi was divided into ten geographical areas (Figure 1(b)) and five soil samples were collected across each area giving a total of fifty samples. The samples were collected from the top soil (2 - 5 cm depth) using a spade. In addition, soil samples were collected using random sampling method away from roads, buildings and rivers and they were subsequently dried under laboratory temperature and sieved through a 2 mm mesh screen. 500 g of each soil sample was placed in well-labelled polythene bottles and sealed tightly for one month for the radionuclides to attain secular equilibrium with their progeny before taking measurements.

2.1 Radioactivity measurement

Each soil sample was placed on a calibrated and well-shielded vertical Canberra High Purity Germanium (HPGe) detector and the gamma-ray spectra of the radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the samples were measured. The calibration was done using the reference materials RGU-1, RGTh-1 and RGK-1 donated by the International Atomic Energy Agency (IAEA) and the same geometry and counting time (10800 seconds) were used for the reference materials and for the samples. The experimental procedure followed has been described elsewhere (Midzi, 2018). The activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ were respectively determined from the gamma transition energies of 0.609 MeV of $^{214}\mathrm{Bi}$, 0.911 MeV of $^{228}\mathrm{Ac}$ and 1.460 MeV of $^{40}\mathrm{K}$. These concentrations were subsequently used to calculate the mean absorbed dose rate and mean effective dose rate as well as different radiation hazard parameters such as the radium equivalent activity, Ra_{eq}.

Table 1: Average activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the three geographical areas of the Ohorongo cement plant. The range of values is given in brackets.

Area	Average activity concentration (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
LO	13.6 ± 3.6 (7.7 - 20.1)	21.2 ± 6.0 (12.7 – 33.1)	284.9 ± 51.5 (204.8 – 381.9)
SO	12.2 ± 3.4 (8.4 -18.6)	20.0 ± 7.0 (12.7 – 35.6)	248.9 ± 87.2 (132.2 – 390.2)
RO	17.9 ± 4.9 (7.3 - 25.6)	31.7 ± 10.8 (13.8 – 43.1)	367.4 ± 109.4 (137.9 – 507.8)
All three areas	**15.0 ± 4.7 (7.3 -25.6)**	**25.1 ± 9.9 (12.7 – 43.1)**	**310.7 ± 97.2 (132.2 – 507.8)**

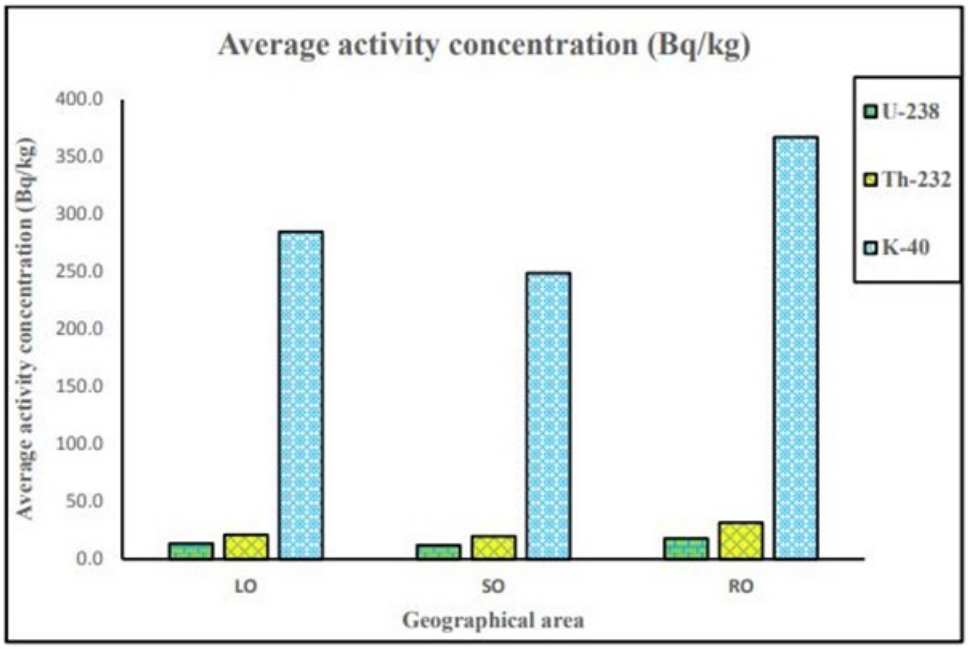


Figure 2: The average activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the three geographical areas of the Ohorongo cement plant.

3 Results

3.1 Activity concentrations of radionuclides at the cement plant

The mean and range of the activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soil samples collected from the three geographical areas of the plant are summarized in Table 1 and shown in Figure 2. The mean activity concentrations of the radionuclides are different in the different areas. As could be observed in the Table, the activity concentrations of $^{238}\mathrm{U}$ in the three areas vary from 7.3 ± 1.2 Bq/kg to 25.6 ± 1.8 Bg/kg with a mean of 15.0 ± 4.7 Bg/kg (Table 1, bottom row). Similarly, the activity concentrations of $^{232}\mathrm{Th}$ in the three areas vary from 12.7 ± 2.2 Bg/kg to 43.1 ± 3.5 Bg/kg with a mean of 25.1 ± 9.9 Bg/kg while the activity concentrations of $^{40}\mathrm{K}$ in the areas vary from 132.2 ± 9.7 Bg/kg to 507.8 ± 22.5 Bg/kg with a mean of 310.7 ± 97.2 Bg/kg. Also, as could be observed in Table 1 and Figure 2, the average activity concentration of each of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ is lowest in the SO area and highest in the RO area. However, the average activity concentrations of $^{238}\mathrm{U}$ and $^{40}\mathrm{K}$ are lower than the worldwide average values of 35 Bg/kg and 400 Bg/kg, respectively for $^{238}\mathrm{U}$ and $^{40}\mathrm{K}$ (UNSCEAR, 2000). In contrast, the average activity concentration of $^{232}\mathrm{Th}$ is slightly higher in the RO area than the worldwide average value of 30 Bg/kg. Furthermore, from Figure 2, the average activity concentration of $^{40}\mathrm{K}$ is the highest among the three radionuclides in all the three areas while that of $^{238}\mathrm{U}$ is the lowest.

Table 2: Average activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the ten geographical areas of Otavi. The range of values is given in brackets.

Area	Average activity concentration (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
TH	24.4 ± 3.6 (21.0 - 30.4)	21.1 ± 2.8 (16.7 - 24.0)	227.4 ± 36.4 (167 - 261.9)
SQ	14.5 ± 1.4 (12.9 -16.2)	13.9 ± 3.3 (10.2 - 18.5)	165.8 ± 29.8 (135.9 - 206.1
KE	25.1 ± 4.3 (18.8 - 29.9)	23.3 ± 4.5 (16.1 - 27.4)	261.5 ± 44.5 (201 - 308.9)
TC	23.5 ± 4.2 (19.5 - 29.5)	23.5 ± 5.2 (18.9 - 31.8)	351.8 ± 68.7 (242.3 - 418.5)
AG	26.3 ± 3.9 (22.5 - 32.3)	28.5 ± 15.2 (19.5 - 55.6)	336.1 ±1 74.7 (220.6 - 645.8)
NM	19.5 ± 4.8 (13.9 - 24-6)	17.1 ± 3.7 (12.9 - 22.7)	182.7 ± 32.9 (136.9 - 215.4)
KS	21.1 ± 1.8 (18.5 - 23.0)	20.5 ± 2.4 (16.4 - 22.5)	278.2 ± 46.1 (217.5 - 327.0)
KH	20.8 ± 5.4 (16.6 - 28.3)	18.4 ± 6.4 (11.3 - 25.8)	224.7 ± 86.5 (148.8 - 349.7)
UH	9.2 ± 2.7 (6.5 - 13.4)	7.5 ± 2.3 (3.7 - 9.8)	113.1 ± 40.6 (76.5 - 182.4)
DR	31.8 ± 7.1 (20.2 - 39.1)	28.9 ± 6.1 (18.9 - 35.2)	422.3 ± 85.0 (218.0 - 503.7)
All ten areas	**21.6 ± 7.2 (6.5 - 39.1)**	**20.3 ± 8.5 (3.7 - 55.6)**	**256.4 ± 113.7 (76.5 - 645.8)**

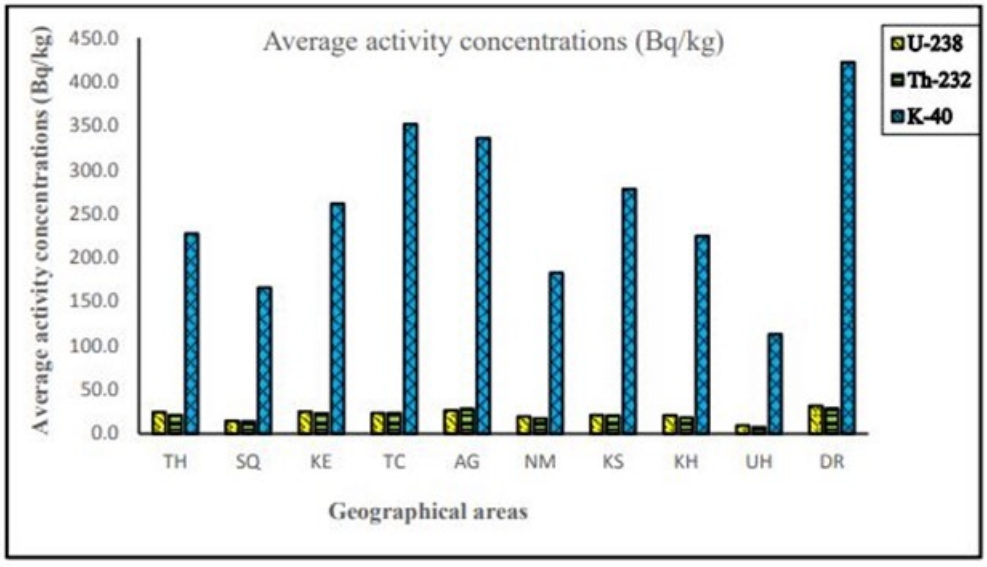


Figure 3: The average activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the ten geographical areas of Otavi

3.2 Activity concentrations of radionuclides in Otavi

The mean and range of the activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soil samples collected from each of the ten geographical areas in Otavi are summarized in Table 2 and shown in Figure 3. Again, the mean activity concentrations of the radionuclides are different in the different areas. As could be observed in the Table, the activity concentrations of $^{238}\mathrm{U}$ in the ten areas are between 6.5 ± 1.3 Bg/kg and 39.1 ± 2.2 Bg/kg with a mean of 21.6 ± 7.2 Bg/kg (Table 2, bottom row). Similarly, the activity concentrations of $^{232}\mathrm{Th}$ in the ten areas are between 3.7 ± 1.5 Bg/kg and 55.6 ± 4.4 Bg/kg with a mean of 20.3 ± 8.5 Bg/kg while the activity concentrations of $^{40}\mathrm{K}$ in all the areas are between 76.5 ± 7.6 Bg/kg and 645.8 ± 27.1 Bg/kg with a mean of 256.4 ± 113.7 Bg/kg. Furthermore, the mean activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ are lowest in the UH area while they are highest in the DR area as could be observed in Table 2 and Figure 3. It therefore follows that the DR area has the highest activity concentrations, while the UH area has the lowest activity concentrations, as could be observed in Figure 3. As in the case of the cement plant, the mean activity concentration of $^{40}\mathrm{K}$ is the highest among the three radionuclides in all the ten areas. Again, the mean activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ from all the samples are below the worldwide average values. A comparison of the average radionuclide concentrations in the soils of the cement plant and town (bottom row in Tables 1 and 2) shows that the average concentration of $^{238}\mathrm{U}$ is higher in Otavi (21.6 ± 7.2 Bg/kg) than in the cement plant (15.0 ± 4.7 Bg/kg) while the average concentrations of $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ are both higher in the plant (25.1 ± 9.9 Bg/kg and 310.7 ± 97.2 Bg/kg) than in the town (20.3 ± 8.5 Bg/kg and 256.4 ± 113.7 Bg/kg).

Table 3: The mean absorbed dose rate, effective dose rate, radium equivalent activity (Ra_{eq}) and external hazard index (H_{ex}) in the three geographical areas of the Ohorongo cement plant. The range of values is given in brackets.

Area	Absorbed dose rate (nGy/h)	Effective dose rate (μSv/y)	Radium equivalent activity, Ra_{eq} (Bq/kg)	External hazard index (H_{ex})
LO	31.0 ± 7.1 (20.9 - 45.2)	38.0 ± 8.7 (25.6 – 55.5)	65.8 ± 15.4 (44.1 - 65.8)	0.18 ± 0.04 (0.12 - 0.26)
SO	28.1 ± 9.2 (18.1 - 46.4)	34.4 ± 11.3 (22.2 - 56.8)	59.9± 19.6 (38.7 - 99.5)	0.16 ± 0.05 (0.10 - 0.27)
RO	42.7 ± 12.9 (18.8 - 58.0)	52.4 ± 15.8 (23.1 - 71.2)	91.5 ± 27.8 (40.3 - 124.2)	0.25± 0.07 (0.11 - 0.34
Average of all samples	**35.1 ± 11.8 (18.1 - 58.0)**	**43.0 ± 14.5 (22.2 -71.2)**	**74.9 ± 25.6 (38.7 - 124.2)**	**0.20 ± 0.07 (0.10 - 0.34)**

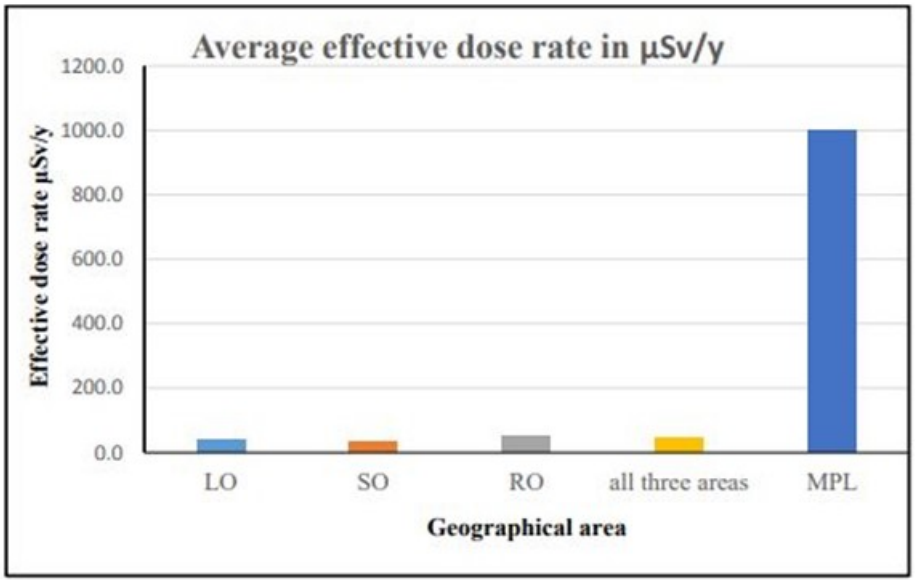


Figure 4: Average effective dose rates due to gamma radiation from $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soil samples collected from the three geographical areas of the cement plant. The average effective dose rate rate over the three areas and the corresponding maximum permissible limit (MPL) are shown in the last two columns respectively.

3.3 Radiological hazards due to the radionuclides in the soil of the cement plant

In order to assess the radiological hazards due to the radionuclides in the soils of the cement plant, the absorbed dose rate, annual effective dose, radium equivalent activity and external hazard index were calculated. These radiological parameters were calculated from the measured activity concentrations of the three main primordial radionuclides in the soil samples. The absorbed dose rates in air at 1 m above the ground where soil samples were collected were calculated using the relation (UNSCEAR, 2000; Oyedele and Shimboyo, 2013).

$$\left(\mathrm{nGyh}^{-1}\right) = 0.0417A_K + 0.462A_U + 0.604A_{Th}, \tag{1}$$

where A_K, A_K and A_{Th} are the activity concentrations (in Bg/kg) of $^{40}\mathrm{K}$, $^{238}\mathrm{U}$, and $^{232}\mathrm{Th}$ respectively. Also, the annual effective dose was calculated using the conversion coefficient from absorbed dose in air to effective dose, $0.7\,\mathrm{Sv\ Gy}^{-1}$ and an outdoor occupancy factor 0.2 (UNSCEAR, 2000; Midzi *et al.*, 2019). The radium equivalent activity (Ra_{eq}) which represents the activity levels of the three primordial radionuclides as a single quantity was calculated using the relation (Midzi *et al.*, 2019).

$$\mathrm{Ra}_{eq} = A_U + 1.43A_{Th} + 0.077A_K, \tag{2}$$

where A_K, A_K and A_{Th} are the activity concentrations (in Bg/kg) of $^{40}\mathrm{K}$, $^{238}\mathrm{U}$, and $^{232}\mathrm{Th}$ respectively, and it was assumed in this work that there was secular equilibrium between $^{238}\mathrm{U}$ and $^{226}\mathrm{Ra}$. The maximum value of the radium equivalent activity is $370\,\mathrm{Bg/kg}$. Similarly, the external hazard index, H_{ex}, was calculated using the expression (Midzi *et al.*, 2019).

$$H_{ex} = A_U/370 + A_{Th}/259 + A_K/4810, \tag{3}$$

where A_K, A_K and A_{Th} are, respectively, the activity concentrations (in Bg/kg) of $^{40}\mathrm{K}$, $^{238}\mathrm{U}$, and $^{232}\mathrm{Th}$. External radiation hazard is negligible if $H_{ex} \leq 1$. The mean and range of these radiological parameters in the different areas of the cement plant are shown in Table 3.

As could be observed in Table 3 (column 2) the mean absorbed dose rate in air is lowest in the SO area with a value of 28.1 ± 9.2 nGy/h and highest in the RO area with a value of 42.7 ± 12.9 nGy/h. The relatively high value of the dose rate in the RO area is not surprising as the area has the highest radionuclide concentrations (Table 1, fourth row). The mean absorbed dose rate in the three areas is 35.1 ± 11.8 nGy/h which is lower than the worldwide average value of 51 nGy/h. The corresponding effective dose rates are shown in Table 3 (column 3) and Figure 4. Again, the SO area has the lowest mean effective dose rate while the RO area has the highest mean effective dose rate. The effective dose rates in the three areas varies from 22.2 ± 1.7 μSv/y to 71.2 ± 3.0 μSv/y, with a mean value of 43.0 ± 14.5 μSv/y (column 3 bottom row). All these values are below the maximum permissible limit (MPL) of 1.0 mSv/y (Figure 4, last column) recommended by ICRP (Wrixon, 2008). This result implies that the Ohorongo cement plant has a normal background radiation.

The results obtained for the radium equivalent activity (Ra_{eq}) and the external hazard index (H_{ex}) in the cement plant are summarized in Table 3 (columns 4 and 5 respectively). The values of Ra_{eq} varies from 38.7 ± 3.2 Bg/kg to 124.2 ± 5.6 Bg/kg with an overall average value of 74.9 ± 25.6 Bg/kg as shown in Table 3 (column 4, bottom row) and Figure 5. As could be observed in the Table, all the values of Ra_{eq} are below the maximum permissible limit of 370 Bg/kg (UNSCEAR, 2000). Similarly, H_{ex} varies between 0.10 ± 0.01 and 0.34 ± 0.02 with an overall average of 0.20 ± 0.07, as shown in Table 3 (column 5) and Figure 6. All the values of Hex are below the maximum permissible value of 1.0 (ICRP, 2007). These results for Ra_{eq} and H_{ex} confirm that radiation hazard is negligible in the Ohorongo Cement plant.

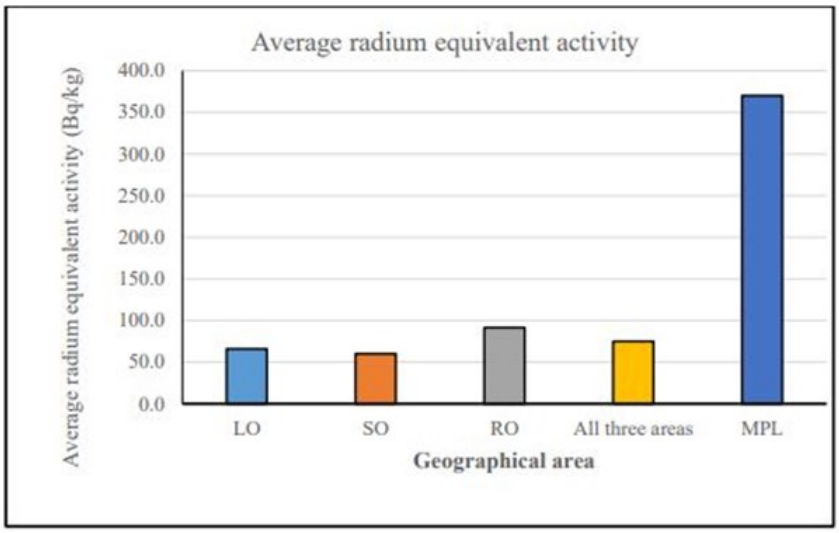


Figure 5: Average radium equivalent activity (Ra_{eq}) due to $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soil samples collected from the cement plant. The average radium equivalent activity over the three areas and the corresponding maximum permissible limit (MPL) are shown in the last two columns respectively.

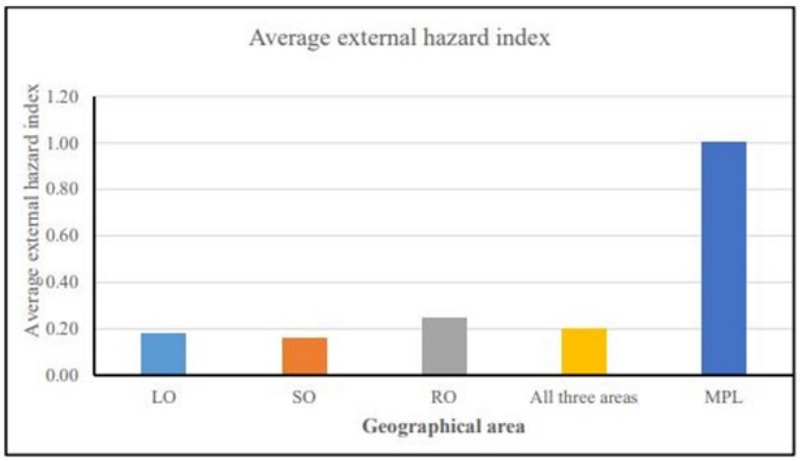


Figure 6: Average external hazard index (H_{ex}) due to $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soil samples collected from the cement plant. The average H_{ex} over the three areas and the corresponding MPL are shown in the last two columns respectively.

Table 4: The mean absorbed dose rate, effective dose rate, radium equivalent activity (Ra_{eq}) and external hazard index (H_{ex}) in the ten geographical areas of Otavi. The range of values is given in brackets.

Area	Absorbed dose rate (nGy/h)	Effective dose rate (μSv/y)	Radium equivalent activity (Ra_{eq}) (Bq/kg)	External hazard index (H_{ex})
TH	33.5 ± 4.1 (27.6 - 38.7)	41.0 ± 5.1 (33.9 - 47.4)	72.0 ± 8.8 (59.6 - 83.0)	0.19 ± 0.02 (0.16 - 0.22)
SQ	22.0 ± 3.2 (18.6 – 25.7)	27.0 ± 4.0 (22.9 -31.6)	47.2 ± 7.0 (39.8 - 55.2)	0.13 ± 0.02 (0.11 - 0.15)
KE	36.3 ± 5.9 (26.8 – 42.2)	44.9 ± 7.3 (32.9 - 51.7)	78.6 ± 12.8 (57.3 -90.6)	0.21 ± 0.03 (0.15 - 0.24)
TC	39.7 ± 7.2 (30.6 – 50.3)	48.7 ± 8.8 (37.6 -61.7)	84.2 ± 15.3 (65.4 - 107.1)	0.23 ± 0.04 (0.18 - 0.29)
AG	43.4 ± 18.0 (32.5 – 75.5)	53.2 ± 22.1 (39.8 - 92.5)	93.0 ± 38.6 (70.0 - 161.6)	0.25 ± 0.10 (0.19 - 0.44)
NM	27.0 ± 5.2 (19.9 – 34.1)	33.1 ± 6.3 (24.4 - 41.8)	58.0 ± 11.2 (42.9 - 73.6)	0.16 ± 0.03 (0.12 - 0.20)
KS	33.7 ± 3.2 (29.1 – 37.5)	41.4 ± 3.9 (35.7 - 46.0)	71.9 ± 6.8 (61.7 - 79.6)	0.19 ± 0.02 (0.17 - 0.21)
KH	30.1 ± 9.9 (20.7 – 43.2)	36.9 ± 12.1 (25.4 - 53.0)	64.3 ± 21.0 (44.2 - 92.1)	0.17 ± 0.06 (0.12 - 0.25)
UH	13.5 ± 3.6 (8.9 – 18.4)	16.6 ± 4.4 (10.9 - 22.6)	28.7 ± 7.5 (18.6 -38.3)	0.08 ± 0.02 (0.05 - 0.10)
DR	49.8 ± 9.8 (32.5 – 57.1)	61.0 ± 12.0 (39.9 -70.0)	105.7 ± 20.9 (68.9 -121.6)	0.29 ± 0.06 (0.19 - 0.33)
Average of all ten areas	**32.9 ± 12.5 (8.9 – 75.5)**	**40.4 ± 15.4 (10.9 -92.5)**	**70.4 ± 26.7 (18.6 – 161.6)**	**0.19 ± 0.07 (0.05 – 0.44)**

3.4 Radiological hazards due to the radionuclides in the soil of Otavi

The results obtained for absorbed dose rates, effective dose rates, radium equivalent activity (Ra_{eq}) and external hazard index (H_{ex}) in the ten geographical areas of Otavi are summarized in Table 4. The absorbed dose rates vary from 8.9 ± 1.1 nGy/h (UH area) to 75.5 ± 3.0 nGy/h (AG area), with an overall average of 32.9 ± 12.5 nGy/h as shown in Table 4 (column 2, last row). The mean absorbed dose rate is lowest in the UH area, with a value of 13.5 ± 3.6 nGy/h while it is highest in the DR area with a value of 49.8 ± 9.8 nGy/h as shown in Table 4 (column 2). However, it is not surprising that the highest average absorbed dose rate is observed in the DR area because the area has relatively high concentrations of radionuclides (Table 2, eleventh row). As observed earlier in the case of the Ohorongo cement plant, the average absorbed dose rate in all the ten geographical areas of Otavi (32.9 ± 12.5 nGy/h) is below the worldwide average value of 51.0 nGy/h. The corresponding effective dose rates vary from 10.9 ± 1.3 μSv/y (UH area) to 92.5 ± 3.7 μSv/y (AG area) with an overall average of 40.4 ± 15.4 μSv/y as shown in Table 4, column 3 (bottom row). This average value and the mean effective dose rates at the ten geographical areas are below the MPL of 1.0 mSv/y recommended by ICRP for public exposure as could be seen in Figure 7. These results imply that the town of Otavi has a normal background radiation.

The average radium equivalent activity (Ra_{eq}) and average external hazard index (H_{ex}) in the ten geographical areas of Otavi are shown in Table 4 (columns 4 and 5) respectively. The values of Ra_{eq} vary from a minimum of 18.6 ± 2.4 Bq/kg to a maximum of 161.6 ± 6.9 Bq/kg with an average of 70.4 ± 26.7 Bq/kg as shown in Table 4 (column 4, bottom row). Also, the values of H_{ex} vary from 0.05 ± 0.01 to 0.44 ± 0.02 with an average of 0.19 ± 0.07 as shown in Table 4 (column 5, bottom row). The calculated average values of Ra_{eq} and H_{ex}, are below their corresponding maximum permissible limits of 370 Bq/kg and 1.0 as could be observed in Figures 8 and 9 respectively. The relatively low average values of Ra_{eq} and H_{ex} confirm that radiation hazard is negligible in the town.

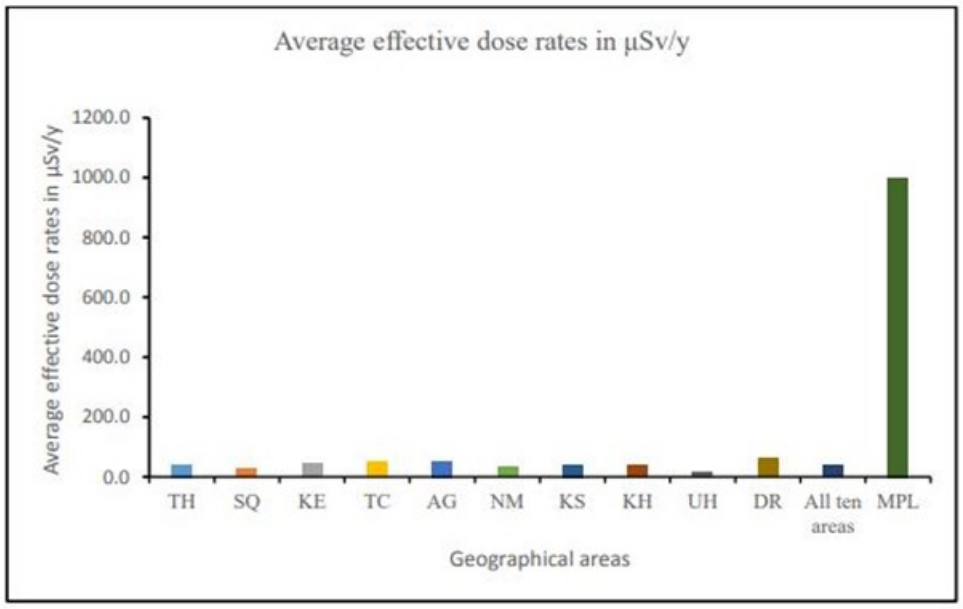


Figure 7: The average effective dose rates in the ten geographical areas of Otavi. The average effective dose rate over all the ten areas and the corresponding MPL are shown in the last two columns.

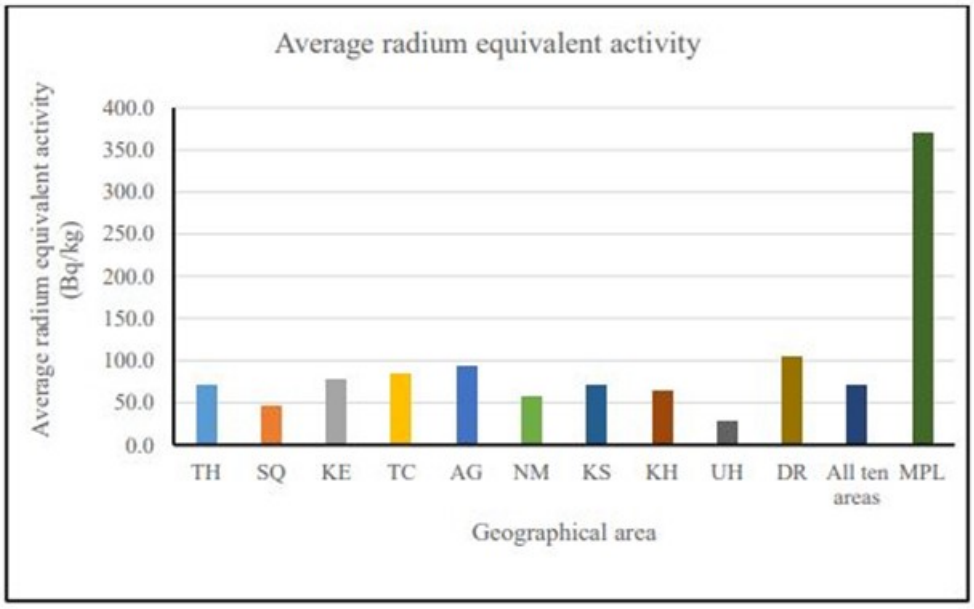


Figure 8: The average radium equivalent activity due to $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the ten geographical areas of Otavi. The average Ra_{eq} over all the ten areas and the corresponding MPL are shown in the last two columns.

4 Discussion

The mean activity concentrations of the radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soils of the different geographical areas of the cement plant and town of Otavi are different from each other. However, the average activity concentration of $^{40}\mathrm{K}$ is the highest among the three radionuclides in all the different geographical areas of the plant and town. This high activity concentration of $^{40}\mathrm{K}$ has also been observed in the soil samples collected in some other towns in Namibia (Shimboyo *et al.*, 2016). In both the plant and town, the mean activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ from all the samples are below the worldwide average values of 35 Bg/kg, 30 Bg/kg and 400 Bg/kg respectively (UNSCEAR, 2000). Different radiological parameters such as effective dose rate and radium equivalent activity were calculated using the activity concentrations. The average effective dose rates of 43.0 ± 14.5 μSv/y and 40.4 ± 15.4 μSv/y obtained for the plant and town respectively are both lower than the corresponding value of 9.5×10^{-2} mSv/y (or 95 μSv/y) obtained for the towns of Karibib and Okahandja in Namibia (Midzi *et al.*, 2019). Also, the average effective dose rates are lower than the corresponding values of 74 μSv/y and 0.63 mSv/y (or 630 μSv/y) obtained for the eastern region of Sichuan province, China, and Northern Rajasthan, India respectively (Wang *et al.*, 2012; Duggal *et al.*, 2014). However, all these different values are lower than the maximum permissible value of 1.0 mSv/y. A comparison of the radiation hazards in the Ohorongo cement plant and the town of Otavi shows that the mean values of the absorbed dose rate, effective dose rate, radium equivalent activity (Ra_{eq}) and external hazard index (H_{ex}) are all slightly higher in the Ohorongo Cement plant (35.1 ± 11.8 nGy/h, 43.0 ± 14.5 μSv/y, 74.9 ± 25.6 Bg/kg and 0.20 ± 0.07 respectively) than in the town of Otavi (32.9 ± 12.5 nGy/h, 40.4 ± 15.4 μSv/y, 70.4 ± 26.7 Bg/kg and 0.19 ± 0.07 respectively. However, all these mean values are lower than the corresponding maximum permissible limit (MPL) thus confirming that the cement plant and the town of Otavi have normal background radiation.

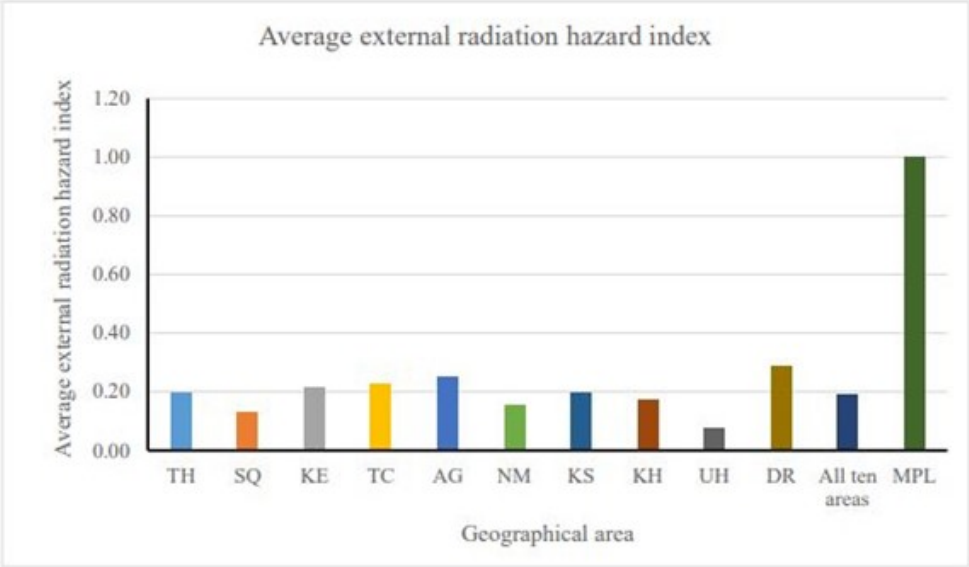


Figure 9: Average external radiation hazard index (H_{ex}) due to primordial radionuclides in the ten geographical areas of Otavi. The average H_{ex} over all the ten areas and the corresponding MPL.

5 Conclusion

The activity concentrations of the radionuclides $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$ in the soil samples collected from the Ohorongo cement plant and the town of Otavi have been determined and used to calculate different radiological parameters. All the average activity concentrations of the three radionuclides in both the cement plant and the town of Otavi are lower than the corresponding worldwide average values. Also, the mean values of the absorbed dose rate, effective dose rate, radium equivalent activity (Ra_{eq}) and external hazard index (H_{ex}) in the plant and town are all lower than the corresponding maximum permissible limit (MPL) thus implying that the cement plant and the town of Otavi have normal background radiation levels and radiological hazard is negligible in the cement plant and town.

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