Natural radioactive environment of urban soils in Shihezi, China

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Abstract Radionuclides, such as ^{238}U, ^{232}Th and ^{40}K, can be found in urban soil. To evaluate the natural radioactivity in the environment, soil samples were collected form Shihezi city and radioisotope concentrations were determined by X-ray fluorescence. The dose rate of urban soil (mGy per year, mGy/a) was calculated. The results indicate that the U, Th and K concentrations of the urban soils were, respectively, 1.2–3.2 mg/kg, 6.4–12.3 mg/kg and 2.05%–2.24%, with the mean values of 2.47 mg/kg, 10.47 mg/kg and 2.16 %. Dose rates of urban soils were 10.04–19.55 mGy/a with the mean value of 16.31 mGy/a. This dose rate is the perfect and maximum value of natural radiation in soil and different with the air absorbed dose rate from terrestrial γ-rays. The mean value of air absorbed dose rate was about 57.42 nGy/h. The annual effective dose rate in air was about 0.07 mSv/a and the average value of Ra_{eq} in urban soil was 120.37 Bq/kg. The relative contribution of *α* particle to the dose rate is higher than that derived from *β*- and *γ*-rays in the urban soils.

Key words Natural radioactivity, Radioactive environment, Dose rate, Urban soil, Shihezi city

1 Introduction

Urban soil is an important part of urban ecological system, in terms of the residents may receive significant doses in exposure to natural radioactivity from radionuclides of potassium, thorium, and uranium in urban soil[1,2], even though the uranium and thorium are trace elements. The radioisotopes, such as ^{238}U, ^{235}U, ^{232}Th, and ^{40}K, and many of the daughter products, emit nuclear radiations when they decay[3]. The ^{40}K, in isotopic abundance of about 0.01%, emits β- and γ-rays, while the heavy nuclides emit α-, β- and γ-rays[4]. The effect of *α* particle is highly localized to within the surface layer of crystal quartz and feldspar in urban soil, compared with β- and γ-rays. However, the gaseous daughter products, such as ^{222}Rn, can be breathed, hence a hazard to human health.

It is necessary to understand the natural radioactivity from radioisotopes in the environment and the radiation hazards. Natural radioactivity in soil samples or building materials has been surveyed, and air-absorbed dose rate, annual effective dose and external hazard index (H_{ex}) in many areas have been studied[5-13]. In this paper, the dose rate of topsoil in Shihezi city was calculated by the U, Th and K concentrations determined by X-ray fluorescence, so as to evaluate the natural radioactivity.

2 Materials and methods

2.1 Study area

Shihezi (Fig.1), an oasis, is situated in arid area of Xingjiang province, northwest China, between 84.7º–86.6ºE and 43.3º–45.3ºN. Its south boarder is on the north edge of the Tianshan Mountains, and its north boarder, on the Gurbantunggut Desert. The average annual temperature of this region is about 8℃, and the average annual precipitation is 120–200 mm. A majority of precipitation occurs between April and July. The physiognomy is simple and comprises the alluvial-proluvial plain and desert, with a mean altitude of 450 m. The soil, of a desert grey soil type, has been changed by urban construction, forestations and cultivation.

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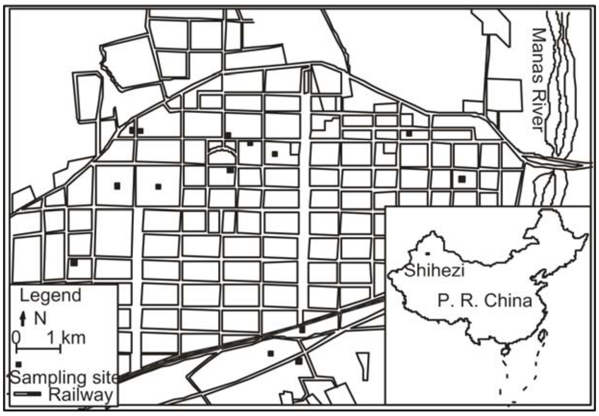

Fig.1 Location of Shihezi city and the sampling sites.

2.2 Sample collection and analytical method

Soil samples were collected from 14 sites in Shihezi (Fig.1). Most of them are in the city's northwest part, which belongs to the old town and has a development of about 60 years. The east and south parts of the city are younger and have less anthropogenic influence. Soil samples were collected from the surface layer (0–5 cm) of five sampling spots at each site. The sub-samples were mixed and weighed approximately 150 g, so as to represent the sampling site. The 14 representative samples were labeled as S1 to S14. In the laboratory of Shaanxi Normal University, each sample air-dried at room temperature was crushed, sieved through a 75 μm mesh after removing plant roots. Finally, 4.0 g soil sample of each site was added with 2.0-g boric acid, and pressed into Φ33mm×4mm wafer under 30-t pressure. U, Th and K concentrations in the urban soil samples were measured by X-ray fluorescence (XRF, PANalytical PW2403).

3 Results and discussion

3.1 The U, Th and K concentrations

The U, Th and K concentrations in soil samples from Shihezi are given in Table 1. The U concentrations range from 1.2 to 3.2 mg/kg, with an average concentration of 2.47 mg/kg and standard deviation (SD) of 0.55. The Th concentrations range from 6.4 to 12.3 mg/kg with an average of 10.47 mg/kg and SD of 1.54. The K concentrations range from 2.05 to 2.24 % with an average of 2.16% and SD of 0.06. The averaged U and K concentrations in Shihezi topsoil are lower than the mean abundance in upper continental crust (UCC), while the averaged Th contents in Shihezi topsoil is higher than the mean UCC abundance[13].

Table 1 Radioelement concentration and dose rate of soil samples collected from Shihezi city, China

Samples	U / mg·kg^{-1}	Th / mg·kg^{-1}	K/ %	Dose rate / mGy·a^{-1}
S1	1.7	8.6	2.20	13.03
S2	1.2	6.4	2.08	10.04
S3	1.9	9.0	2.09	13.72
S4	2.8	11.1	2.20	17.65
S5	2.5	10.3	2.05	16.15
S6	2.5	11.4	2.13	17.03
S7	2.7	11.3	2.19	17.53
S8	2.8	11.5	2.14	17.88
S9	3.2	12.3	2.21	19.55
S10	2.3	10.1	2.16	15.60
S11	2.8	11.0	2.17	17.54
S12	2.9	11.4	2.22	18.14
S13	3.0	11.3	2.24	18.35
S14	2.3	10.9	2.10	16.12
Mean	2.47	10.47	2.16	16.31
SD	0.55	1.54	0.06	2.53

The correlation coefficients of the three major natural radionuclides are shown in Fig.2. No obvious correlation is found between Th and K (R^2=0.2271) and between U and K (R^2=0.3101), but the Th and U concentrations are correlated (R^2=0.9113). This Th-U correlation has been found, too, in the loess plateau, China (Fig.2d). Correlation between ^{232}Th and ^{226}Ra (R=0.92), the production of radioactive decay of ^{238}U and weak correlation between ^{226}Ra and ^{40}K (R=0.45) and between ^{232}Th and ^{40}K (R=0.57) in Chinese commercial marble[14-17].

3.2 Dose rate of the soil samples

In using the dose rate of natural radioactivity in soil to evaluate natural radioactive environment, the k value, or α coefficient, has been adopted, because, for a given amount of absorbed energy, α particles are less effective in inducing OSL (Optically Stimulated Luminescence) signal than β- and γ-rays. In other words, the absorbed dose measured by OSL is only part of the dose contributed by the radionuclides. In this paper, however, we use the dose rate contributed by the radionuclides, rather than dose rate by the OSL crystal, hence no need of considering the α coefficient. The total dose rate (in mGy/a) due to the U, Th and K contents in the soil samples can be calculated by Eq.(1)–(4)[4]

$$D=D_\alpha+D_\beta+D_\gamma+D_c \quad (1)$$

$$D_\alpha=2.31C_U+0.644C_{Th} \quad (2)$$

$$D_\beta=0.145C_U+0.0273C_{Th}+0.782C_K \quad (3)$$

$$D_\gamma=0.113C_U+0.0478C_{Th}+0.243C_K \quad (4)$$

where the D_α, D_β, D_γ and D_c are components of the dose rate from alpha, beta, gamma and cosmic rays, respectively. The C_U, C_{Th} and C_K are the U, Th and K concentration in urban soil, respectively.

The dose rate of cosmic rays, D_c, (in mGy/a) can be calculated by Eq.(5)[18],

$$D_c=0.21\ \exp[-0.070d\rho\ +0.0005(d\rho^2)] \quad (5)$$

where d is depth (m) below the surface and ρ is density (g/cm^3). The D_c in a region is related to the region's altitude, longitude and latitude, and the depth of soil. The mean value of dose rate of cosmic rays in urban soil of Shihezi is 0.223 mGy/a (25.41 nGy/h), which is lower than the national average of 37.4 nGy/h and the global average of 32 nGy/h[16].

Table 1 shows the estimated total dose rate due to the radioisotopes of U, Th and K and cosmic rays in Shihezi, being 10.04–19.55 mGy/a with the mean of 16.31 mGy/a and SD of 2.53. An environmental dose rate depends primarily on geological and geographical conditions of the region, depositional conditions and agrotype. The top soil in Shihezi is desert grey soil formed on a proluvial fan. Parentsoilmaterial of the urban soil is homogeneous in a geographic area. It was also found that the U, Th and K concentrations are not affected by human activity (architecture and irrigation) over the past 60 years. Therefore, the average dose rate of 16.31 mGy/a can be used to estimate environmental radiation level in top soil of Shihezi.

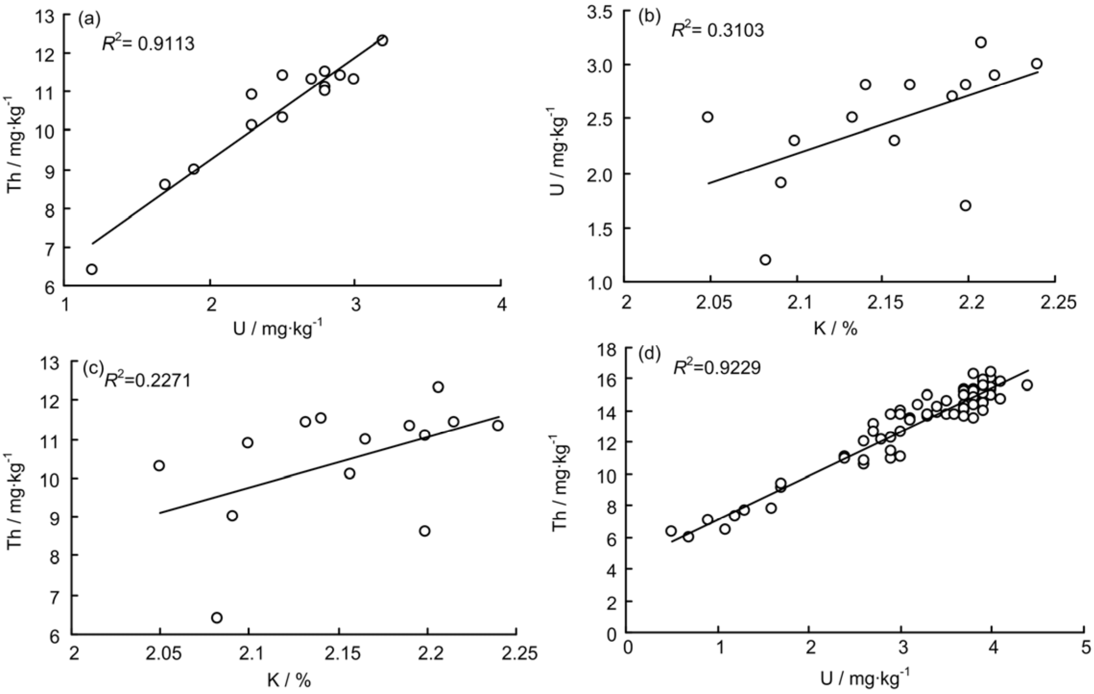

Fig.2 Correlations between uranium and thorium (a), potassium and uranium (b), potassium and thorium (c) in urban soil Shihezi and between uranium and thorium (d) in loess of loess plateau, China.

3.3 Terrestrial γ-radiation

To estimate external terrestrial γ-radiation, the total air absorbed dose rate (nGy/h) one meter above the ground due to the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K (Bq/kg) was calculated using Eq.(6)[2,14].

$$D_\beta=0.0417C_K+0.462C_{Ra}+0.604C_{Th} \quad (6)$$

where C_{Ra}, C_{Th} and C_k are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq/kg, respectively. Eq.(6) has been used all over the world to estimate dose rate in soil, sand, marble, and water[5-12]. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the samples was usually determined using γ-ray spectrometric system. Using the data in Ref.[15], where the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were respectively 26.46–38.15 Bq/kg (average concentration at about 27.26 Bq/kg), 32.77–35.63 Bq/kg (averaged concentration at 32.88 Bq/kg), and 593.37–661.54 Bq/kg (averaged concentration at 598.64 Bq/kg), the air absorbed dose rate in Shihezi can be calculated as 53.3–62.2 nGy/h with a mean value of 57.42 nGy/h (Table 2). This is lower than the average value of the natural γ-ray dose rate of Xinjiang (62.21 nGy/h) and the Chinese average terrestrial γ-ray dose rate (81.5 nGy/h) measured by scintillation detector and high pressure-ionizing chamber[16], but is higher than the estimated average global primordial dose rate of 55 nGy/h[14]. Average value of the calculated dose rates was also lower than average dose rate from terrestrial γ exposure (69.9 nGy/h) calculated from radionuclide content in soil in mainland China[16].

Table 2 Activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil and literature data for comparison.

Site	^{232}Th / Bq·kg^{-1}	^{226}Ra / Bq·kg^{-1}	^{40}K / Bq·kg^{-1}	Air absorbed dose rate / nGy·h^{-1}
Shihezi[15]	32.77–35.63(32.88)	26.46–38.15 (27.26)	593.37–661.54 (598.64)	53.3–62.2 (57.42)
Xinjiang[15]	10.45–190.44(38.96)	10.93–203.45 (31.41)	190.47–1792.3 (579.63)	18.0–264.1 (62.21)
China[16]	10.3–1844 (54.6)	2.8–533 (37.6)	ND-1548 (584)	11.6–522.9 (81.50)
Global[12]	4–130 (40)	8–160 (32)	100–700 (420)	(55.00)

Estimated annual average effective dose equivalent received by an individual was calculated using a conversion coefficient of 0.7 Sv/Gy, which was used to convert the dose rate in the air to human effective dose with an outdoor occupancy factor of 0.2[5]. The effective dose rate, $D_{\rm eff}$(in mSv/a), was calculated by

$$D_{\rm eff}=8760D\times0.2\times0.7\times10^{-6} \qquad (7)$$

The mean annual effective dose rate in the air, calculated by Eq.(7), was about 0.07 mSv/a. This is lower than the mean value of Chinese effective dose rate from natural γ-rays (0.1 mSv/a) and is within the average annual external effective dose rate from terrestrial radionuclide (460 μSv/a) in areas with normal background radiation defined by UNSCEAR[19]. Obviously, the environment of Shihezi can be regarded as an area with normal natural background radiation.

It is important to assess the soil γ radiation hazards to human health. The most widely used radiation hazard index, radium equivalent activity ($\rm Ra_{eq}$) can be calculated by

$$\mathrm{Ra_{eq}}=C_{\rm Ra}+1.43C_{\rm Th}+0.077C_{\rm K} \qquad (8)$$

where $C_{\rm Ra}$, $C_{\rm Th}$ and $C_{\rm k}$ are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq/kg, respectively. According to Eq.(8), 1 Bq/kg of ^{226} Ra, 0.7 Bq/kg of ^{232}Th or 13 Bq/kg of ^{40}K yields the same γ-ray dose. The average value of $\rm Ra_{eq}$ in urban soil of Shihezi is 120.37 Bq/kg. This is lower than the mean $\rm Ra_{eq}$ value of Xingjiang soil (131.75 Bq/kg) and the suggested maximal admissible value of 370 Bq/kg recommended by the Organization for Economic Cooperation and Development[19].

3.4 Relative contribution

Relative contributions of α-, β- and γ-rays to the maximum dose rate of urban soil are shown in Fig.3a. The average relative contribution by individual components of natural radioactivity is 76.0% from α-ray, 14.5% from β-ray, and 8.1% from γ-ray. The radiation from α and β particles is localized in soil and cannot affect the air dose rate at about 1 m above the ground, unlike the γ-rays, which cannot be totally stopped in soil. But in urban soil, the relative contribution of γ-rays to the dose rate is the lowest and the mean value of γ-ray dose rate is 1.3 mGy/a (148.4 nGy/h). This is because the average γ-ray dose rate without absorption of water in urban soil is about 2.6 times higher than the air dose rate.

Sources of natural radiation in top soil include cosmic radiation and soil radiation. Generally, cosmic radiation depends on the altitude and magnetic latitude. Soil radiation depends on radionuclide content in soil and other environment. The dose rates in urban soil were contributed by U, Th, K and cosmic rays in various proportions. Fig.3b shows the relative contributions of U, Th, and K to the dose rate in urban soil. The average relative contribution by U, Th, and K is 38.5%, 46.2% and 13.9%, respectively, while the cosmic ray contribution is just about 1.37%.

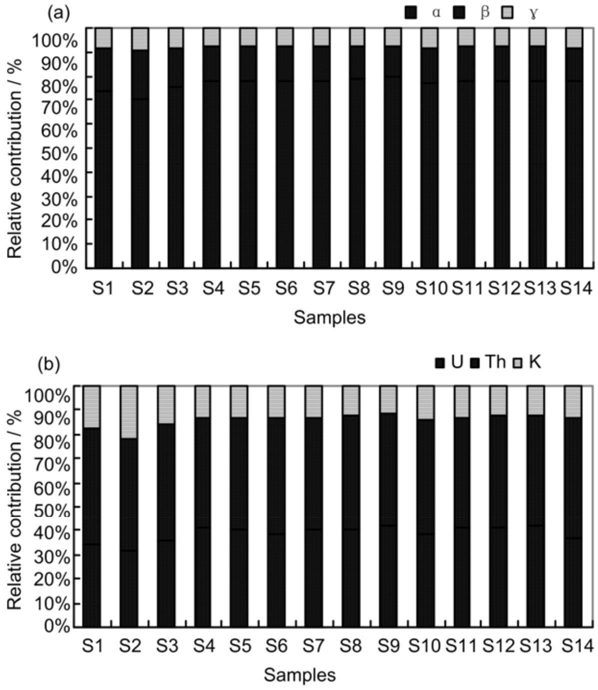

Fig.3 Relative contributions to the dose rate of urban soil owing to (a) α-,β- and γ–rays, and (b) U, Th and K.

4 Conclusion

Air dose rate at 1 m above the ground is a widely used index to evaluate external terrestrial γ radiation. This depends on the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in topsoil. The average air dose rate in Shihezi is 57.42 nGy/h, which is the same as the estimate of average global primordial radiation of 55 nGy/h, but lower than the Chinese average terrestrial gamma radiation (81.5 nGy/h). The mean annual effective dose in the air is about 0.07 mSv/a, which is lower than the mean value of China effective dose rate from naturalγ-rays (0.1 mSv/a). The average value of Ra_{eq} in urban soil in Shihezi is 120.37 Bq/kg, being lower than the mean Ra_{eq} value of Xingjiang soil (131.75 Bq/kg). Therefore the natural radioactive environment of Shihezi can be regarded as an area with normal natural background radiation.

The average U and K contents in Shihezi topsoil are lower than the mean abundance in upper continental crust (UCC), while the average Th content in Shihezi topsoil is higher than the mean abundance in upper continental crust. The dose rates of urban soil range from 10.04 to 19.55 mGy/a with the mean value of 16.31 mGy/a. The mean value of cosmic ray dose in Shihezi is about 0.223 mGy/a (25.41 nGy/h), which is lower than Chinese average cosmic ray dose.

The relative contribution of α particles (76%) is much larger than that of β-and γ-rays. U and Th contribute about 84.69% of the soil dose rate, while K contributes about 13.9% and cosmic rays contribute about 1.37%.

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