Radiological analysis of the suitability of Erongo granite for building material

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\textbf{ABSTRACT}

This study measured the natural radioactivity of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in 20 granite samples obtained from the Erongo Mountain Belt and Usakos Dome of the Erongo region, Namibia. All the samples were analysed using high purity germanium (HPGe) detector after 30-days to allow for secular equilibrium. The average activity concentrations of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were $39.22 \pm 3.79 \text{Bqkg}^{-1}$, $35.76 \pm 17.18 \text{Bqkg}^{-1}$ and $1601.45 \pm 212.18 \text{Bqkg}^{-1}$ respectively. The average activity concentrations of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were used to estimate the average hazard indices and the results obtained further showed that radium equivalent activity, absorbed dose rate in air, external hazard indices (in and out), internal hazard index, external radioactivity index, internal radioactivity index, activity utilization index, annual effective dose equivalent (in and out door), exposure rate, and excess lifetime cancer risk were $213.85 \text{Bqkg}^{-1}$, $105.95 \text{nGyh}^{-1}$, $107.11 \text{nGyh}^{-1}$, $0.58$, $0.29$, $0.68$, $0.82$, $0.20$, $1.77$, $0.52 \text{mSv.y}^{-1}$, $0.13 \text{mSv.y}^{-1}$, $462.03 \text{mRh}^{-1}$ and $1.82$ respectively. The results obtained revealed that the radiological hazard indices were lower than their respective acceptable critical values. However, the average value of effective dose equivalent (indoor) obtained was higher than the acceptable limit.

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\section{1. Introduction}

Human population has always received natural radionuclides on a daily basis (Omeje \textit{et al.} 2017). Humans are exposed to radiation externally through two main sources namely; terrestrial gamma rays and cosmic rays. Terrestrial gamma radiation originates from natural radionuclides associated with $^{238}\text{U}$ and $^{232}\text{Th}$ decay series and $^{40}\text{K}$ radionuclide, and are found in the earth’s crust (UNSCEAR 2000; Murty and Karunakara 2008; Psichoudaki and Papaefthymiou 2008). They building materials...
obtained from the earth’s crust (rocks and soils), which contain radionuclides such as Uranium and Thorium series ($^{238}$U and $^{232}$Th) as well as radioactive isotope of Potassium ($^{40}$K), which are emitters of either beta or alpha particles may be ingested or inhaled and can ultimately increase internal exposure. Moreover, other radiation emitters may emit gamma radiation following their nuclear decay (Sharma et al.)
Since natural radionuclides are not uniformly distributed, the knowledge of the natural radioactivity in building materials is important for the evaluation of population exposure to radiation, and as most individuals spend more than 80% of their time indoors, the internal and external radiation exposures from building materials create prolonged exposure situations (ICRP 1999; Lu and Zhang 2007).

Granite is an intrusive igneous rock that is strongly enriched with Uranium (U) and Thorium (Th) (on an average content, 5 ppm Uranium and 15 ppm Thorium) (Faure 1986; Ménager et al. 1994). For centuries, granite has been widely used in building construction and architectural design. Granitic materials are exteriorly used in building bridges, paving and monuments (El-Taheer et al. 2004). In addition, interior indoor polished granite slabs and tiles are used in countertops, tile floor and stair treads (Allam et al. 2013). In building construction, the existence of natural radionuclides in the granite may lead to undesirable radiation exposure to the public (Omeje et al. 2018). Most worrisome is the fact that the concentrations of $^{238}U$, $^{232}Th$ and $^{40}K$ in building material such as granite vary depending on the local geological and geographical conditions as well as the geochemical characteristics of the parent materials (Joel et al. 2018). A large number of studies carried out in the Erongo region of Namibia have shown that some parts of the Erongo region have high background radiation (Zivuku et al. 2016; Onjefu et al. 2017; Zivuku et al. 2018).

Thus, in this study, the radiological analysis of granite samples collected from Erongo granite belt and Usakos dome was carried out to assess the radiation exposure risk associated with the use of that granite which has found wide applications as building and ornamental materials in Namibia and sub region.

2. Methods and materials

2.1. Study area

The study area is located along the D1935 road and north of Usakos town in the Erongo Region, western central Namibia (Figure 1). Earlier study indicated that the granite covered in this study falls within the Central Zone of the Damara orogen, Namibia. The granite in the area forms part of the regionally widespread granite suite that intruded the local landscape of amphibolite-facies rocks of the Damara Super-group at ca. 550-540 Ma (Miller and Mc 1983). It is a product of millions of years of geological evolution of continental mass collisions, melting and cooling processes. The earliest granites are represented by biotite-rich megacrystic granites, followed by leucocratic megacrystic granites and a final stage of voluminous, garnetiferous and tourmaline-bearing, medium-grained leucogranites (Ostendorf and Jung 2010).

Granites are key sources of modern raw material-base and supports for both large and small-scale building industries in Namibia. The different granite-based industries in Namibia include:

(i) Large-scale uranium mining such as the Rössing Uranium Mine;
(ii) Medium size dimension stone mining widely used for kitchen decorations, table tops, tiles, building interior and exterior walls cladding, tombstones,
monuments as well as various construction and decorative applications of granite-based fragments, and;

(iii) Small-scale gemstones mining widely used in granite landscapes.

Granites are also part of the natural landscape and underground conditions where houses, settlements and towns are built, and the fractured granite terrains are a great source of groundwater supply for rural communities in the arid and semiarid regions of Namibia including the Usakos area.

The industrial and socio-economic significance of these granite rocks in Namibia clearly show that the people are in constant contact with these rocks at various levels of the society. In addition to their various minerals compositions, granites are also a source of radioactivity linked to their contents of some accessory minerals such as uranium, thorium, and potassium. Thus, it is expedient to determine the levels of radioactivity associated with granites, such as the Erongo granite which found wide applications under different local conditions, and advise on its suitability as building material based on regulatory guideline limits.

2.2. Samples collection and preparations

In this study, 20 samples of granites were collected from two different mining areas in the Erongo region: Erongo mountain belt and Usakos dome as listed in Table 1. Each labelled sample was crushed and ground to small powder in an agate motor separately. After which 1 kg in weight were dried in an oven at about 110°C to ensure the complete removal of moisture content. The oven-dried samples were

| Location        | Sample ID | $^{226}$Ra (Bq kg$^{-1}$) | $^{232}$Th (Bq kg$^{-1}$) | $^{40}$K (Bq kg$^{-1}$) |
|-----------------|-----------|---------------------------|---------------------------|--------------------------|
| EMB EMB-1       | 66.68 ± 12.99 | 8.87 ± 1.01               | 893.67 ± 117.06           |
| EMB EMB-2       | 24.18 ± 2.14  | 5.88 ± 0.77               | 1029.56 ± 134.80          |
| EMB EMB-3       | 22.96 ± 2.04  | 3.46 ± 0.59               | 1403.00 ± 183.50          |
| EMB EMB-4       | 32.76 ± 2.85  | 5.64 ± 0.77               | 1303.99 ± 170.62          |
| EMB EMB-5       | 32.32 ± 2.83  | 5.55 ± 0.36               | 1690.26 ± 220.98          |
| EMB EMB-6       | 35.04 ± 3.07  | 3.62 ± 0.61               | 1143.17 ± 187.29          |
| EMB EMB-7       | 23.38 ± 2.09  | 5.02 ± 0.67               | 1010.30 ± 132.30          |
| EMB EMB-8       | 28.12 ± 2.48  | 3.87 ± 0.42               | 1074.34 ± 140.63          |
| EMB EMB-9       | 152.71 ± 13.10 | 2.35 ± 0.40             | 1351.41 ± 176.80          |
| EMB EMB-10      | 21.27 ± 1.89  | 2.07 ± 0.34               | 2029.86 ± 283.13          |
| EMB EMB-11      | 20.21 ± 1.80  | 10.02 ± 1.07              | 1157.00 ± 151.40          |
| Usakos Dome UD-12 | 10.78 ± 1.01 | 4.73 ± 0.70               | 2166.61 ± 283.13          |
| Usakos Dome UD-13 | 25.35 ± 2.24 | 7.95 ± 0.86               | 1878.18 ± 245.56          |
| Usakos Dome UD-14 | 106.46 ± 9.15 | 207.42 ± 17.14          | 2095.49 ± 273.93          |
| Usakos Dome UD-15 | 31.81 ± 2.79 | 10.99 ± 1.22              | 1971.53 ± 257.70          |
| Usakos Dome UD-16 | 38.99 ± 3.41 | 207.54 ± 17.18          | 2067.06 ± 270.12          |
| Usakos Dome UD-17 | 44.62 ± 3.89 | 197.92 ± 16.34          | 1992.28 ± 260.20          |
| Usakos Dome UD-18 | 19.34 ± 1.73 | 5.15 ± 0.81              | 1670.61 ± 218.44          |
| Usakos Dome UD-19 | 21.84 ± 1.94 | 5.55 ± 0.81              | 2306.98 ± 301.51          |
| Usakos Dome UD-20 | 25.59 ± 2.26 | 11.69 ± 1.13             | 1793.66 ± 234.46          |
| Minimum         | 10.78 ± 1.01  | 2.07 ± 0.34               | 893.67 ± 117.06           |
| Maximum         | 106.46 ± 9.15 | 207.54 ± 17.18          | 2306.98 ± 301.51          |
| Average         | 39.22 ± 3.79  | 35.76 ± 3.16             | 1601.45 ± 212.18          |
| MPL            | 35         | 45                       | 420                     |

Key: EMB = Erongo Mountain Belt, UD = Usakos Dome, MPL = Maximum permissible limit
transferred into 500 ml Marinelli beakers, firmly sealed, and stored for four weeks to ensure secular equilibrium is attained (Onjefu et al. 2017).

2.3. Gamma spectroscopy analysis of the radionuclides

The counting time for each prepared sample was measured for 50,000–100,000 s depending on the concentration of the radionuclides using the coaxial high purity germanium (HPGe) detector (ORTEC model GC4520 SN 10882) with a relative efficiency of 45% and full width at half maximum (FWHM) of 1.7 keV energy resolution for the 1332 keV gamma ray line of $^{60}$Co. The spectrum was analyzed using Genie 2000 software made by Canberra Industries Inc, USA. The detector is 10-cm thickness lead to reduce the background radiation from other sources.

The gamma spectrometry system was energy calibrated using a range of gamma-ray energies from 0.060 MeV to 2 MeV, and efficiency calibrated using a mixed radionuclides standard in a 500 ml Marinelli beaker, counted for 12 hours. The energy range were analysed for absolute photo-peak efficiency and energy calibration of the HPGe detector using a multi-nuclide calibration standard with an initial activity of 40 kBq homogeneously distributed in silicone matrix, supplied by Eckert & Ziegler Nuclitec GmbH, Germany, SN. AM 5599.

Energy calibration was performed by matching the gamma energy peaks in the spectrum of the reference standard with the spectrometer channel number. The centroid channels and corresponding radionuclide energy peaks were then recorded and used to make a calibration curve of Energy versus Channel Number. The calibration curve performed through the counting of standard radionuclides with known activities and gamma energy peaks from 60 keV to 2000 keV.

The efficiency calibration was validated by running the same standard and analysed against certified activity. The mathematical efficiency was calculated from Equation 1.

$$\eta(E) = \frac{N_T - N_B}{P_E A_{STD} T_{STD}}$$

where $N_T$ represents the total counts under a photopeak, $N_B$ denotes the background count, $P_E$ is the gamma ray yield, $A_{STD}$ represents the activity of calibration standard during the time of measurement in Becquerels (Bq), while $T_{STD}$ represents the counting time of the standard.

The energy calibration and relative efficiency calibration in this study used the gamma sources of $^{60}$Co and $^{40}$K because of the wide range of gamma-ray energies emitted over the entire energy range of interest. The activity concentration of $^{226}$Ra was determined as the weighted mean from the average concentrations of $^{214}$Pb gamma transition of 295.21 keV and 351.92 keV and $^{214}$Bi gamma transition of 609.32 keV. Similarly, the gamma-ray lines of $^{212}$Pb (238.63 keV), $^{208}$Ti (583 keV), $^{228}$Ac (911 keV) and $^{228}$Ac (969 keV) were employed for the activity concentration for $^{232}$Th. The activity concentration of $^{40}$K was determined by its single gamma transition of 1461 keV. Each radionuclide activity was obtained using Equation 2 (IAEA 1989a):
where \( A \) is the activity concentration in Bq kg\(^{-1}\) of each radionuclide in the granite sample, \( N \) represent the net number of count in the photo peak, \( \varepsilon_\gamma \) is the detector efficiency of the specific gamma-ray, \( \rho_\gamma \) is the intensity at the corresponding gamma-ray energy, \( T_s \) is the time taken for each sample to be counted in seconds and \( M \) denotes the mass of the sample in kg.

### 3. Results and discussion

#### 3.1. Radioactivity concentrations

The distribution of natural radionuclides in granite samples is presented in Table 1. The highest activities concentrations of \(^{226}\)Ra, \(^{232}\)Th, and \(^{40}\)K in the granite samples are 106.46 ± 9.15 Bq kg\(^{-1}\) (Usakos Dome), 207.54 ± 17.18 Bq kg\(^{-1}\) (Usakos Dome), and 2306.98 ± 301.51 Bq kg\(^{-1}\) (Usakos Dome), respectively, while the lowest result obtained in the same granite samples were 10.78 ± 1.01 Bq kg\(^{-1}\) (Usakos Dome), 2.07 ± 0.34 Bq kg\(^{-1}\) (Erongo Mountain Belt), and 893.67 ± 117.06 Bq kg\(^{-1}\) (Erongo Mountain Belt) respectively. The average value of \(^{226}\)Ra is 39.22 ± 3.79 Bq kg\(^{-1}\) and it was found to be 0.78 time lower than the permissible maximum value of 50 Bq kg\(^{-1}\) (UNSCEAR 2008). For \(^{232}\)Th, the average value obtained was 35.76 ± 3.16 Bq kg\(^{-1}\) and is lower than the allowed value of 50 Bq kg\(^{-1}\) by a factor of 0.72 (UNSCEAR 2008). However, the average value of \(^{40}\)K (1601.45 ± 212.18) was higher than the permissible maximum value of 500 by a factor of 3.20 (UNSCEAR 2008; Sahin 2018). The higher average value of \(^{40}\)K may be attributed to the chemical composition and formation of molten rock with a simultaneous sedimentation of mineral particles containing uranium and thorium, which may have informed the elevated activity concentrations (Omeje et al. 2018).

The average activity concentrations of \(^{226}\)Ra, \(^{232}\)Th, and \(^{40}\)K in the samples follow the order of \(^{40}\)K > \(^{226}\)Ra > \(^{232}\)Th. This result is consistent with the finding of an earlier study by Omeje et al. (2018). The results of the activity concentrations of \(^{226}\)Ra and \(^{232}\)Th in this work are lower than the results for granite in Turkey, Egypt, Greece and Brazil (Moura et al. 2011; Amin 2012; Onargan et al. 2012; Papadopoulos et al. 2011).
However, the concentration of $^{40}$K was higher than the results of $^{40}$K published in these countries. The results of the correlation analyses between the average activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K as shown in Figures 2–4 revealed weak positive correlations with respective coefficient of $(R^2 = 0.01)$ for $^{40}$K and $^{226}$Ra, $(R^2 = 0.184)$ for $^{40}$K and $^{232}$Th, and $(R^2 = 0.09)$ for $^{232}$Th and $^{226}$Ra. The weak positive correlations indicate that while the activity concentrations of these radionuclides tend to go up in response to one another, the relationship between them is not very strong and hence, could be attributed to their varying sources of inputs in the granite.

3.2. Radiological health risk parameters

3.2.1. Radium equivalent ($R_{eq}$) activity

In order to overcome the non-uniformity of radionuclides $^{226}$Ra, $^{232}$Th, and $^{40}$K in natural samples, the radium equivalent activity ($R_{eq}$) index was used. $R_{eq}$ activities for all the samples were obtained on the basis of the estimation of $370 \text{ Bq kg}^{-1}$ of $^{226}$Ra, $259 \text{ Bq kg}^{-1}$ of $^{232}$Th, and $4810 \text{ Bq kg}^{-1}$ of $^{40}$K (Beck 1980; Krieger 1981; Beretka 1985; IAEA 1989b; Papadopoulos et al. 2013). The $R_{eq}$ measured in Bq kg$^{-1}$ was calculated using Equation 3:

$$R_{eq} = C_{Ra} + 1.43 \ C_{Th} + 0.077 \ C_{K} \tag{3}$$

where $C_{Ra}$, $C_{Th}$, and $C_{K}$ are the specific activities of $^{226}$Ra, $^{232}$Th, and $^{40}$K measured in Bq kg$^{-1}$, respectively. The $R_{eq}$ values obtained in this study varied from the maximum concentration of 564.42 Bq kg$^{-1}$ in Usakos Dome to the minimum concentration of 108.35 Bq kg$^{-1}$ in Erongo Mountain Belt, with an average concentration value of 213.85 Bq kg$^{-1}$. Although the average concentration of the $R_{eq}$ in this study is below the critical value of 370 Bq kg$^{-1}$, values from UD-14, UD-16 and UD-17 exceeded the recommended limit of 370 Bq kg$^{-1}$ (UNSCEAR 2000). On comparing between Erongo Mountain Belt (EMB) and Usakos Dome (UD), it was observed that values of $R_{eq}$ obtained for EMB were lower than those obtained for UD (Table 2). This could be attributed to the high activity concentrations of radionuclides distribution in the granite samples from Usakos Dome. The granite samples from Usakos Dome contain more of these radioactive elements than those of EMB, and this depends on the chemical composition and formation of the parent rock. Geologists
provide an explanation of this behaviour in the course of partial melting and fractional crystallization of magma (Aquino and Pecequilo 2015). The correlation analysis between \( R_{aeq} \) and \(^{226}\text{Ra} \) activity concentration also indicated weak positive correlation with coefficient of \( R^2 = 0.223 \) as shown in Figure 5.

### 3.2.2. Absorbed gamma dose rate in air (\( D_{air} \))

The terrestrial absorbed dose rates due to terrestrial gamma rays at 1 m above the ground surface were evaluated from the activity concentrations of \(^{226}\text{Ra}, \ ^{232}\text{Th}, \) and

![Figure 4. The correlation between \(^{232}\text{Th} \) and \(^{226}\text{Ra}\) activity concentrations in the samples.](image-url)

![Table 2. Radium equivalent (\( R_{aeq} \)), indoor absorbed dose rate in air (\( D_{air-in} \)), outdoor absorbed dose rate in air (\( D_{air-out} \)), indoor external hazard index (\( H_{ext(in)} \)), outdoor external hazard index (\( H_{ext(out)} \)), and internal hazard index (\( H_{in} \)) recorded in the different granite samples.](table-url)
40K using the conversion factors (0.462, 0.604 and 0.0417, respectively), as given by UNSCEAR (UNSCEAR 2000) and Sahin (UNSCEAR 2008). The indoor absorbed dose rate in air ($D_{air-in}$) measured in unit of nGyh$^{-1}$ was calculated using Equation 4 (UNSCEAR 2008):

$$D_{air-in}(\text{nGyh}^{-1}) = 0.462C_{Ra} + 0.604C_{Th} + 0.0417C_{K}$$

(4)

The calculated indoor absorbed gamma dose rate in air ($D_{air-in}$) ranged between 55.96 and 261.84 nGyh$^{-1}$. All the present ($D_{air-in}$) values, except for seven granite samples (EMB-1, EMB-2, EMB-3, EMB-4, EMB-6, EMB-7, EMB-8), are higher than the critical value of 80 nGyh$^{-1}$ (Table 2). This suggests that people using these samples will receive the excessive gamma radiation that may demand further attention from radiation safety point of view.

The conversion coefficients used to evaluate the outdoor absorbed gamma dose rate in air ($D_{air-out}$) per unit radioactivity concentration of 226Ra, 232Th, and 40K in (1Bqkg$^{-1}$) was calculated using the relationship in Equation 5 (UNSCEAR 2008):

$$D_{air-out}(\text{nGyh}^{-1}) = 0.462C_{Ra} + 0.621C_{Th} + 0.0417C_{K}$$

(5)

The outdoor absorbed dose rate ($D_{air-out}$) recorded in this study varied from 56.05 to 265.37 nGyh$^{-1}$. The average value of ($D_{air-out}$) due to the presence of 226Ra, 232Th, and 40K in the samples was 107.11 nGyh$^{-1}$. This value is higher than the critical value of 57 nGyh$^{-1}$ by a factor of 1.9 (Table 2) owing to the contribution from some granite rock samples of high thorium and potassium content. Again, these contributions are consistent with those obtained for indoor absorbed dose rate in air.

3.2.3. External hazard index ($H_{ex}$)

The external hazard index ($H_{ex}$) calculated from the activity concentrations of 226Ra, 232Th, and 40K determined in the present study is shown in Table 2. The $H_{ex}$ was calculated for two cases. Case 1, $H_{ex(in)}$ is a scenario for a room in the house where the inhabitants live with infinitely thick walls without windows and doors for good ventilation (Cox 1991; Al-Zahrani 2017). Case 2, $H_{ex(out)}$ is a scenario for a room in...
the house where the inhabitants live with infinitely thick walls having windows and doors for proper ventilation (Darwish et al. 2015; Maxwell et al. 2018). $H_{\text{ex(in)}}$ and $H_{\text{ex(out)}}$ were estimated using Equations 6 and 7 respectively.

$$H_{\text{ex(in)}} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810}$$ (6)

$$H_{\text{ex(out)}} = \frac{A_{Ra}}{740} + \frac{A_{Th}}{518} + \frac{A_{K}}{9620}$$ (7)

where $A_{Ra}$, $A_{Th}$, and $A_{K}$ are the average activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in Bq kg$^{-1}$ respectively.

For the radiation hazard to be acceptable, it is recommended that the values of $H_{\text{ex(in)}}$ and $H_{\text{ex(out)}}$ be less than unity (Baykara et al. 2011; Allam et al. 2013). The calculated values of $H_{\text{ex(in)}}$ in all samples from the Erongo Mountain Belt are lower than the 1 limit value. However, the values of $H_{\text{ex(in)}}$ in Usakos Dome UD-14 and UD-16 exhibited higher values greater than 1. It may be due to the geological formation of UD-14 and UD-16. The estimated $H_{\text{ex(out)}}$ for all the samples varied from 0.15 to 0.76 with an average value of 0.29.

### 3.2.4. Internal hazard index ($H_{\text{in}}$)

The internal hazard index for this present study is shown in Table 2. This index gives the internal exposure to radon and its progeny and was calculated using Equation 8 (Bendibbie et al. 2013; Papadopoulos et al. 2013):

$$H_{\text{in}} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810}$$ (8)

For a building material to be considered radiologically safe, the internal hazard must be less than 1 (Xinwei 2005; Ghose et al. 2012; Onjefu et al. 2017). In the present study, all the values of $H_{\text{in}}$ are less than 1 except EMB-9, UD-14, UD-16 and UD-17 where the samples exhibited higher values than the 1 limit value, due to the high activity concentrations of radionuclides distribution in the samples. This suggests that the granite samples are not radiologically safe to use in building construction without restrictions because of its $^{40}$K and $^{232}$Th content that were twice as much as the average values.

### 3.3.5. External radioactivity level index ($I_{\gamma}$)

The external radioactivity level index which give the distribution of the values of the gamma index for the building materials measured in this study are presented in Table 3. The recommended critical value is unity (UNSCEAR 2008). According to European Commission Radiation Protection Report (EC-RP 112), controls on the activity concentrations of any material employed for building purposes can be based on the dose criterion and exemption level. Effective dose exceeding the dose criterion of 1 mSv y$^{-1}$ should be important in terms of radiation protection and safety (Kant et al. 2006; UNSCEAR 2008; Alharbi et al. 2011; Sahin 2018).
The external radioactivity level index \( (I_\gamma) \) is calculated using Equation 9 (EC 1999):

\[
I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000}
\]

As shown in Table 3, the values of \( I_\gamma \) ranged from 0.44 to 2.09 with an average value of 0.82. Clearly, the results of the calculated values of \( I_\gamma \) in the samples shows higher values for samples UD-14, UD-16, and UD-17 than the recommended limit of unity. These high values may be attributed to the kind of soil, rock and geological formation of the samples (UNSCEAR 2008).

### 3.3.6. Internal radioactivity level index \( (I_\infty) \)

The internal radioactivity index \( (I_\infty) \) is an important index associated with excess alpha radiation from radon emanating from building materials. If the radium activity level in building material exceeds the values of 200 Bqkg\(^{-1}\), there may be radon build up exceeding 200 Bq.m\(^{-3}\). The International Commission on Radiation Protection recommended an action level of 200 Bq.m\(^{-3}\) for radon in dwellings structures (Kant et al. 2006; Uosif et al. 2014; Omeje et al. 2018). Similarly, radium activity levels below 100 Bqkg\(^{-1}\) is indicative of radon exhalation from building materials which may not cause indoor concentration greater than 200 Bq.m\(^{-3}\) (ICRP 1994). The critical value of \( (I_\infty) \) is 1 and is calculated from equation 10 (UNSCEAR 2008; Xinwei and Xiaolon 2008):

### Table 3. External radioactivity level index \( (I_\gamma) \), internal radioactivity level index \( (I_\infty) \), activity utilization index \( (I) \), indoor annual effective dose equivalent \( (AEDE_{in}) \), outdoor annual effective dose equivalent \( (AEDE_{out}) \), exposure rate \( (ER) \), and excess lifetime cancer risk \( (ELCR) \) of the granite samples.

| Location       | Sample ID | \( I_\gamma \) | \( I_\infty \) | \( I \) | \( AEDE_{in} \) | \( AEDE_{out} \) | \( ER \) (\( \mu \text{R} \cdot \text{h}^{-1} \)) | \( ELCR \) (mSv.y\(^{-1} \)) |
|----------------|-----------|----------------|----------------|--------|----------------|----------------|------------------|------------------|
| EMB EMB-1      | 0.54      | 0.33           | 0.99           | 0.36   | 0.09           | 311.64         | 1.26              |
| EMB EMB-2      | 0.45      | 0.12           | 1.00           | 0.28   | 0.07           | 246.81         | 0.98              |
| EMB EMB-3      | 0.46      | 0.13           | 1.30           | 0.35   | 0.09           | 304.52         | 1.23              |
| EMB EMB-4      | 0.57      | 0.16           | 1.25           | 0.36   | 0.09           | 311.56         | 1.26              |
| EMB EMB-5      | 0.70      | 0.16           | 1.59           | 0.44   | 0.11           | 379.62         | 1.54              |
| EMB EMB-6      | 0.52      | 0.18           | 1.10           | 0.32   | 0.08           | 281.41         | 1.12              |
| EMB EMB-7      | 0.44      | 0.12           | 0.97           | 0.27   | 0.06           | 239.42         | 0.95              |
| EMB EMB-8      | 0.47      | 0.14           | 1.03           | 0.30   | 0.07           | 256.65         | 1.05              |
| EMB EMB-9      | 0.97      | 0.76           | 1.46           | 0.63   | 0.16           | 538.68         | 2.21              |
| EMB EMB-10     | 0.76      | 0.11           | 1.84           | 0.47   | 0.12           | 409.60         | 1.65              |
| EMB EMB-11     | 0.50      | 0.10           | 1.15           | 0.31   | 0.07           | 273.76         | 1.09              |
| Usakos Dome UD-12 | 0.78  | 0.05           | 1.97           | 0.48   | 0.12           | 421.64         | 1.68              |
| Usakos Dome UD-13 | 0.75  | 0.13           | 1.77           | 0.47   | 0.12           | 406.78         | 1.65              |
| Usakos Dome UD-14 | 2.09 | 0.53           | 4.01           | 1.29   | 0.33           | 1162.29        | 4.52              |
| Usakos Dome UD-15 | 0.81  | 0.16           | 1.89           | 0.48   | 0.13           | 444.33         | 1.68              |
| Usakos Dome UD-16 | 1.86 | 0.19           | 3.87           | 1.10   | 0.29           | 1029.35        | 3.85              |
| Usakos Dome UD-17 | 1.80 | 0.22           | 3.72           | 1.10   | 0.28           | 999.53         | 3.85              |
| Usakos Dome UD-18 | 0.65  | 0.10           | 1.55           | 0.40   | 0.10           | 350.31         | 1.40              |
| Usakos Dome UD-19 | 0.87  | 0.11           | 2.12           | 0.54   | 0.13           | 470.10         | 1.89              |
| Usakos Dome UD-20 | 0.74  | 0.13           | 1.73           | 0.46   | 0.12           | 402.65         | 1.61              |
| Minimum     | 0.44      | 0.05           | 0.97           | 0.27   | 0.06           | 239.42         | 0.95              |
| Maximum     | 2.09      | 0.53           | 4.01           | 1.29   | 0.33           | 444.33         | 4.52              |
| Average     | 0.82      | 0.20           | 1.77           | 0.52   | 0.13           | 462.03         | 1.82              |
| Critical value | 1        | 1              | 2              | 0.48   | 0.48           | 600            | 0.29              |

Key: EMB = Erongo Mountain Belt, UD = Usakos Dome
The calculated results of $I_x$ in the present study varied from 0.05 to 0.53 with an average value of 0.20. This results obtained for $I_x$, suggest that all the samples have values smaller than the recommended limit of 1 (Table 3).

### 3.3.7. Activity utilization index ($I$)

The natural radionuclides activity concentrations ($^{226}$Ra, $^{232}$Th, and $^{40}$K) in building materials are the main contributors that affect the indoor absorbed dose. The calculation of the activity utilization index involves the combination of the activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K and is evaluated using Equation 11 (UNSCEAR 2000):

$$I = \frac{A_{Ra}}{50} f_{Ra} + \frac{A_{Th}}{50} f_{Th} + \frac{A_{K}}{500} f_{K}$$

where $f_{Ra}$, $f_{Th}$ and $f_{K}$ are fractional percentages to the total dose rate from $^{226}$Ra, $^{232}$Th, and $^{40}$K, respectively ($f_{Ra} = 8.09\%$, $f_{Th} = 47.98\%$, $f_{K} = 43.98\%$) (UNSCEAR 2008). The activity utilization index is 2 by definition and it implies a dose rate of 80 nGy h$^{-1}$ (UNSCEAR 2000). As presented in Table 3, activity utilization index ($I$) of the radionuclides studied varied from 0.97 to 4.01. The highest value of 4.01 was recorded at Usakos Dome-14 and the lowest value of 0.97 was noted in Erongo Mountain Belt. However, all the samples recorded activity utilization index below the critical value of 2 except for UD-14, UD-16 and UD-17 respectively with values above 2.

### 2.3.8. Annual effective dose equivalent (AEDE)

The indoor and outdoor annual effective dose equivalent is estimated from the indoor absorbed dose rate in air ($D_{air-in}$) and outdoor absorbed gamma dose rate in air ($D_{air-out}$), the occupancy factors of 80% and 20% and 8766 h in a year. AEDE in this present study was determined using the relation in Equations 12 and 13 below:

For indoor:

$$AEDE_{in} = D_{air-in} (nGy^{-1}) \times 8766 \text{ h} \times 0.8 \times 0.7 \text{ Sv Gy}^{-1} \times 10^{-6}$$

For outdoor:

$$AEDE_{out} = D_{air-out} (nGy^{-1}) \times 8766 \text{ h} \times 0.2 \times 0.7 \text{ Sv Gy}^{-1} \times 10^{-6}$$

where 0.7 Sv Gy$^{-1}$ is the conversion factor used to convert the absorbed dose in air to effective dose received by the adult (Usif et al. 2014).

The values of AEDE ranged from 0.27 to 1.29 mSv.y$^{-1}$ for indoor and 0.06 to 0.33 mSv.y$^{-1}$ for outdoor. The average values were found to be 0.52 mSv.y$^{-1}$ and 0.13 mSv.y$^{-1}$ for indoor and outdoor respectively. The average value of $AEDE_{in}$ is higher than the critical value by a factor of 1.08 while the value of $AEDE_{out}$ is lower.
than the critical value by a factor of 0.27. The high average value of $AEDE_{in}$ may be attributed to the presence of relatively high amount of radioactivity in some monitoring locations. The variation of natural radioactivity levels at the different sampling sites was due to the variation of concentrations of radionuclides in the geological formations. Hence, the variation in the $AEDE$. According to Kinyua et al. (2011), younger granites represent the highest elevation while the older rock is relatively low. The presence of such high values in younger granites may be attributed to the presence of relatively increased amount of accessory minerals such as zircon, iron oxides, fluorite and other radioactive related minerals.

3.3.9. Exposure rate (ER)
The exposure rate was estimated using the relation in Equation 14 (Kinyua et al. 2011).

$$ER(\mu Rh^{-1}) = 1.90A_{Ra} + 2.82A_{Th} + 0.179A_K$$ (14)

The calculated values of $ER$ are presented in Table 3 and the results ranged from 239 to 1162 $\mu Rh^{-1}$ with an average value of 462.03 $\mu Rh^{-1}$. All the samples were below the recommended limit. However, samples UD-14, UD-16 and UD-17 displayed a higher value than the critical limit of 600 $\mu Rh^{-1}$. Again, these values are consistent with those of internal and external hazard indices, activity utilization index, and the internal and external radioactivity indices. Therefore, the samples may pose an internal radiological risk when used as building material.

3.3.10. Excess lifetime cancer risk (ELCR)
Excess lifetime cancer risk (ELCR) was evaluated by using the relation in Equation 15:

$$ELCR = AEDE \times DL \times RF$$ (15)

where $DL$ is the duration of life taken to be 70 years and $RF$ is risk factor ($Sv^{-1}$) fatal cancer risk per Sievert. For stochastic effect, (ICRP 60) employs the value of 0.05 for the general public (UNSCEAR 2000; Akhtar et al. 2005; Taskin et al. 2009). The calculated values of ELCR in the present study are presented as Table 3. The mean value for ELCR was estimated and found to be below the recommended limit of $3.75 \times 10^{-3}$ (UNSCEAR 2000). However, the values of samples UD-14, UD-16 and UD-17 were above the critical value. This might constitute population exposure concerns from the three-sampled points, as granites obtained from the study area are valuable building materials widely used in Namibia. It has been identified that long-term exposure to radiation has some risks of causing cancer (Holm and Ballestra 1989). Radiation exposure can cause cancer in any living tissue, but high-dose whole-body external exposure is mostly associated with leukemia (Ménager et al. 1994). This is even as research report has shown that in today’s world, cancer is a major disease for communities (Ibikunle et al. 2018) and that one of the cancer reasons is the radiation effect on biological cell (US EPA 1999; Abbasi 2017; Abbasi and Bashiry 2020). Elsewhere in the United States of America, report from Surveillance, Epidemiology, and End Results (SEER) Cancer Statistics Review by the National Cancer institute
showed that American men have a 44% lifetime risk of cancer, while their women have a 38% lifetime risk (Holm and Ballestra 1989). The review further showed that long time exposure to cancer-causing materials resulted in additional risk that someone might have cancer in a lifetime (Holm and Ballestra 1989). This is a major concern in the study area as the radiation-bearing granites are utilized in different forms for building houses where humans live for their lifetime.

4. Conclusion

The levels of natural radioactivity of $^{226}$Ra, $^{232}$Th and $^{40}$K in granite samples collected from Erongo granite belt and Usakos dome were determined using gamma ray analysis, and to assess the radiation exposure risk associated with the use of the granite widely used as building and ornamental materials in Namibia and the sub region. Based on the results obtained, the average activity concentrations of $^{226}$Ra and $^{232}$Th in the granite samples were below their maximum permissible values for the protection of human health. However, the average activity concentration of $^{40}$K in the granite samples was higher than its acceptable health regulatory limit. In particular, the calculated radiological parameters for the granite samples UD-14, UD-16 and UD-17 exceeded their health regulatory limits and thus, present radiological exposure risk to humans in using the granite as building and ornamental materials. It is therefore recommended that all appropriate regulatory measures in compliance with the basic safety standards to minimize indoor exposure to natural radionuclides should be adopted to screen the granite in the study area prior to its use as building and ornamental materials. This could help towards devising practical approaches aimed at minimizing natural radiation exposure associated with the use of the granite as building materials.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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