Interdependency of Soil-gas Radon-222 Concentration on Soil Porosity at different Soil-depths

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Abstract. Origination of Radon-222 (222Rn) from soil and its concentration, contributing to the highest exposure of ionizing radiation to the public is natural. It is a known radioactive gas and its percentage in concentrations contributing to outdoor radon atmospheric level depends on some physical parameters of the soil. To ascertain some of its dependency on soil porosity, a radiometric survey was carried out on soil depths at varying locations and the laboratory analysis was carried out on the soil sample at each location and depth in order to determine its porosity. The measurements were done using radon detector at five (5) locations. At each location, data were collected at four (4) different soil depths of 20, 40, 60 and 100 cm respectively. In addition, soil samples at these locations and depths were taken to the laboratory for porosity test. The result showed that highest value of 222Rn concentration at 100 cm depth is $24680 \pm 1960 \text{ Bq m}^{-3}$ with maximum porosity level of 69.92%, while the lowest concentration at 100 cm depth is $7370 \pm 1139 \text{ Bq m}^{-3}$ with minimum porosity level 51.61% respectively. Inferentially, a statistical analysis carried out using Pearson correlation showed that there exist some relationships between soil-gas 222Rn concentrations measured and soil porosity determined at each measurement soil-depths. The nature of the established relationship shows interdependency of 222Rn on soil porosity at different depths, such that if the soil porosity is known, its corresponding soil-gas radon concentration can be determined.

Keywords: Radon concentration, Soil porosity, Radon detector, Soil depths, Pearson correlation

1. Introduction

Soil-gas radon-222 concentrations, contributing to the outdoor radon in the atmosphere depends on some physical parameters of soil. The parameters include soil porosity, moisture content of soil, radium concentration and its distribution, grain size; shape and pore size of soils, air and soil temperature pore, and atmospheric pressure above the earth surface [1]. Radon-222 is an odourless, colourless and tasteless radioactive noble gas known for its ability to promote carcinogenesis [2]. It occurs naturally as an oblique decay product of thorium and/or uranium within the soils and rocks of the Earth [3]. Radon itself is the immediate decay product of radium and, 222Rn is the most stable isotope of the three (3) isotopes of radon. The half-life of 222Rn is 3.8 days, which makes it one of the rare elements on Earth, because of its fast decay process.
Radon originates from the soil and its presence in air is a function of the characteristics and type of soil in that vicinity. [4] and [5] reported that radon is highly concentrated in Basement Complex rocks, which is the parent rock in the study area. Its availability in water also comes from soil. Concentrated inhalation of radon has been reported as the second major cause of lung cancer, while smoking has been identified as the lead cause [2]. To date, many researchers find it difficult to quantitatively determine the effect of granular pores on emanation of radon [1]. This could be as a result of high cost or unavailability of the equipment required, or difficulties in quantifying the number and pore sizes of various soil types.

Soil porosity is determined as the ratio of the pore spaces within the soil particle to the total volume of soil. The pore spaces of soil particles may be increased through the movement of insects within the subsurface and plant roots, which expand the gas filled region by water, or the dissolution of the parent rock [6]. Research also showed that soil texture and grain-size particle can affect soil porosity. The basic character of the pore spaces is governed by the soil behaviour, which include: water, air and other fluid movement; transport and the reactions of chemicals within the roots; as well as roots movement [7].

Radon emanation and diffusion through the soil interstitial space to the global environment depends on the soil geophysical formation as revealed in Figure 1. However, a research work carried out to experiment the emanation, diffusion and movement of soil gas Radon-222 to air, depending on soil porosity will provide essential information on radon concentration in soil, water and air, which is the aim of this study. Thus, having fundamental needs of knowledge on soil-gas Radon-222 concentration and its dependency on some soil geophysical formation at different soil-depths provides probable information on the apparent level of radon concentration in air, which is one of the required facts in assessing radiological health risks of people and as other environmental indicator.

Radon within the rocks and overburden is partially released to its surroundings through the pore spaces of the materials. The principal transport mechanism for radon includes diffusion, convection and fluid flow within the subsurface. A highly porous medium increases the rate of diffusion. In addition, moisture content plays an important role in diffusion rate, because the higher the moisture contents, the lower the diffusion rate [8-10]. The amount of air present in soil depends on its permeability and density. Radon finds its way to the soil gas through diffusion from a radon-rich material or soil particles. The concentration of radon in soil gas decreases as it escapes to the surface of the Earth or open space above the ground. With some basic fact on Radon-222 and its dispersal mechanisms in the soil depths, this study used in-situ measurement to determine the soil-gas Radon-222 concentration in some locations of Ogbomoso, SW Nigeria using electronic active radon detector (RAD-7), which is specially made for Radon and Thoron detection.
2. Geology of the study area

The study area is bounded by latitude 8.04362 – 8.17045°N and longitude 4.14302 – 4.26700°E (Figure 2), which is located within Ogbomoso, SW Nigeria. The geology of the study area is concealed within the Basement Complex rocks of SW Nigeria, which is of PreCambrian in age [11-23] as revealed in Figure 3. The rocks of Ogbomoso is an integral part of the Proterozoic Schist belt [14, 24], which is developed towards the western half of Nigeria. The lithological units in Ogbomoso include Granite-Gneiss, Banded Gneiss and Quartzite (Figure 4). Augen and agmatitic gneisses are also present in the study area. The quartzite occurs as elongated ridges, which trends in NW-SE orientation. The quartzites are observed as Schistose, which dominates the southern region, while granite gneisses covered the northeastern region of the town. Other lithological units are noticed in other regions of Ogbomoso land [25].
3. Materials and Methods

Measurements of soil-gas Radon-222 concentration at different soil-depths were done using Soil Gas Probe extending from Steel Soil Gas Probe in soil-depth through a Desiccant to the electronic active radon detector (RAD-7) manufactured by Durridge Company, USA. The detailed setup of the equipment used for this study is revealed in Figure 5. The measurements were done at five (5) locations (Figure 2) within Ogbomoso land. At every location, with a calibrated pilot rod hammered to the required depth, a soil gas probe was inserted and through tube connection to the RAD-7, the soil-gas radon concentration was measured. Four different depths of 20, 40, 60 and 100 cm were considered for the measurements. At each soil-depth in a particular location, the soil-gas radon-222 concentrations were measured four times for replicability and precision, while its mean and standard deviation values are presented in Table 1.
Soil samples were taken at each depth and point of survey for soil porosity test, which was done at the Laboratory of the Federal Polytechnic, Offa, Nigeria. Twenty (20) soil samples were taken to the laboratory for analysis using “Direct Method”. A beaker is filled with water to its half, and marked using glass-marking crayon. The water was poured into the graduated cylinder, its volume was measured and record as “Total Volume” on the “Activity Sheet”. The beaker was dried and left for some time, before the beaker was filled up with soil sample up till the marked point. 100 ml of water measured into the graduated cylinder was poured into the beaker with the soil sample till saturation. The amount of water needed to saturate the soil sample was recorded as the “Pore Space.” This procedure was repeated for the rest of the samples. Mathematically, percentage of soil was determined using Eq. (1).

\[ \text{Porosity(\%)} = \left( \frac{\text{Pore Space}}{\text{Total Volume}} \right) \times 100 \] (1)

The obtained porosity values within the study area at varying depths are shown in Table 1. A statistical test was carried out using Pearson correlation to determine the level of correlation and significant of relationship that exist between Radon-222 concentrations and soil porosity measured at each measurement soil depths.

4. Result and Discussion

The variation and concentration of soil-gas radon-222 measured at each soil depths in the locations across the study area are presented in Table 1. The radon concentration in the study area ranges between 680 ± 392 and 24680 ± 1960 Bqm\(^{-3}\) at 20 and 100 cm soil-depths respectively. At 100 cm depth, the highest concentration of 24680 ± 1960 Bqm\(^{-3}\) was found in location 1 and the lowest concentration of 7370 ± 1139 Bqm\(^{-3}\) was found in location 4. Also, the percentage of soil porosity determined at each measurement soil-depths across the locations in the study area are as well shown in Table 1. The percentage of soil porosity in the study area ranges between 25.81 and 69.92 % at 20 and 100 cm soil-depths respectively. At 100 cm depth, the highest percentage of 69.92 % was obtained in location 1 and the lowest percentage of 51.61 % was obtained in location 4.

It is revealed from Table 1 that the highest value of Radon-222 at 100 cm in P1 corresponds to the peak value of soil porosity, while the least concentration at 100 cm in P4 corresponds to the minimum value of porosity at this depth. Inferentially, using the mean value of all the data set at each depth as shown in Table 2, the results of Pearson correlations test are presented in Table 3.
Table 1: Radon Concentration and Soil Porosity at different Soil Depths

| Location | Sampling Depths (cm) | Radon concentration (Bqm$^{-3}$) | Porosity (%) |
|----------|----------------------|----------------------------------|--------------|
| P1       | 20                   | 2920 ± 368                      | 38.71        |
|          | 40                   | 8760 ± 840                      | 45.16        |
|          | 60                   | 13800 ± 1090                    | 54.84        |
|          | 100                  | 24680 ± 1960                    | 69.92        |
| P2       | 20                   | 890 ± 433                       | 25.81        |
|          | 40                   | 2950 ± 730                      | 32.26        |
|          | 60                   | 3530 ± 807                      | 32.26        |
|          | 100                  | 18400 ± 1765                    | 61.29        |
| P3       | 20                   | 3520 ± 342                      | 35.48        |
|          | 40                   | 7630 ± 730                      | 45.16        |
|          | 60                   | 9100 ± 1232                     | 51.61        |
|          | 100                  | 22680 ± 1872                    | 66.14        |
| P4       | 20                   | 2360 ± 651                      | 32.26        |
|          | 40                   | 680 ± 392                       | 25.81        |
|          | 60                   | 4220 ± 894                      | 41.94        |
|          | 100                  | 7370 ± 1139                     | 51.61        |
| P5       | 20                   | 4110 ± 1950                     | 41.94        |
|          | 40                   | 6520 ± 586                      | 45.16        |
|          | 60                   | 4400 ± 1370                     | 41.94        |
|          | 100                  | 20700 ± 10900                   | 66.14        |

* Note: for Radon concentration, the 1st and 2nd values are the mean and deviation values at each depth.

Table 2: Mean Radon-222 Concentration and Soil Porosity at different Soil-Depths

| Sampling Depth (cm) | Radon Concentration (Bqm$^{-3}$) | Porosity (%) |
|---------------------|----------------------------------|--------------|
| 20.00               | 2715.386                         | 34.840       |
| 40.00               | 5920.763                         | 38.710       |
| 60.00               | 7786.923                         | 44.518       |
| 100.00              | 20581.539                        | 63.020       |

As presented in Table 3, the Pearson correlation results ranges from 0 to 1 (i.e. 0% to 100%), which describes the degree of relationship that exist with the highest at 1.00 (100%) level and lowest at 0.00 (0.00%) level. Also, the level of significant, which must be or less than $\alpha$ value (i.e. $0.01 \geq \alpha \leq 0.05$) 2-tailed provide that the relationship is significant at a particular level. Therefore, the results obtained (Table 3) showed that the natures of relationships that exist are found to be interdependent and highly correlated at 0.004 with 99.6% and 0.027 with 97.3% significant 2-tailed and Pearson correlation respectively for soil-gas radon-222 concentration measured against soil porosity and soil-depths respectively.
Table 3: Pearson Correlations on Radon-222 Concentration and Soil Porosity at Different Soil Depths

| Type                        | Correlation          | Mean Radon Conc. (Bqm$^{-3}$) | Porosity (%) | Mean Soil Depths (cm) |
|-----------------------------|----------------------|-------------------------------|--------------|-----------------------|
| Mean Radon Conc. (Bqm$^{-3}$) | Pearson Correlation  | 1                             | 0.996**      | 0.973*                |
|                            | Sig. (2-tailed)      |                               | 0.004        | 0.027                 |
|                            | N                    |                               | 4            | 4                     |
| Porosity (%)                | Pearson Correlation  | 0.996**                       | 1            | 0.984*                |
|                            | Sig. (2-tailed)      |                               | 0.004        | 0.016                 |
|                            | N                    |                               | 4            | 4                     |
| Mean Soil Depths (cm)       | Pearson Correlation  | 0.973*                        | 0.984*       | 1                     |
|                            | Sig. (2-tailed)      |                               | 0.027        | 0.016                 |
|                            | N                    |                               | 4            | 4                     |

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Based on the mean radon-222 concentrations and soil porosity levels determined at each measurement soil-depths (Table 2), a model was derived (Eq. 2). This model could be a useful tool to estimate radon-222 concentration based on soil porosity at different soil-depths.

$$\hat{R}_n = \hat{\beta}_1 p + \hat{\beta}_2 d + \alpha$$

$$R^2 = 99.3\%$$

(2)

where,

$\hat{R}_n$ is the estimated value of radon-222 concentration,

$\alpha$, $\hat{\beta}_1$ and $\hat{\beta}_2$ are the constant estimated variables determined for the model at different soil porosity ($p$) and soil-depths ($d$) considered for the measurement.

However, the following conditions satisfied the applicability of the Eq. (2):

(i) $\hat{R}_n$ is positive and valid only, when $20 \leq d \leq 100$ cm; and
(ii) $\hat{R}_n$ is negative when $d \leq 0$ and invalid when $d < 20$ cm

The above conditions satisfied the depths of 20 and 100 cm because, the modeled variables fluctuates between 20 and 100 cm below the surface of the Earth. The modeled estimated values for Eq. (2) are presented in Table 4.

Table 4: Model Estimated Values

| $\alpha$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ |
|----------|----------------|----------------|
| -21,208.735 | 720.00         | -40.570        |
5. Conclusion

The origination of radon-222 from soil and its concentrations, contributing to the highest exposure of ionizing radiation to the public is natural. The results of its in-situ measurement in correlation with soil porosity at different soil depths for this study showed that, the highest value of radon-222 concentration measured at 100 cm depth was $24680 \pm 1960 \text{ Bqm}^{-3}$ with maximum soil porosity level of 69.92% at P1, while the lowest concentration of radon at 100 cm depth was $7370 \pm 1139 \text{ Bqm}^{-3}$ with minimum porosity level of 51.61% at P4 respectively. When compared the results of radon-222 concentration with that of laboratory test on soil porosity, the results showed an existence of some relationships between the three variables and the nature of relationships showed were interdependent with value of 0.004 and 0.027 level of significant 2-tailed between radon-222 concentration against soil porosity and different soil-depths considered. The percentage of soil porosity examined at different soil-depths determines the degree of exhalation, diffusion and movements of soil-gas Radon-222 concentration in soil through the soil interstitial (porous) spaces to the global environment. The model obtained in this study could be a yardstick for further study on Radon-222 concentration at different soil depths, especially in Ogbomoso, SW Nigeria.

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