Natural Radioactivity Evaluation of Local Soil used as Building Materials in Xinchang Section of Beishan Pre-selected Area, Northwest China

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Abstract. To investigate the radiation background level of jijicao block and rock mass around Xinchang section in the pre-selected area of Beishan, northwest China, the relevant soil samples and data have been obtained, and the natural radioactivity of the soil samples has been measured by gamma-ray spectroscopy with hyper-pure germanium detector. The mean activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in soil samples are determined as 23.72 (from 11.2 to 48.6 Bq·kg$^{-1}$), 28.72 (from 11.9 to 33.0 Bq·kg$^{-1}$) and 612.93 Bq·kg$^{-1}$ (from 244.0 to 907.0 Bq·kg$^{-1}$), respectively, which are all lower than the Juquan background values, among which the concentration of $^{40}$K is higher than UNSCEAR 2008 and Beishan background value. The calculated data of radium equivalent, representative level index, external standard, internal standard, and annual effective dose are less than the recommended limits. Therefore, it can be concluded that the building being constructed of the materials is safe for the inhabitants. The findings from this research will be useful to assess the radiation hazards of building materials in humans. It is valuable for the environmental impact assessment of the underground research laboratory of high-level radioactive waste and the assessment of the hazard of radioactive building materials to human body.

1. Introduction

Soil is the basic resource for human survival and plays an extremely important role in the ecological environment. Generally speaking, the soil environment which is not affected by human activities in the natural state will not change after being placed in the humid environment for a certain period of time. Soil environmental conditions will show relatively stable characteristics. The background level of the soil environment is mainly determined and affected by the concentration of natural radionuclides such as rock, $^{226}$Ra, $^{232}$Th and $^{40}$K in the earth's crust [1]. Diversity in geological conditions, bedrock composition, soil development types and topographic distribution in varied areas will lead to significant differences in the concentration of natural radionuclides $^{232}$Th, $^{226}$Ra and $^{40}$K in the soil [2]. However, with the development of the industrial revolution, radionuclides caused by human activities enter the soil environment, which leads to soil radionuclide contamination and long-term radiation hazard to human health [3].

Beishan pre-selected area is characterized by convenient transportation, weak economic conditions (such as lack of farmland, mineral resources, animal, and plant resources) and sparse population in Gansu province, northwest China. It has been selected as the most suitable area for HLW repository in China because of its superior social, economic and natural conditions [4]. In July 2011, the China Atomic Energy Authority, together with the Ministry of Ecology and Environment, approved that the...
Beishan area is “the first priority area” for China’s HLW repository [5]. In order to use radionuclide soil as the building materials, it is of great significance to investigate and evaluate the radioactive environment of Beishan area.

In this research, the background levels of radionuclides such as $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in the jijicao block and the rock mass around Xinchang section in the pre-selected area of Beishan have been investigated. The radiation hazard of building materials to human body have been evaluated by calculating radium equivalent, gamma index, external standard, internal standard, absorbed dose and annual effective dose, which will be the basis for the construction, operation and management of URL of HLW.

2. Material and methods

2.1. Study area

The pre-selected area of the HLW disposal repository locates in the arid desert region of Gansu Province, northwest China. The study area lies in Xinchang section of Beishan pre-selection area, as shown in Figure 1. It has the characteristics of sparse rainfall, large evaporation, cold and dry wind, low temperature, short summer and long winter. The elevation is 1,600-1,800 m. The relative height difference of the terrain is within 100 m. The soil type on the hillside is mainly aeolian sandy soil, and the soil layer is relatively thin. Precipitation is mostly concentrated in summer, with an average annual precipitation of 85.2 mm and an average annual evaporation of 3,072.9 mm.

![Geological Map of China](image1.jpg)

**Figure 1.** The location of the study area in Beishan, Gansu province [6].

2.2. Sampling and analysis

60 sampling points (No. 108-167) were selected around the jijicao block and the rock mass in the open uncultivated area in spring (Figure 2). The geographic location of the sampling point is recorded using the global positioning system (GPS) [7]. 60 surface soil samples were collected by the five-point sampling method. Stones, roots and other sundries are removed from all soil samples and each sample with the weight no less than 1 kg was put into plastic bag [8]. After the air is discharged, it is sealed and stored in a polythene bag with sampling information indicated, and then sent back to the laboratory for refrigeration.

The samples were weathered in a dry environment for 30 days and dried in an oven at 110 °C for 6 hours [9]. The activity concentrations of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ for all homogenized and equilibrium samples were measured by a gamma ray spectrometry (GB/T 11743-2013) by using a high purity Germanium (HPGe) detector (25% relative efficiency) and a coaxial-type vertical dipstick cryostat [10]. The detection limits of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were 7.05, 0.80, and 0.43 Bq·kg$^{-1}$, respectively [11]. The $^{226}\text{Ra}$ specific activities were estimated from $^{214}\text{Bi}$ (609.3 keV) and $^{214}\text{Pb}$ (295.2 and 352.0 keV), and the $^{232}\text{Th}$ specific activities were estimated from $^{228}\text{Ac}$ (911.1 keV), $^{212}\text{Pb}$ (583.1 keV), and $^{208}\text{TI}$ (238.6 keV), while the specific activity of $^{40}\text{K}$ was determined directly from its gamma emission at 1460.83 keV. The analytical results of all samples met the quality control requirements of technical criteria for radiation environmental monitoring (HJ/T 61-2001) [12].
2.3. Methodology

2.3.1 Radium equivalent activity (Ra_eq). To assess the radiation hazard associated with the building materials, Ra_eq was evaluated. Where it is assumed that all decay products of 226Ra and 232Th are in radioactive equilibrium with their precursors. Ra_eq is calculated according to the following equation [13]:

\[
Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_{K}
\]  

where A_Ra, A_Th and A_K are the specific activities of 226Ra, 232Th and 40K in Bq·kg\(^{-1}\), respectively. The equation is based on the estimation that 1 Bq·kg\(^{-1}\) 226Ra, 0.7 Bq·kg\(^{-1}\) 232Th and 13 Bq·kg\(^{-1}\) 40K produce the same gamma-ray dose rates [14]. Ra_eq is related to both internal doses due to the radon and external gamma doses, and it should have the highest value of 370 Bq·kg\(^{-1}\) for safe use in building materials [15].

2.3.2 Representative level index (I_r). Representative level index (I_r) used to estimate the standard of gamma radiation hazard associated with the natural radionuclides in specific building materials may exceed 1 mSv·y\(^{-1}\). It is calculated using the following equation [16]:

\[
I_r = \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} + \frac{C_{K}}{3000}
\]

where C_Ra, C_Th and C_K in Bq·kg\(^{-1}\) are the concentration of 226Ra, 232Th, and 40K, respectively.

2.3.3 External hazard index (H_{ex}) and internal hazard index (H_{in}). The two hazard indexes (H_{ex} and H_{in}) are used to characterize the external and internal hazards due to the emitted gamma radiation. The primary objectives of H_{ex} and H_{in} are to limit the radiation dose to the equivalent limit of 1 mSv·y\(^{-1}\), and the two equations are as follows [17]:

\[
H_{ex} = A_{Ra} / 370 + A_{Th} / 259 + A_{K} / 4810
\]

\[
H_{in} = A_{Ra} / 185 + A_{Th} / 259 + A_{K} / 4810
\]

2.3.4 Absorbed gamma dose rate (D_G) and annual effective dose rate (D_E). The outdoor absorbed dose rate (nGy·h\(^{-1}\)) in air from terrestrial gamma radiation at 1 m above the ground is calculated after applying the conversion factors (in nGy·h\(^{-1}\) per Bq·kg\(^{-1}\)) to transform A_Ra, A_Th and A_K into D_G according to the equation provided by UNSCEAR [18]:

\[
D_G = 0.08A_K + 0.92A_{Ra} + 1.1A_{Th}
\]
To estimate $D_E$, it is necessary to use the conversion coefficient from the absorbed dose in air to the effective dose (0.7 Sv· Gy$^{-1}$) and the outdoor occupancy factor (0.2 Sv· Gy$^{-1}$) proposed in UNSCEAR. The annual time is calculated by 8760 hours. Therefore, $D_E$ is determined as follows [19]:

$$D_E = D_G \times 0.2 \times 0.7 \times 8760 \times 10^{-6} \quad (6)$$

In UNSECEAR 2008, it is stipulated that the standard values of $D_G$ and $D_E$ are 84 nGy· h$^{-1}$ and 0.48 mSv· y$^{-1}$, respectively [20].

3. Results and discussion

3.1 The concentration of natural radionuclides in building materials

| Building material | Sample number | Sample size | $^{226}$Ra | $^{232}$Th | $^{40}$K |
|-------------------|---------------|-------------|------------|------------|--------|
|                   |               |             | Mean | Range | Mean | Range | Mean | Range |
| Sand stone        | 108,109,110,112,113,114,115, 116,118, 119,120,122,123,124,126,128, 130,132,134, 135,138,139,143,144,145,146, 147,149,153, 156,157,158,159,160,167, 121,127,129,137,140,148,150, 151,152 | 35 | 24.15 | 12.5 | 32.8 | 28.85 | 14.0 | 48.6 | 611.71 | 291.0 | 907.0 |
| Sand soil         | 154,155,162,163,164,165,166 | 16 | 23.47 | 11.9 | 33.0 | 27.68 | 11.2 | 47.2 | 623.44 | 244.0 | 861.0 |
| Stiff soil        | 111,117,125 | 3 | 20.0 | 12.2 | 26.6 | 28.93 | 19.9 | 39.0 | 682.0 | 648.0 | 725.0 |
| Mollisol          | 131,136,161 | 3 | 22.53 | 21.0 | 23.4 | 28.6 | 23.0 | 34.0 | 524.33 | 462.0 | 615.0 |
| White soil        | 133,141,142 | 3 | 25.0 | 21.4 | 31.6 | 32.67 | 21.9 | 40.1 | 590.67 | 418.0 | 763.0 |
| Total             | —             | 60 | 23.72 | 11.9 | 33.0 | 28.72 | 11.2 | 48.6 | 612.93 | 244.0 | 907.0 |
| Beishan background value [21] | — | — | 34.3 | — | 38.8 | — | — | 652.1 | — | — |
| Jiuquan background value [22] | — | — | 25.4 | — | 35.7 | — | — | 429.2 | — | — |
| UNSCEAR 2008 [23] | —             | — | 50.0 | — | 50.0 | — | — | 500.0 | — | — |

Table 1 lists the ranges and the mean values of the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K for sixty types of building materials in Xinchang section around the jijiao block and the rock mass. From Table 1, the mean value of radionuclides of $^{226}$Ra, $^{232}$Th and $^{40}$K are 23.72, 28.72 and 612.93 Bq· kg$^{-1}$ in soil samples, respectively. The concentration of $^{40}$K in soil sample is higher than that prescribed in UNSCEAR 2008 and Beishan background value, but is lower than Jiuquan background value. The mean value of $^{226}$Ra, $^{232}$Th and $^{40}$K in sand stone, sand soil, stiff soil, mollisol and white soil used as building materials are 24.15, 28.85, 611.71 Bq· kg$^{-1}$, 24.37, 27.68, 623.44 Bq· kg$^{-1}$, 20.0, 28.93, 682.0 Bq· kg$^{-1}$, 22.53, 28.6, 524.33 Bq· kg$^{-1}$ and 25.0, 32.67, 590.67 Bq· kg$^{-1}$, respectively. According to the mean value of $^{226}$Ra, the soil active concentration of $^{226}$Ra is used as building material decrease following the order of white soil > sand stone > sand soil > mollisol > stiff soil. The mean radionuclide
concentrations of $^{232}$Th is showed as white soil $>$ stiff soil $>$ sand stone $>$ mollisol $>$ sand soil. And the mean value of $^{40}$K increases in order of mollisol $<$ white soil $<$ sand stone $<$ sand soil $<$ stiff soil.

Table 1 also shows that the mean radionuclide concentrations of $^{226}$Ra and $^{232}$Th of all soils used as building materials are lower than the background values of Beishan, Jiuquan and the value specified in UNSCEAR 2008, while the concentration of $^{40}$K of stiff soil is slightly higher than Beishan background value. $^{40}$K concentrations of sand stone, sand soil, stiff soil, mollisol and white soil are all higher than the value specified in UNSCEAR 2008, and there are 1.3 to 1.45 times higher than Jiuquan background value.

Table 2 shows the comparison of the radioactivity concentration of different types of soil in China and other parts of the world. The ranges of the mean values of the natural radionuclide concentration in building materials differ from one country to another, depending on the soil used for their formation. Except for $^{40}$K, the concentration of radionuclides of $^{226}$Ra and $^{232}$Th in the soil types used as building materials in Xinchang section around the jijiao block and the rock mass is lower than the mean value in China. $^{226}$Ra concentration of the different types of soil from Xinchang section is higher than the mean value in Pakistan, Cuba and Greece, but is lower than that in Iran and Brazil. The concentration of $^{232}$Th is higher than that in Cuba, Greece, and Iraq, however it is lower than that in Pakistan and Brazil. The radionuclide concentration of $^{40}$K is 1.4 to 4.5 times higher than those in the countries of Brazil, Pakistan, Greece, Cuba and Iraq. The previous research results revealed that the concentration of $^{40}$K exceeds the Jiuquan background value and UNSCEAR 2008 may be caused by nuclear research and radioactive waste disposal activities in nearby area [24].

3.2 Radium equivalent activity ($Ra_{eq}$) in building materials

The mean value of the radium equivalent activity ($Ra_{eq}$) for sample soils of building materials is presented in Figure 3. The maximum $Ra_{eq}$ is 117.2 Bq·kg$^{-1}$ in white soil, while the minimum $Ra_{eq}$ found in mollisol is approximately 103.805 Bq·kg$^{-1}$. The mean value of $Ra_{eq}$ are 111.05, 112.51, 113.89 Bq·kg$^{-1}$ in sand soil, sand stone and stiff soil, respectively. The estimated mean value of $Ra_{eq}$ in the soil samples is 111.99 Bq·kg$^{-1}$, which is significantly less than the upper limit of 370 Bq·kg$^{-1}$, and it does not pose any radiological hazard when used for the construction of buildings.

| Country  | $^{226}$Ra (Bq·kg$^{-1}$) | $^{232}$Th (Bq·kg$^{-1}$) | $^{40}$K (Bq·kg$^{-1}$) | References |
|----------|--------------------------|--------------------------|------------------------|------------|
| China    | 32                       | 41                       | 440                    | [25]       |
| Pakistan | 20                       | 29                       | 383                    | [26]       |
| Cuba     | 17                       | 16                       | 208                    | [27]       |
| Greece   | 18                       | 17                       | 367                    | [28]       |
| Iraq     | 43.57                    | 1.98                     | 135.02                 | [29]       |
| Brazil   | 36.3                     | 49.4                     | 444.32                 | [30]       |
| Worldwide| 32                       | 45                       | 420                    | [31]       |

Figure 3. Mean values of $Ra_{eq}$ of building materials.
3.3 Representative level index ($I_r$) in building materials

The mean value of the activity utilization index for different types of soil of building materials in Xinchang section around the jijicao block and the rock mass is shown in Figure 4. The mean activity utilization of $I_r$ are 0.43, 0.42, 0.44, 0.39 and 0.44 mSv·y$^{-1}$ in sand stone, sand soil, stiff soil, mollisol and white soil, respectively. And the mean value of $I_r$ of different types of soil used in building material is 0.43. $I_r < 1$ implies that the building materials in Xinchang section around the jijicao block and the rock mass are less than the specified value of 1 mSv·y$^{-1}$. The result indicates that the five types of soil are safe for using as building materials.

Figure 4. Mean values of $I_r$ of building materials.

3.4 External hazard index ($H_{ex}$) and internal hazard index ($H_{in}$) in building materials

The calculated mean values of $H_{ex}$ and $H_{in}$ for all types of building materials are presented in Figure 5. The higher $H_{ex}$ of 0.32 and 0.31 are found in white soil and stiff soil, respectively. The obtained mean values of sand stone and mollisol used as building materials in this study are lower than the total mean value. The mean value of $H_{ex}$ estimated in total is 0.3 mSv·y$^{-1}$, which is significantly less than the upper limit of 1 mSv·y$^{-1}$. While the mean values of $H_{in}$ is 0.37 mSv·y$^{-1}$, and the mean value of $H_{in}$ are 0.37, 0.36, 0.36, 0.34 and 0.38 mSv·y$^{-1}$ in sand stone, sand soil, stiff soil, mollisol and white soil, respectively, which are all less than the recommended level of 1 mSv·y$^{-1}$. We can say that the radiation hazard is insignificant for the population. Therefore, the five types of soil in this study can be safely used in the construction of buildings.

Figure 5. Mean values of $H_{ex}$ and $H_{in}$ of building materials.
3.5 Absorbed gamma dose rate ($D_G$) and annual effective dose rate ($D_E$) in building materials

The mean values of $D_G$ in air for different types of soil used for building materials are shown in Figure 6. The maximum $D_G$ is 106.19 nGy· h$^{-1}$ in white soil, while the minimum $D_G$ found in mollisol is approximately 94.14 nGy· h$^{-1}$. The estimated mean value of $D_G$ in the soil samples is 102.45 nGy· h$^{-1}$, which is slightly higher than world (populated-weighted) (UNSCEAR 2008) indoor $D_G$ of 84 nGy· h$^{-1}$ by about 1.2 times. The mean annual outdoor $D_E$ of different types of soil for building material are also given in Figure 6. These values vary from 0.12 mSv· y$^{-1}$ for mollisol to 0.13 mSv· y$^{-1}$ for white soil. The estimated mean value of the annual $D_E$ of 0.13 mSv· y$^{-1}$ is less than the permissible limit of 0.48 mSv· y$^{-1}$. Figure 6 also presents the mean $D_G$ and $D_E$ of 102.89, 101.91, 104.79 nGy· h$^{-1}$ and 0.13, 0.12, 0.13 mSv· y$^{-1}$ in sand soil, sand stone and stiff soil, respectively. The results indicate that the various types of building materials along with the $D_G$ and the $D_E$, respectively. According to the current research progress, the five types of soil used as building materials in Xinchang section around the jijicao block and the rock mass shall be classified and used according to limits of radionuclides in building materials (GB6566-2010)[32].

![Figure 6. Mean values of $D_G$ and $D_E$ of building materials.](image_url)

At present, there are few studies on the effects of the soil types of radiation hazard indexes used as building materials. We compared the effects of the radiation hazard indexes related to the desert areas on the granite used as building materials. Table 3 shows the comparison of the radiation hazards of the granite samples in China and other parts of the world. The mean value of $Ra_{eq}$, $I$, $H_{ex}$, $H_{in}$, $D_G$ and $D_E$ in the soil types used as building materials in Xinchang section around the jijicao block and the rock mass is lower than the mean value of the granite samples used as building materials in China, Pakistan and Saudi Arabia, but it is higher than that in Iran, Italy and Egypt. The previous research results revealed that granite is generally considered to be a building material with high concentration of radionuclides, but its radioactive background value is still related to its type [33].

| Country        | $Ra_{eq}$ (Bq kg$^{-1}$) | $I$ (mSv· y$^{-1}$) | $H_{ex}$ (mSv· y$^{-1}$) | $H_{in}$ (mSv· y$^{-1}$) | $D_G$ (nGy· h$^{-1}$) | $D_E$ (mSv· y$^{-1}$) |
|---------------|-------------------------|---------------------|------------------------|------------------------|---------------------|----------------------|
| China         | 228.35                  | 0.863               | 0.617                  | 0.741                  | 109.78              | 0.539                |
| Pakistan      | 273.52                  | 1.027               | 0.739                  | 0.914                  | 130.64              | 0.641                |
| Iran          | 4.63                    | 0.017               | 0.012                  | 0.017                  | 2.19                | 0.011                |
| Italy         | 14.03                   | 0.049               | 0.038                  | 0.048                  | 6.28                | 0.031                |
| Saudi Arabia  | 271.61                  | 1.035               | 0.733                  | 0.483                  | 131.75              | 0.646                |
| Egypt         | 7.31                    | 0.027               | 0.019                  | 0.028                  | 3.47                | 0.017                |
| Worldwide     | 129.84                  | 0.492               | 0.351                  | 0.914                  | 62.60               | 0.307                |
4. Conclusions
The radioactivity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in Xinchang section around the jijicao block and the rock mass are all lower than the background values of Jiuquan, among which the concentration of $^{40}$K is higher than the background values of Beishan and the specified value in UNSCEAR 2008. The soils are divided into five types, in which the concentrations of $^{40}$K radionuclides of sandstone, sand soil, stiff soil, mollisol and white soil are all higher than the background values of Jiuquan and the specified value in UNSEAR 2008, and the mean values of stiff soil are also higher than the background values of Beishan. The excessive concentration of $^{40}$K may be related to nuclear research and radioactive waste disposal activities in nearby areas.

The mean values of $Ra_{eq}$ and $I_{n}$ for all types of building materials are significantly lower than the upper limit of 370 Bq·kg$^{-1}$ and 1 mSv·y$^{-1}$, respectively. $H_{ex}$ and $H_{in}$ of all kinds of soils used as building materials are less than the upper limit of the recommended level of 1 mSv·y$^{-1}$, which indicated that the radiation hazard had few effect on the residence and activities of the population. $D_{G}$ of the soil (0.48 mSv·y$^{-1}$) is less than the upper limit of 1 mSv·y$^{-1}$, and the $D_{G}$ of five types of soil used as building materials are slightly higher than world mean value (populated-weighted) (UNSCEAR 2008) indoor $D_{G}$ of 84 nGy·h$^{-1}$. We suggest that the five types of soil in Xinchang section around the jijicao block and the rock mass shall be classified and used according to limits of radionuclides in building materials.

The works of this research can provide reference for the construction of a URL and the environmental impact assessment of HLW, and also provide a quantitative basis for the assessment of human health hazards caused by radioactive building materials.

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