

**ORIGINAL RESEARCH ARTICLE****Naturally occurring radioactive materials and their activity levels in “machine-cut stone” quarries in Juja Sub County, Kiambu County, Kenya**

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ABSTRACT

Naturally occurring radioactive materials and their activity levels among “machine-cut stone handlers in selected” quarries in Juja Subcounty, Kiambu County, Kenya,”. Radiation occurs naturally in the environment; levels depend on the occurrence of natural radionuclide. Open cast mining exposes the radionuclides hidden deep in the earth. Radionuclides in quarry products are of concern especially in construction materials. The main objective was to determine the occurrence and activities of naturally occurring radioactive materials (NORM); ²³²Th, ²³⁸U and ⁴⁰K in “Machine cut stone handlers in selected” quarries in Kiambu County. The subjects were recruited randomly from the selected quarries and samples obtained from the study sites. The sampling frame was developed from the list of all quarries in Kiambu. The quarries that met the selection criteria were randomly selected from the list of all quarries in Kiambu. Data was collected until the level of saturation was achieved. Samples of quarry dust were collected from the selected 25 quarries in Juja sub-county which process rock into machine cut stones for construction of houses. The quarry dust samples were collected from the topmost points and the bottom (deepest) parts of the quarries. Quantitative data was collected in questionnaires coded cleaned and entered in Microsoft Access and exported in SPSS Version 23.0 for analysis. Composite samples were crushed into powder and passed under sieves to give a consistent homogeneous powder. NORM activity concentrations were determined using Gamma spectroscopy employing the SpectraLineGP software recorded as Becquerel per Kilogram (Bq/Kg). The active quarries ranged between 6-24 months with most having been in operation for a period of 24 months. The quarries-based on meters above sea level were in the range of 1466 – 1531 masl with a mean of 1494.88±13.88 masl. The NORM Activity concentrations of ²³²Th, ²³⁸U and ⁴⁰K were determined in Quarry dust in Bq/kg with slight variations between the sites. The order of the radioisotopes in ascending order was ⁴⁰K> ²³²Th>²³⁸U. The range of the means were 71.1 – 152.2 for ²³²Th, 40.5-107.4 for ²³⁸U whereas that of ⁴⁰K was in the range of 763.8 – 1661.2 Bq/Kg. The study revealed that stones from some of the quarries studied had risk of exposure to occupants of machine cutting had 2 odds of risks from quarry dust due to failure to use personal protective equipment’s 0.05). The houses had low risk (to ionizing radiations p value >0.05 at 95% Confidence interval).

Key Words: Radioactive, Radionuclides, Alpha, Beta, Gamma

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1.0 Introduction

Radiation can be found naturally within our environment. However, their distribution within a region depends on their absorption levels. They are abundant in both working and public environments, although their activity concentrations vary considerably (IAEA, 2005). The occurrence of these radionuclides in construction materials, mainly from quarry products is due to the gamma radiation of ^{40}K and members of Uranium and Thorium decay series (IAEA, 2005). Quarry products consist of different natural rocks that have a variety of mineral contents, crushed into various sizes, such as, granite, diorite, granodiorite (IAEA, 2005). According to WHO Air Quality Guidelines, the particulate matter mean concentration over a 24-hour exposure period of PM10 is 45 $\mu\text{g}/\text{m}^3$ while for PM2.5 is 15 $\mu\text{g}/\text{m}^3$ (Kimanzi, 2022).

Lithophile elements such as potassium, uranium and thorium are natural radioactive elements widely spread in crustal rocks concentrated in acid igneous rocks compared with intermediate and basic varieties (Alnour et al., 2012). Potassium is widely spread in crustal rocks, 2.5% of calcium rich granites, Thorium occurs as trace elements in phosphates and silicates, monazite, thorianite and thorite (Alnour et al., 2012). Uranium is also found in rocks with various mineral species such as apatite, sphene and zircon) or form its own minerals. The atoms of uranium and thorium undergo radioactive decay emitting radionuclides which spontaneously decay until they form stable atoms. The radionuclides are also radioactive. IAEA, (2005) noted that exposures to natural sources of radioactive materials mostly do not raise any regulatory concern, however, exposure to natural sources may raise such concerns and whether or not controls are applied. Radon exposure has commonly been known as the historical cancer hazard among miners. UNSCEAR (2000) report that radiation exposure has been linked to many forms of cancer as well as leukemia.

Quarrying activities aggravate the release of the radionuclide materials from the earth's crust. Currently in Kenya, there is an increase number of cancer related deaths on workers in the construction industry, raising concerns as to whether the materials in use could be the source of high levels of radiation that is contributing to these deaths. Juja Sub-county in Kiambu County is the major source of "machine-cut stones" in Kenya. There is insufficient information on the presence and concentration levels of radioactive nuclides and radiation levels within quarries in the sub-county. The radionuclides also have potential of translocation to vegetation. There is need for assessment of radionuclides, radiation levels in quarries. This study provides data on various radioactive elements and levels of concentration in various materials and also provide mapping of the various concentrations of the radioactive materials within "Machine-cut stone" quarries in Juja, Kiambu County.

1.1 Radioactivity

Radioactivity is the spontaneous decomposition or decay of an unstable nucleus to a more stable nucleus, in the process energy is released and subatomic particle. The decomposition occurs in a specific and determinable manner, the energy emitted and the subatomic particles released can be mathematically calculated. There are three major radioactivity: alpha (α), beta (β) and gamma (γ) radiations. An alpha particle is represented by a Helium (^4_2He) charged ion.

When a radioactive nucleus decays with release an alpha ray, its mass number is reduced by two and atomic number reduces by four. The Helium-4 nucleus can only traverse very short distances.

Beta particles are electron like; the formed daughter nucleus carries a +1 atomic number compared to the parent nucleus. Beta radiation is can pass through a sheet of paper. Gamma radiation result in high energy photons with high penetrating power, this makes them dangerous as they can ionize human tissues and cells. These transitions have no effect to ether the mass or atomic number of the parent nucleus.

1.2 Natural radiation

UNSCEAR, 2000 report an increase in the environmental pollution caused by radiation. Two main contributors to radiation exposures include cosmic radiation and terrestrial radiation. Terrestrial dose rate is evaluated through outdoor occupational exposures, sampled across various places and determined from soil samples (NRC, 2006). Natural radioactivity is common in the environmental and geological materials. Mining increases exposure to radioactive elements that occur naturally (Shoeib, 2014). Occurrence of radionuclides in quarry products is due gamma radiation of ^{40}K , Uranium and Thorium decay series. Natural radionuclides are abundant in the environments with varying concentrations. UNSCEAR, 2022 estimates that close to 22.8 million workers are exposed to ionizing radiation and 13 million being exposed to natural sources with 9.8 million to artificial sources.

1.3 Concentration of radionuclides in materials from quarries

Natural radiation; uranium and thorium are found in traces in rocks, soil, sands and waters. Atmospheric radon is formed during decay of radionuclides; radon is formed, it diffuses and enter the atmosphere. The extent of diffusion depends on the bedrock permeability (UNSCEAR, 2000). The occupational exposure to radiation should not exceed 20 mSv per year, whereas public exposure should not exceed 1 mSv per year (UNSCEAR, 2000). Baykara, 2011 reports the natural radioactivity from construction material; the lowest (36.5 Bqkg^{-1}) radium activity was noted in bricks while highest (405.2 Bqkg^{-1}) in concrete. The activity ranged from 1.6 Bqkg^{-1} to 4928 Bqkg^{-1} . The indoor radon concentration in a newly constructed floor was 364.3 Bqm^{-3} which is higher than the global value.

In Kenya, a measurement of radiation of geological samples from Mrima hill, showed high radiation with an annual effective dose rate of 106 mSvy^{-1} (Mbandi, 2017). Shikali et al., 2014, reports radiation levels of 128.05 Bq/Kg , 98.37 Bq/Kg and 756.39 Bq/Kg for ^{238}U , ^{232}Th and ^{40}K with an annual dose rates of 0.48 mSv/y and 0.92 mSv/y which are below recommended limit were reported. Mustapha et al. (1997) analyzed tuffs, phonolites, gneisses, granites, red lateritic soils and sandy soils; phonolites were found to have an annual effective dose rate of 1.27 mSv/y which is above the acceptable limit of 1 mSv/y .

1.4 Exposure pathways to radiation

Exposure to low levels of radiation over a long period can increase in cancer risk (NRC, 2006; Okedeyi et al., 2012). Risks considered low to individual could cause cancers in a population over time (Shore, et al., 2018). EPA has set safe limits and recommends emergency response below 100 millisieverts.

The risk of exposure to a radionuclide depends on:

- i. The energy in the radiation.
- ii. The type of radiation
- iii. Its activity
- iv. Source of radiation

Exposure to a radiation source outside the body is referred to as external exposure whereas internal exposure occurs via ingestion, inhalation or injection of radionuclides, ingestion and inhalation of significant quantities are disastrous (UNSCEAR, 2000; Aguko, W. O., Kinyua, R., & Githiri, J. G., 2020).

The exposure to ionizing radiation from naturally occurring radioactive materials (NORM) is a common source of exposure on earth. Two main sources of natural radiation include: cosmic ray particles incident and radionuclides from the earth's crust; this leads to external and internal exposures (UNSCEAR, 2000).

Cosmic radiation and high-energy particles from the sun, these interact with atmospheric constituents producing several reaction products in the atmosphere. Cosmic ray interactions with other nuclei produce cosmogenic radionuclides such as; ^3H and ^{14}C (UNSCEAR, 2000).

Naturally occurring radionuclides occur in the terrestrial all segments of the environment. Most occur in small quantities apart from human activity. Exposure to the human body is mainly by gamma radiation from ^{238}U and ^{232}Th series and ^{40}K . ^{238}U and ^{232}Th series and ^{40}K are present in the body and irradiate expose several organs to alpha, beta particles and gamma rays. Other important terrestrial radionuclides, are ^{235}U , ^{87}Rb , ^{138}La , ^{147}Sm , and ^{176}Lu , which are found in nature in minute concentrations (UNSCEAR, 2000).

External exposures outdoors are mainly due to terrestrial radioactive isotopes available in trace levels in all soils and bedrock. Igneous rocks; granite present higher radiation levels. Phosphate rocks have relatively high content of radionuclides and thus radioactivity levels. Background levels of radionuclides in soils are associated with absorbed dose rates in air. The absorbed dose rate in the air can be measured directly, this provides an extensive evaluation of the background exposure levels. Measurements using gamma spectroscopy reveal that most of the radiation is due to gamma-emitting radionuclides; ^{238}U and ^{232}Th series and ^{40}K for both outdoors and indoors. Uranium and thorium decay chains cannot be assumed to be in radioactive equilibrium. The isotopes ^{238}U and ^{234}U are in equilibrium and are separated nuclides, ^{234}Th and ^{234}Pa

(UNSCEAR, 2000). The decay products of ^{226}Ra include the gaseous element radon, which diffuses out of the soil, reducing the exposure rate from the ^{238}U series (Aguko et al., 2020).

1.5 Analytical techniques for determination of radionuclide

An analytical method for determining the stable isotope concentration of trace elements in the bulk of a sample. It is a highly sensitive non-destructive technique for qualitative and quantitative determination of atomic composition of a sample. Traces of various elements can be identified and measured by analyzing the gamma rays they give off after being irradiated with neutrons or other nuclear particles (Kinsara et al., 2014). Method used for determination of elements in complex samples like minerals, environmental samples as it provides a simple alternative to much more difficult, tedious techniques.

A weighed quantity of radioactively tagged analyte with known activity is added to an amount of sample. The mixture is homogenized and a part of the compound of interest is isolated and purified. Analysis is based on the activity of the isolated fraction (Kinsara et al., 2014).

Measurement is based on interaction of ionizing radiation with matter using specialized equipment. Quantitative determination of radiation is based on the measurement of ionization and excitation produced in interaction of radiation with the medium (Kinsara et al., 2014). Several instruments are used to detect, measure, characterize, and classify radiation. The detectors convert the energy into an electrical current, amplify and record.

These measure the ionization produced by incident particle passing through a medium. Ionizing effect of radiation upon a gas-filled sensor is employed. Particle has enough energy to ionize a gas, A current flow resulting is measured (Kinsara et al., 2014). The detectors include; Geiger-Muller tubes, proportional counters and Ionization chambers.

Detects and quantifies ionizing radiation using a scintillator. Radiation passing through scintillators e.g. phosphors, fluoresce by emitting photons the photons are transduced and amplified as electrical signals. Data on intensity and energy is calculated from the output pulse. Also known as the semiconductor radiation detector; a semiconductor material such as a silicon or germanium crystal is the detecting media. Consists of a *p-n* junction across which a pulse current develops when a particle of ionizing radiation traverses. The pulses are amplified, recorded and analyzed to determine number, energy or identity of the charged particle (Kinsara et al., 2014). Sensitivity of these detectors is increased by operating at low temperatures in liquid nitrogen, which suppresses the random formation of charge carriers through thermal vibration.

Gamma spectroscopy is used on radionuclide concentrations of the various samples. Standards and the procedure of γ -beam cooperation are introduced here. Respective photon energies are used to identify which particular radionuclide in the sample material. Quantitative and qualitative analyses of a gamma ray spectrum identify unknown radioactive elements. The gamma ray spectrum is characteristic of the gamma emitting radionuclides in the source. The

interaction mechanisms of gamma rays include photoelectric absorption, pair production, and Compton scattering (Mutiullah et al., 2014).

The objectives of the present study are to assess the natural radioactivity levels in quarries in Kiambu County that supply construction stones to the Nairobi Metropolitan and the neighboring areas. This was done through measurement of the natural radioactivity level of ^{238}U (^{226}Ra), ^{232}Th and ^{40}K quarry dust from selected active and inactive quarries. The presence of ^{238}U is represented by concentration of ^{226}Ra . Assessment of radiation levels were investigated by calculation of Radium equivalent activity, air absorbed external gamma radiation exposure, annual effective radiation dose, and external and internal radiation hazard index. These were used to assess risk exposure to radiation for workers in the sector.

2.0 Materials and methods

Kiambu County and has a total area of 2,543.5 km² (CGK, 2018). The county is located between Latitudes 1.0314° South and Longitude 36.8681° East with respect to the equator. The study area has an area in Juja Sub-County with several quarries referred to as machine-cut stone quarries. The location of the study area is presented in Figure 1.1 below.

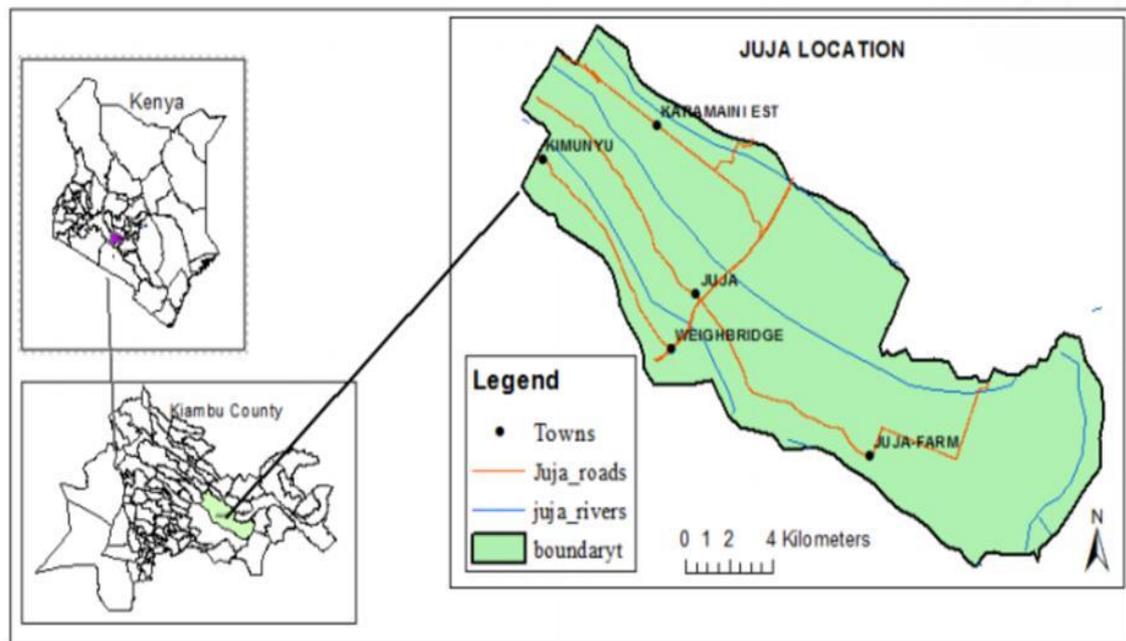


Figure 1.1: Location of Kiambu County

The county is 1,300 meters above sea level (CGK, 2018). The main type of rock is volcanic with easily eroded soils. Three wide types of soils: volcanic, upland and plateau soils which are fertile and of volcanic origin. The county receives long rains between March to May, June to August a cold season and short rains in October to November. The average rainfall is 1,200 mm. The mean temperature is 26 °C with a range from 7°C to 34°C. The coldest period is in months of July and August whereas the hottest months are from January to March (CGK, 2018).

The study population consisted of purposively selected quarries in Juja sub-county in Kiambu County. The sampling methods used were dependent on the analyte of concern. The quarries included active, abandoned and one control site with no quarrying activity was included in the study. The area is divided into six blocks namely; Kigue (5), Gachororo (2), Benfa (4), Komo (5), Nyasaba (5) and Mastore (4).

2.1 Sample collection

Quarry dust was collected as composites of 3 Kgs from the bottom (deepest point) of the quarries. Sampling at the top surface was mainly used for dumping quarry dust from the quarry floor. The Global Positioning System (GPS) and meters above sea level were measured at the deepest point of each quarry and recorded using GPS meter, model Gamin ETREX 30x.

2.2 Determination of NORM ^{40}K , ^{232}Th and ^{238}U

Samples were collected and stored in plastic sampling bags; these were later dried in the oven at 105°C for 24 hours. The samples were ground, pulverized and sieved through a 150µm sieve, after sieving, samples are weighed and transferred to 450mls Marinelli beaker plastic containers. These were compacted and brought to the marked level of the container. The containers were sealed around the edges of the lids with plastic electrical tape to prevent loss of ^{222}Rn . All samples were appropriately labeled using sample number, weight of sample, and date of encapsulation on a piece of masking tape and placing it on the lid of the sample container. Labelling was to insure maintaining the traceability of the samples. Samples were stored for 21 days (three weeks) before counting to allow the short-lived radioisotopes to reach secular equilibrium with their long-lived parents.

The optimum count time was set to no less than 10,000 seconds since most samples are low level sample. The analysis was done using the SpectraLineGP software and the spectrum saved once acquisition time is reached. Standard reference materials were run together with the samples for purposes of method validation.

Energy and Efficiency calibrations are determined using a multi-nuclide calibration standard with BB-3591; 10 nuclides; $V \sim 450\text{mls}$; $D \sim 1\text{g/cm}^3$ in the same geometry with the samples and is used. Energy calibration is for identifying the nuclides and Efficiency calibration is for activity calculations.

The Efficiency calibration file was opened and each spectrum loaded individually in SpectraLineGP software. The sample weight was input and the respective Nuclide activities present in the sample calculated. The Nuclides were reported as ^{40}K (1461 keV), ^{232}Th (238 and 911 keV) and ^{238}U (352 and 609 keV). The NORM activity concentrations were reported as Bq/Kg.

2.3 Radium equivalent (Ra_{eq}) activity

The weighted sum of ^{40}K , ^{232}Th and ^{226}Ra activities is referred to as the Radium equivalent (Ra_{eq}) activity with the assumption that 13 Bq·kg⁻¹ of ^{40}K , 1 Bq·kg⁻¹ of ^{238}U and 0.7 Bq·kg⁻¹ of ^{232}Th

produce same radiation dose rates. The radium equivalent activity can be estimated using equation below;

$$Ra_{eq} (Bq \cdot kg^{-1}) = C_U + 1.43C_{Th} + 0.077C_K$$

Where, C_U , C_{Th} , and C_K are activity concentrations in $Bq \cdot kg^{-1}$ of ^{238}U , ^{232}Th and ^{40}K .

2.4 Hazard indices

Hazard indices for external gamma radiation (H_{ex} and I_γ) Two indices were used in assessing the gamma radiation excess from materials used in building to ensure these materials safety. From the building materials, a hazard index describing the external gamma radiation dose is calculated as described (Raghu et al., 2015):

$$H_{ex} = \frac{A_{Ra}}{370 Bq/kg} + \frac{A_{Th}}{259 Bq/kg} + \frac{A_K}{4810 Bq/kg}$$

Where, A_{Ra} , A_{Th} and A_K are the activity concentrations, in $Bq \cdot kg^{-1}$ of Uranium (^{238}U), Thorium (^{232}Th) and potassium (^{40}K) respectively.

2.5 Hazard indices for internal alpha radiation (H_{in} and I_α)

Hazard indices for internal alpha radiation (H_{in} and I_α) Alpha (I_α) and internal hazard (H_{in}) indices are the two indices used in assessing alpha radiation excess due to radon gas coming from building materials. Raghu et al. (2017) mathematically defines H_{in} as in equation 11 below and can be used for internal radiation excess consideration owing to ^{222}Rn inhalation together with its short-lived decay products from building materials.

$$H_{in} = \frac{A_{Ra}}{185 Bq/kg} + \frac{A_{Th}}{259 Bq/kg} + \frac{A_K}{4810 Bq/kg}$$

Where, A_{Ra} , A_{Th} and A_K are the activity concentrations, in $Bq \cdot kg^{-1}$ of Uranium (^{238}U), Thorium (^{232}Th) and potassium (^{40}K) respectively.

3.0 Results and discussions

3.1 Sampling points and site descriptions

The quarries were described based on; block, active or abandoned, meters above sea level and the age of the quarry in months. The site description for quarries sampled are presented in Table 1.1.

Table 1.1: Descriptions of sampling sites

| Sample ID | Status | GPS | Masl (floor) | Age |
|-----------|-----------|-----------------------------|--------------|-----------|
| A1 | Active | S010°4.535' E037°00.757' | 1510 | 24 months |
| A2 | Abandoned | S01°05.020' E037°01.549' | 1498 | Unknown |
| A4 | Greystone | S01°04.713' E037°02.178' | 1490 | 24 months |
| A3 | Active | S01°04.628' E037°02.347' | 1500 | 12 months |
| A5 | Active | S01°04.595' E037°01.179' | 1490 | 24 months |
| A6 | Abandoned | S01°04.653' E037°01.061' | 1494 | Unknown |
| A7 | Active | S01°05.706' E037°02.998' | 1497 | 6 months |
| A8 | Active | S01°05.656' E037°02.848' | 1499 | 24 months |
| A9 | Control | S01°05.164' E037°02.400' | 1500 | Unknown |
| A10 | Active | S01°06.479' E037°02.605' | 1493 | 12 months |
| A11 | Active | S01°06.078' E037°02.510' | 1492 | 12 months |
| A12 | Active | S01°07.271' E037°03.907' | 1494 | 24 months |
| A13 | Active | S01°07.101' E037°03.031' | 1489 | 24 months |
| A14 | Active | S01°06.893' E037°02.759' | 1475 | 12 months |
| A15 | Active | S01°07.379' E037°03.936' | 1466 | 24 months |

The GPS locations are presented in Table 1.1 above. Two (2) quarry sites had been abandoned and data on its age was unknown. The quarries, based on meters above sea level were in the range of 1466 – 1531 masl with a mean of 1494.88 ± 13.88 masl as shown in Figure 1.2.

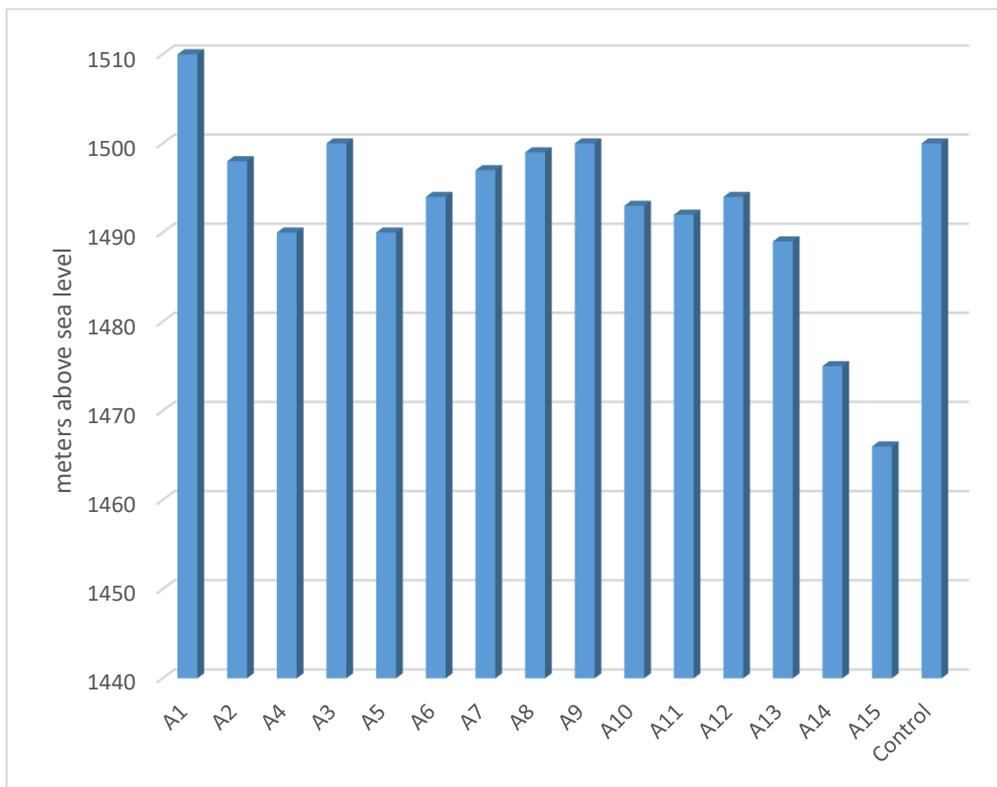


Figure 1.2: Meters above sea level for quarries studied

The active quarries ranged between 6-24 months with most having been in operation for a period of 24 months (Figure 1.3).

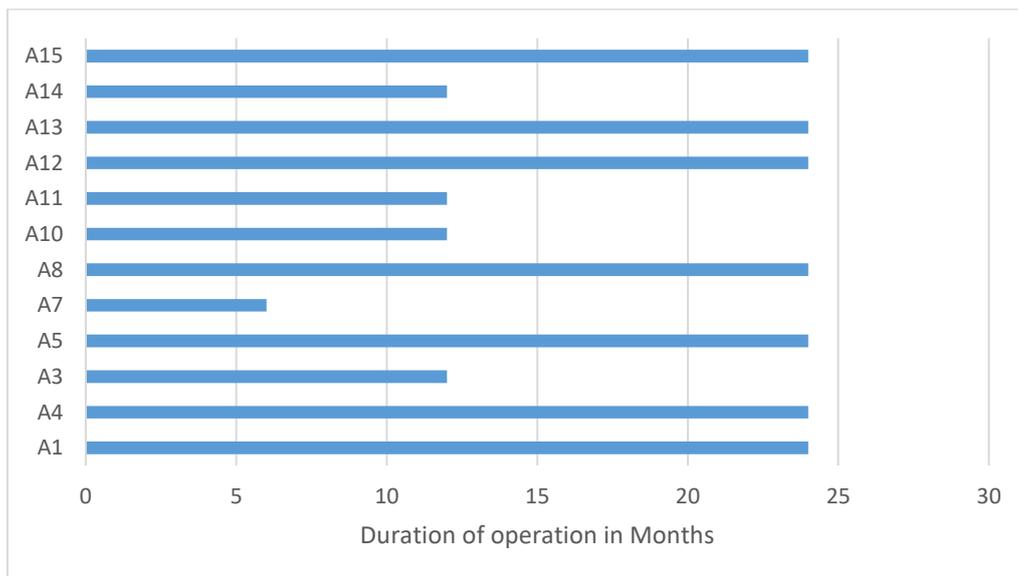


Figure 1.3: Meters above sea level for quarries studied

The depths of the quarries were found to vary and this depended on the age of the quarry which is also the estimate of the stone’s excavation period. One control site was included in a site as shown in table 1.1.

3.2 NORMs activity concentrations of ²³²Th, ²³⁸U and ⁴⁰K

The NORM Activity concentrations of ²³²Th, ²³⁸U and ⁴⁰K were determined in Quarry dust in Bq/kg and the results are presented in Table 1.2. The order of the radioisotopes in ascending order was ⁴⁰K> ²³²Th>²³⁸U. The range of the means were 71.1–152.2 for ²³²Th, 40.5-107.4 for ²³⁸U whereas that of ⁴⁰K was in the range of 763.8 – 1661.2 Bq/Kg.

Table 1.2: NORMs Activity concentrations of ²³²Th, ²³⁸U and ⁴⁰K in Quarry dust (Bq/kg)

| Quarry | ²³² Th | ²³⁸ U | ⁴⁰ K | R _{aeq} (BqKg ⁻¹) |
|--------|-------------------|------------------|-----------------|--|
| A1 | 114.1±10.1 | 107.3±9.1 | 1495.5±146.4 | 385.62 |
| A2 | 112.3±5.6 | 101.6±2.3 | 1462.6±48.5 | 374.84 |
| A3 | 90.7±9.7 | 72.9±8.9 | 1768.3±94.8 | 338.76 |
| A4 | 83.2±10.8 | 59.7±8.7 | 1592.2±95.9 | 301.27 |
| A5 | 100.3±10.3 | 75.2±8.6 | 1763.1±90.5 | 354.38 |
| A6 | 146.2±13.2 | 77.8±9.0 | 1200.8±78.4 | 379.33 |
| A7 | 92.6±7.8 | 73.3±6.1 | 1485.9±122.3 | 320.13 |
| A8 | 84.9±5.4 | 54.5±4.2 | 1096.3±77.5 | 260.32 |
| A9 | 94.4±11.1 | 54.2±3.6 | 932.2±65.8 | 260.97 |
| A10 | 129.5±10.2 | 99.5±8.1 | 1444.1±144.2 | 395.89 |
| A11 | 71.1±8.1 | 71.4±8.5 | 1518.4±119.1 | 289.98 |
| A12 | 152.2±11.2 | 40.5±15.2 | 1261.5±147.2 | 355.28 |
| A13 | 134.3±9.3 | 61.3±6.3 | 858.4±49.1 | 319.45 |
| A14 | 129.2±15.5 | 107.4±13.1 | 1587.3±110.2 | 414.09 |
| A15 | 123.1±16.4 | 84.7±6.2 | 1661.2±113.3 | 388.65 |

The variations of the NORM activity concentrations of ²³²Th, ²³⁸U and ⁴⁰K is illustrated in Figure 1.4. The variation of natural radioactivity levels at different sampling sites is due to the variation of concentrations of radionuclides in the geological formations in quarries (Wafula et al, 2022)

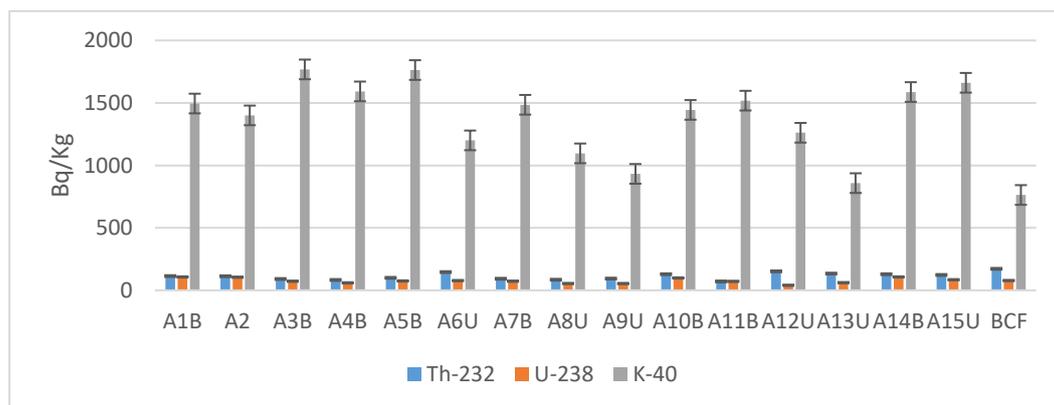


Figure 1.4: NORM activity concentrations of ²³²Th, ²³⁸U and ⁴⁰K Isotopes in quarry dust

3.3 Radium equivalent (Ra_{eq}) activity

The weighted sum of ^{40}K , ^{232}Th and ^{226}Ra activities is referred to as the Radium equivalent (Ra_{eq}) activity with the assumption that $13 \text{ Bq}\cdot\text{kg}^{-1}$ of ^{40}K , $1 \text{ Bq}\cdot\text{kg}^{-1}$ of ^{238}U and $0.7 \text{ Bq}\cdot\text{kg}^{-1}$ of ^{232}Th produce same radiation dose rates.

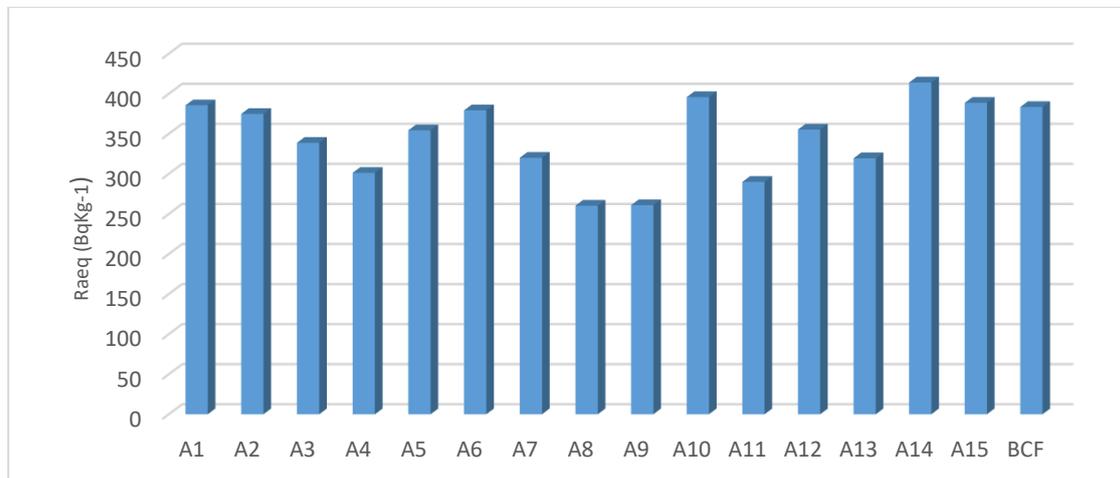


Figure 1.5: Radium equivalent (Ra_{eq}) activity

The Radium equivalent activity ranged from $260.32 - 414.09 \text{ Bq}\cdot\text{kg}^{-1}$. Quarries A2, A1, A6, A10, A14 and A15 had levels above $370 \text{ Bq}\cdot\text{kg}^{-1}$ and thus considered above safe limits whereas all the others were within safe limits.

3.4 Hazard indices

The External Hazard Index (Hex) was calculated to evaluate the indoor radiation dose rate due to the external exposure to gamma radiation from the natural radionuclides in building materials of dwellings. The calculated index values ranged between $0.7 - 1.12$ as summarized in figure 1.6. Quarry A14 had the highest hazard index whereas A8 had the lowest. The study reveals that the hazard indices exceeded acceptable limits for quarries A1, A2, A6, A10, A14 and A15 whereas quarries A3, A4, A5, A7, A8, A9, A11, A12 and A13 had values lower than unity which are considered safe.

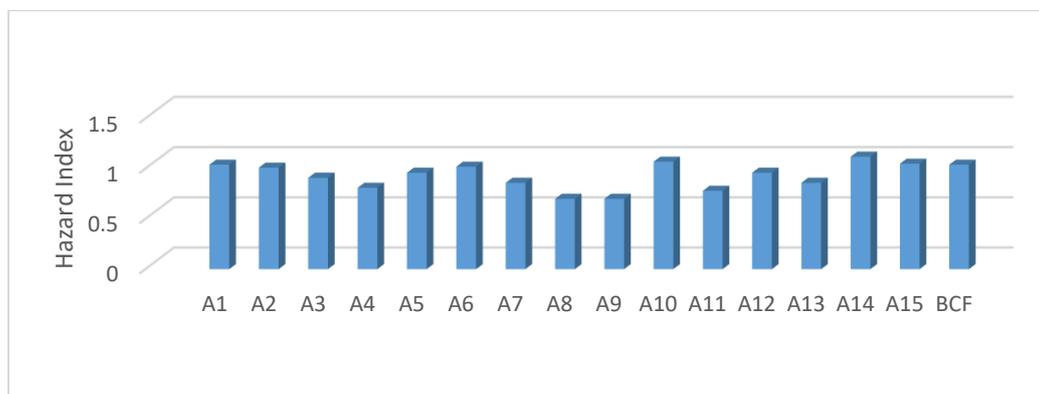


Figure 1.6: External Hazard Index (Hex)



4.0 Conclusions

The study show that the rock derived from some the quarries could present some radioactivity threat to occupiers of buildings built using materials from such sources. The risk is however considered low.

5.0 Acknowledgements

5.1 Funding

None

5.2 General acknowledgement

None.

5.3 Conflict of interest

None.

6.0 References

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