Physical-mechanical Properties and Radon Exhalation of Fiber-reinforced Uranium Tailings Geopolymer Solidified Bodies

Fuliang Jiang (✉ jfljfd@163.com)

University of South China <https://orcid.org/0000-0002-2391-9795>

Biao Tan

University of South China

Zhe Wang

University of South China

Yong Liu

University of South China

Yuying Hao

University of South China

Chao Zhang

University of South China

Haonan Wu

University of South China

Changshou Hong

University of South China

Research Article

Keywords: Uranium tailings, Fiber reinforced geopolymer solidification, Pore volume, Volume resistivity, Compressive strength, Radon exhalation rate

Posted Date: June 18th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-632674/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Physical-mechanical properties and radon exhalation of fiber-reinforced uranium tailings geopolymer solidified bodies

Fuliang Jiang ^{1,2,3,4*}, Biao Tan ¹, Zhe Wang ¹, Yong Liu ^{1,2,3}, Yuying Hao ¹, Chao Zhang ¹, Haonan Wu ¹, Changshou Hong ^{1,2,3}

(1. School of Resource & Environment and Safety Engineering, University of South China, Hengyang 421001, China; 2. Hunan Province Engineering Technology Research Center of Uranium Tailings Treatment Technology, Hengyang 421001, China; 3. Hunan Province Engineering Research Center of Radioactive Control Technology in Uranium Mining, Hengyang 421001, China; 4. Hengyang City Key Laboratory of Occupational Safety and Health Technology, Hengyang 421001, China)

Abstract: Uranium tailing ponds are a potential major source of radioactive pollution. Solidification treatment of uranium tailings can control the diffusion and migration of radioactive elements in uranium tailings to safeguard the surrounding ecological environment. Literature review and field investigation were conducted in this study prior to fabricating 11 solidified uranium tailings samples with different proportions with PVA fiber, basalt fiber, metakaolin, and fly ash. The samples' pore structure, volume resistivity, compressive strength, and radon exhalation rate variations were analyzed. The pore size of the solidified samples is mainly between 1-50 nm, the pore volume is between 0.726-1.750 cm³/g, the volume resistivity is between 1411.33-1937.33 Ω·m, and the compressive strength is between 20.61-36.91 MPa. The radon exhalation rate is between 0.0397-0.0853 Bq·m²·s⁻¹, which is lower than the national standard. Based on a comprehensive analysis of the physical and mechanical properties and radon exhalation rate of the solidified

✉Fuliang Jiang
jfljfd@163.com

samples, the basalt fiber is found to outperform PVA fiber overall. The solidification effect is optimal when the 0.6% basalt fiber is added.

Key words: Uranium tailings; Fiber reinforced geopolymer solidification; Pore volume; Volume resistivity; Compressive strength; Radon exhalation rate

1. Introduction

Rapid advancements in the nuclear industry have produced a large amount of radioactive waste ([Juliana, et al. 2017](#)) including uranium tailings, low-level radioactive waste produced by uranium mining and smelting. To date, more than 20 billion tons of uranium tailings and more than 40 billion tons of uranium waste rock have been accumulated globally ([Tang, et al. 2021](#)). Many uranium tailings are deposited in a uranium tailings pond, which seriously threatens the surrounding ecological environment ([Liu, et al. 2020](#)) and urgently requires a solution.

At present, uranium tailings are mainly treated by covering method, solidification method, and bio-chemical remediation method. The most common solidification methods mainly include cement solidification ([R.O. and A.A. 2020](#); [Matthew, et al. 2020](#)), asphalt solidification ([Xu, et al. 2020](#)), glass solidification ([Kang, et al. 2021](#); [Sawada, et al. 2020](#)), and geopolymer solidification ([S. Petlitckaia, et al. 2020](#); [Valeria, et al. 2020](#)). Cement solidification is a relatively mature and widely applicable solidification technology which has certain shortcomings such as high nuclide leaching rate and poor durability. Compared with cement solidification, asphalt solidification has lower nuclide leaching rate, stronger corrosion resistance, and better volume reduction effect, but also has disadvantages such as poor long-term stability of the solidified body and harmful gas that is released during the curing process. Glass solidification can be used to effectively solidify all the components

of radioactive waste, but it is energy-consumptive and requires a lengthy sintering time. The stability of a glass solidified body gradually decreases with the continuous exothermic release of radioactive waste. In recent years, geopolymer solidification has been widely researched and has shown significant advantages in the solidification of heavy metal elements, mainly terms of energy saving and environmental protective effects, favorable physical and mechanical properties, high long-term stability, and low nuclide leaching rate ([Guo, et al. 2020](#); [Zhang, et al. 2017](#)). Studies have shown that the incorporation of appropriate fiber materials can further improve the mechanical properties of the solidified body ([Saloni, et al. 2020](#); [Ramanathan, et al. 2021](#)).

However, there have been few previous studies on the combination of microstructure parameter evolution and macroscopic physical and mechanical properties of fiber-reinforced geopolymer solidified bodies. Research on the properties of such materials is also yet lacking. In this study, uranium tailing was used as a solidified object with sodium hydroxide and sodium silicate as alkali activators. PVA fiber, basalt fiber, metakaolin, and fly ash were added to prepare geopolymer solidified bodies. The relationship between pore structure, volume resistivity, compressive strength and radon exhalation rate in solidified uranium tailings with different ratios was analyzed to observe the solidification mechanism of the tailings.

2. Test materials and sample preparation

2.1 Test materials

The uranium tailing sample used in this test was taken from the center of a uranium tailing pond in southern China. Based on previous research, the radon exhalation rate of uranium tailing is $1.5386 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$ and its chemical composition is as shown in Table 1 ([Jiang, et al. 2021](#)). The main

admixtures used are grade I fly ash and high activity metakaolin of the chemical compositions shown in Table 2. The sodium hydroxide is solid flake (analytically pure) and the alkali activator is liquid sodium silicate with a modulus of 3.3. The fibers are PVA fiber and basalt fiber.

Table 1 Chemical composition of uranium tailings (mass fraction, %) (Jiang, et al. 2021)

Chemical composition	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	MnO	FeO	K ₂ O	U	Others
Content (%)	85.250	1.630	6.180	0.078	0.007	0.360	3.180	0.006	3.309

Table 2 Chemical composition of main admixtures (mass fraction, %)

	Chemical constituents (mass fraction, %)				
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO+MgO	Others
Flyash	53.36	29.09	3.87	3.23	10.45
Metakaolin	53.00	42.00	1.00	0.80	3.20

2.2 Sample preparation

The raw materials were weighed separately on an electronic scale with a range of 0.1 g. The various admixtures were coordinated as shown in Table 3. Then PVA fiber and basalt fiber were mixed with uranium tailings respectively and stirred for 2 min until thoroughly mixed. Metakaolin and fly ash were added and stirred for another 2 min. The prepared alkali activator and high efficiency water reducer were added and stirred for another 2 min, then the mixture was injected into a $\Phi 50 \times 50$ mm cylindrical mold for vibration molding, then left to stand at room temperature for 24 h and removed. The sample (Fig. 1) was moved to a constant temperature and humidity curing box with a temperature of $20 \pm 2^\circ\text{C}$ and relative humidity $\geq 95\%$ for 28 days of curing.

Table 3 Mixture proportions of fiber reinforced uranium tailings solidified bodies

Sample name	Metakaolin (g)	Flyash (g)	Water glass (g)	NaOH (g)	Water (g)	Uranium tailings (g)	Water reducing admixture (g)	PVA fiber (%)	Basalt fiber (%)
M	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0	0
P1	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0.2	0

P2	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0.4	0
P3	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0.6	0
P4	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0.8	0
P5	24.0	16.0	24.0	4.8	4.1	127.1	8.0	1.0	0
B1	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0	0.2
B2	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0	0.4
B3	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0	0.6
B4	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0	0.8
B5	24.0	16.0	24.0	4.8	4.1	127.1	8.0	0	1.0

Note: ① M represents the sample without fiber; P represents the sample doped with single PVA fiber; B represents the sample mixed with a single basalt fiber. ② PVA fiber and basalt fiber with the selected dosage have relatively low mass, so the influence of its quality is not considered here. The ratio of fiber represents the ratio between the dosage of fiber and the total mass of other raw materials.

Fig. 1 Sample of fiber reinforced geopolymer

3. Test method

3.1 Scanning electron microscopy and Pore structure measurements

Scanning electron microscopy (SEM) tests were conducted on a Sigma 300 test machine. An approximately 10 mg sample was first randomly selected to prepare 0.5-5 mm powder. The sample was gold-sprayed for 50 s, then pasted with conductive adhesive prior to testing.

The pore structure test was carried out on an ASAP 2460 physical adsorption instrument. The solidified samples were tested via nitrogen adsorption method. Approximately 5 g of the solidified body sample was crushed to 1-5 mm in size and loaded into the sample tube. The sample was dried at 110°C, then other gas components were removed in a vacuum environment. The desorption

temperature was set to 150°C and the desorption time was 6 h. The samples and instruments were filled with 99.999% nitrogen prior to measurement.

3.2 Volume resistivity measurements

Volume resistivity measurements were taken on a ST2643 ultra-high resistance micro-current tester (Fig.2) per the national standard *Test Method for Volume Resistivity and Surface Resistivity of Solid Insulating Materials* (GB/T 1410-2006 2006).

Fig. 2 Volume resistivity test of sample body

3.3 Compressive strength test

An RMT-150C rock mechanics test system was used to measure the compressive strength of the samples (Fig.3). The sample to be tested was placed in the center of the pressure plate of the press, then the pressure plate was adjusted to ensure uniform force acting on the sample. Each sample was loaded at a rate of 0.5 kN/s until it was completely destroyed. The maximum load at the time of destruction was recorded and plugged into Equation (1) to calculate compressive strength:

$$f_c = \frac{F}{A} \quad (1)$$

where F_c is the uniaxial compressive strength, MPa; F is the maximum failure load of the sample, kN; A is the cross-section area in the vertical loading direction, mm².

(a) Initial stage of sample loading (b) Final stage of sample loading

Fig. 3 Loading process of sample

3.4 Radon exhalation test

A RAD7 radon meter ([Jiang, et al. 2021](#)) was used to measure the accumulated radon concentration of solidified samples via closed chamber method ([Feng, et al. 2019](#)) (Fig. 4). Firstly, the outer surface of a wide mouth glass collector cylinder was wrapped and sealed with tin foil, then the sample was wrapped so that one side or one side and the bottom were bare (referred to from here on as “single exposed” or “double exposed”, respectively). The wrapped sample was then placed in the wide mouth glass collector cylinder for testing.

Fig. 4 Schematic diagram of radon measuring device (Jiang, et al. 2021)

After the accumulated radon concentrations of single and double exposed samples were obtained in the radon exhalation test, software was used to fit the data and radon exhalation rates were calculated as follows:

$$J_1 = \frac{K_1 \cdot V_e}{S_1} \quad J_2 = \frac{K_2 \cdot V_e}{S_2} \quad (2)$$

where J_1 and J_2 are radon exhalation rates of single and double sides of the sample, $\text{Bq} \cdot \text{m}^2 \cdot \text{s}^{-1}$; K_1 and K_2 are the fitting curve slopes of single and double exposed cumulative radon concentrations, $\text{Bq} \cdot \text{m}^2 \cdot \text{s}^{-1}$; S_1 and S_2 are the bottom areas of the sample exposed on one and two sides, respectively, m^2 ; V_e is the effective volume of the radon space except for the sample, m^3 .

The radon exudation rate on the single-exposed sample surface is expressed as:

$$J_1 = D \frac{d}{dx} C_{|x=0} = (J_0 - \sqrt{\lambda \eta D C_0}) \tanh\left(\sqrt{\frac{\lambda \eta}{D}} h\right) \quad (3)$$

and for the double-exposed sample it is:

$$J_2 = D \frac{d}{dx} C_{|x=0} = (J_0 - \sqrt{\lambda \eta D C_0}) \tanh\left(\frac{1}{2} \sqrt{\frac{\lambda \eta}{D}} h\right) \quad (4)$$

Additionally,

$$J_0 = \sqrt{\lambda \eta D} \frac{C_{Ra} S_e \rho}{\eta} \quad (5)$$

where J_0 is the inherent radon exhalation rate; λ is the effective decay constant of radon, $2.1 \times 10^{-6} \text{s}^{-1}$; η is the porosity of the sample; D is the diffusion coefficient of radon, $\text{m}^2 \cdot \text{s}^{-1}$; C_0 is the initial radon concentration in the closed gas collector, $\text{Bq} \cdot \text{m}^{-3}$; H is the height of the sample, m ; C_{Ra} denotes

radium content, $\text{Bq}\cdot\text{kg}^{-1}$; S_e is the ejection coefficient; ρ is the density of the sample, $\text{kg}\cdot\text{m}^{-3}$.

4. Test results and analysis

4.1 Results and analysis of SEM

SEM test results of some samples are shown in Fig 5.

Fig. 5 SEM of some samples

SEM test results of some of the samples are given in Fig. 5. Fig. 5(a) shows that the surface of sample M is loose, with some obvious pores. Fig. 5(b) shows obvious fiber penetration in sample

P1, where fibers fill in the pores. Fig. 5(c) shows obvious cracks on the surface of sample P5. We believe that the excessive incorporation of PVA fiber caused the original pore structure of the sample to be broken. Fig. 5(d) shows that the fiber in sample B5 presents an agglomeration phenomenon with obvious cracks on the surface of the sample. We determined accordingly that the incorporation of excessive fiber is detrimental to the solidified body.

4.2 Pore structure test results and analysis

According to the pore size stipulation of the International Union of Pure and Applied Chemistry (IUPAC) [\(K. S. W. Sing, 2013\)](#), pores can be divided into macropore (>50 nm), mesopore (2-50 nm), and micropore (<2 nm) categories by size. Macropores between unreacted particles in the geopolymer samples used in this study. Mesopores are the typical pores formed between gel phases or between gel phases and particles in the geopolymer. Micropores mainly exist in the gel network structure of the geopolymer. The pore size distribution curve of geopolymer-solidified fiber-reinforced uranium tailing bodies is shown in Fig. 6.

Fig. 6 Pore size distribution curves of cured samples with different fiber content

Table 4 Statistical table of sample pore volume and proportion

Sample number	Total pore volume (cm ³ /g)	Micropore volume (cm ³ /g)	Microporous ratio	Mesopore volume (cm ³ /g)	Proportion of mesopores	Macropore volume (cm ³ /g)	Proportion of macropores
M	1.352	0.008	0.59%	0.830	61.38%	0.514	38.03%
P1	0.911	0.019	2.09%	0.892	97.91%	0	0
P2	1.326	0.003	0.20%	1.502	79.34%	0.271	20.46%
P3	1.503	0.008	0.54%	0.932	62.02%	0.563	37.44%
P4	1.602	0.008	0.50%	1.109	69.25%	0.485	30.25%
P5	1.750	0.011	0.65%	1.267	72.39%	0.472	26.96%
B1	0.948	0.012	1.25%	0.936	98.75%	0	0
B2	0.898	0.009	1.03%	0.889	98.97%	0	0
B3	0.726	0.010	1.42%	0.716	98.58%	0	0
B4	0.928	0.019	2.01%	0.909	97.99%	0	0
B5	1.556	0.010	0.65%	1.199	77.08%	0.346	22.27%

As shown in Fig. 6 and Table 4, we hold that the incorporation of an appropriate amount of

fiber can improve the pore structure of the solidified body sample, and there is an optimal dosage that controls this improvement. The pore structure of the solidified body doped with basalt fiber is better than that of solidified body doped with PVA fiber. Fig.6(a) and Table 4 show that the total pore volume of the sample without fiber is $1.352 \text{ cm}^3/\text{g}$, and that pores are mainly mesopores and macropores accounting for 61.38% and 38.03% of the total, respectively. Fig. 6(b)-(f) and Table 4 show that when the PVA fiber content is 0.2%, the total pore volume is $0.911 \text{ cm}^3/\text{g}$, which is $0.441 \text{ cm}^3/\text{g}$ lower than that of the sample without PVA fiber at a decrease of 32.6%. There are zero macropores and the proportion of mesopores reached 97.91%. When the PVA fiber content is 0.2-1%, the number of mesopores and macropores increases significantly. Fig. 6 (g)-(k) and Table 4 show that when the basalt fiber content is 0.2-0.8%, there are zero macropores in the sample, and the pore size distribution is mainly concentrated in the mesopore category, accounting for more than 97%. When the content of basalt fiber is 0.6%, the total pore volume is the smallest at $0.726 \text{ cm}^3/\text{g}$, which is 46.3% lower than that of the sample without fiber. When the basalt fiber content is 1%, the number of macropores increases significantly, accounting for 22.27% of the total. Therefore, we hold that the optimal PVA fiber content is 0.2% and the optimal basalt fiber content is 0.6%. When the fiber contents exceed the best content, the pore structure of the solidified body will be destroyed and some macropores will be produced.

4.3 Volume resistivity measurement test results and analysis

The volume resistivity values of uranium tailings geopolymer solidified bodies mixed with PVA and basalt fibers are shown in Table 5.

Table 5 Volume resistivity data of cured bodies with different fiber content

Sample number	Volume resistivity ($\Omega \cdot m$)			Average value of volume resistivity ($\Omega \cdot m$)	Standard deviation of volume resistivity
	1	2	3		
M	1022	1027	1011	1020.00	6.68
P1	1949	1939	1924	1937.33	10.27
P2	1860	1845	1854	1853.00	6.16
P3	1931	1924	1928	1927.67	2.87
P4	1674	1681	1676	1677.00	2.94
P5	1420	1401	1413	1411.33	7.85
B1	1601	1586	1595	1595.00	6.16
B2	1761	1753	1740	1751.33	8.65
B3	1825	1816	1806	1815.67	7.76
B4	1665	1662	1655	1660.67	4.19
B5	1539	1544	1527	1536.67	7.13

Fig. 7 Variation of volume resistivity of cured body with fiber content

As shown in Table 5 and Fig. 7, the volume resistivities of cured bodies with different fiber contents generally increase first and then decline. The volume resistivity of the solidified body doped with fiber is significantly higher than that without fiber incorporation; this effect is stronger with PVA fiber than basalt fiber. When PVA fiber content is 0-0.2%, volume resistivity increases rapidly. When PVA fiber content is 0.2-0.4%, volume resistivity decreases slightly. When PVA fiber content is 0.4-0.6%, volume resistivity increases slightly. When PVA fiber content is more than 0.6%, volume resistivity decreases rapidly. When PVA fiber content is 0.2%, the volume resistivity reaches a maximum of 1937.33 $\Omega \cdot m$, compared to the sample without fiber, volume resistivity

increases by 89.93% and the average resistivity is $1761.27 \Omega \cdot m$. When basalt fiber content is 0-0.6%, the volume resistivity increases; it decreases at 0.6-1%. When basalt fiber content is 0.6%, volume resistivity reaches its maximum value of $1815.67 \Omega \cdot m$. Compared to the sample without fiber, volume resistivity increases by 78.01% and the average resistivity is $1671.80 \Omega \cdot m$.

4.4 Compressive strength test results and analysis

The compressive strength of uranium tailings geopolymer solidified bodies mixed with PVA fiber and basalt fiber are shown in Fig. 8.

Fig. 8 Compressive strength curve of solidified samples

As shown in Fig. 8, the compressive strength of the solidified sample first increases and then decreases as fiber content increases. When PVA fiber content is 0-0.2%, the compressive strength increases; it decreases when PVA fiber content is 0.2-1%. When PVA fiber content is 0.2%, the compressive strength reaches its maximum value of 35.49 MPa, which is 4.80 MPa higher than the reference strength (solidified sample without fiber) at an increase of 15.64%. When PVA fiber content is 1%, the compressive strength reaches its minimum value of 20.61 MPa. The average compressive strength is 27.85 MPa. Compressive strength increases when the basalt fiber content is 0-0.6%, then decreases when the content is 0.6%-1%. When basalt fiber content is 0.6%, the

compressive strength reaches its maximum value of 36.91 MPa, which is 6.22 MPa higher than the reference strength (a 20.27% increase). When basalt fiber content is 1%, the compressive strength reaches its minimum value of 28.12 MPa. The average compressive strength is 33.52 MPa.

An appropriate amount of fiber can improve the compressive strength of the cured body, but decreases it upon reaching a critical value. An excessive amount of fiber cannot effectively disperse, which creates more bubbles and cracks in the cured body, resulting in an uneven distribution of bonding stress in the body and the formation of a local stress concentration that drives down its pressure resistance. The strength of the fiber itself can also affect the strength of the cured body. Basalt fiber is stronger than PVA fiber, so the compressive performance of the cured body with basalt fiber is better than that with PVA fiber.

4.5 Analysis of pore volume-volume resistivity, volume resistivity-compressive strength

Fig. 9 Pore volume-volume resistivity of solidified samples with different fiber contents

As shown in Fig. 9, there is negative correlation between the pore volume and volume resistivity of the solidified body samples with different fiber contents. Therefore, we believe that an appropriate amount of fiber incorporation can fill part of the internal pores of the solidified body so

that the internal structure is more compact, thus improving its volume resistivity. If there is too much fiber in the solidified body, however, the fiber does not readily disperse and creates a tunnel in the pore structure through which conductive ions can move freely, thus decreasing the volume resistivity.

Fig. 10 Volume resistivity-compressive strength of solidified samples with different fiber contents

As shown in Fig. 10, there is positive correlation between the volume resistivity and compressive strength of the cured body samples with different fiber contents. The change rule of solidified body compressive strength accurately reflects changes in the volume resistivity of the solidified body. This may be because the volume resistivity and compressive strength of the solidified body are related to the compactness of its internal structure. A pore diameter indicates a denser internal structure, which indicates higher volume resistivity and compressive strength.

4.6 Radon exhalation test results and analysis

4.6.1 Cumulative radon concentration

The variation curves of accumulated radon concentration with radon accumulation time of solidified samples with different fiber contents, both single- and double-exposed, are shown in Figs. 11-14.

Fig. 11 Single-exposed cumulative radon concentration diagram of PVA fiber solidified sample

Fig. 12 Double-exposed cumulative radon concentration diagram of PVA fiber solidified sample

Fig. 13 Single-exposed cumulative radon concentration diagram of basalt fiber solidified sample

Fig. 14 Double-exposed cumulative radon concentration of basalt fiber solidified sample

Figs. 11-14 show that the accumulated radon concentration of the solidified sample gradually increases as radon accumulation time increases. Origin software was used to perform first-order linear fitting on the variation curve of accumulated radon concentration with radon accumulation time, and the results showed that the fitting correlation coefficients R^2 were all greater than 0.969, indicating that the fitting correlation was good.

4.6.1 Radon exhalation rate

According to the fitting equation of the curves of accumulated radon concentration and radon accumulation time of the solidified samples with different fiber content in the above figure, the radon exhalation rate of the solidified samples with single and double exposed surfaces was calculated as shown in Table 6.

Table 6 Statistical table of radon exhalation rate of solidified sample exposed on single side and double sides

Sample number	Radon exhalation rate ($\text{Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$)	
	Single side	Double side
M	0.0827	0.0424
P1	0.0776	0.0401
P2	0.0803	0.0414
P3	0.0813	0.0418
P4	0.0821	0.0421
P5	0.0834	0.0425
B1	0.0802	0.0412
B2	0.0784	0.0404
B3	0.0765	0.0397
B4	0.0803	0.0411
B5	0.0853	0.0434

As shown in Table 6, the radon exhalation rate of single- and double-exposed samples first decreases and then increases as fiber content increases. When PVA fiber content is 0-0.2%, the radon exhalation rate of the solidified sample decreases gradually. When PVA fiber content is 0.2-1%, the radon exhalation rate of the solidified sample increases gradually. When the content reaches 1%, the radon exhalation rates of single- and double-exposed samples reach their maxima at $0.0834 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$ and $0.0425 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$, respectively, both of which exceed that of the sample without fiber. The optimum PVA fiber content is 0.2%, where the radon exhalation rates of single- and double-exposed solidified bodies is the lowest at $0.0776 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$ and $0.0401 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$, respectively. When basalt fiber content is 0-0.6%, the radon exhalation rate of the solidified body decreases gradually.

When basalt fiber content is 0.6-1%, the radon exhalation rate increases gradually. When basalt fiber content is 1%, the radon exhalation rates of single- and double-exposed samples reach their maxima at $0.0853 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$ and $0.0434 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$, respectively. The optimal basalt fiber content is 0.6%, where the radon exhalation rates of single- and double-exposed solidified bodies are lowest at $0.0765 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$ and $0.0397 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$, respectively.

In general, the radon exhalation rates of uranium tailings solidified by fiber reinforced geopolymer samples fall between $0.0397 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$ and $0.0853 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$, which are 17.04-19.11 times lower than that of an uncured uranium tailing body.

4.7 Analysis of pore volume-radon exhalation rate, volume resistivity-radon exhalation rate and compressive strength-radon exhalation rate

The radon exhalation rates of double-exposed solidified body samples with different fiber contents were determined and analyzed in tandem with pore volume, volume resistivity and compressive strength data. The results are shown in Fig. 15-17.

Fig. 15 Pore volume-radon exhalation rate of solidified bodies with different fiber contents

Fig. 16 Volume resistivity-radon exhalation rate of solidified bodies with different fiber contents

Fig. 17 Compressive strength-radon exhalation rate of solidified bodies with different fiber contents

As shown in Fig. 15-17, there is a positive correlation between the pore volume and radon exhalation rate of solidified body samples mixed with PVA or basalt fibers. The change rules of volume resistivity-radon exhalation rate and compressive strength-radon exhalation rate are essentially the same for the different solidified bodies, showing a negative correlation on the whole. This may be because the volume resistivity, compressive strength, and radon exhalation rate of the solidified body are related to its internal pore structure. Smaller pore volume is indicative of a more compact pore structure, which increases the volume resistivity and compressive strength of the sample and thus reduces its radon exhalation rate.

5. Conclusion

Geopolymer solidified bodies of fiber-reinforced uranium tailings were prepared in this study with 11 different fiber content configurations. The effects of different fiber contents on the pore structure, volume resistivity, compressive strength, accumulated radon concentration and radon exhalation of the solidified bodies were examined. The conclusions of this work can be summarized as follows.

(1) An appropriate amount of fiber improves the solidified sample's pore structure, the pore structure of the solidified body with basalt fiber is better compared to that with PVA fiber. The pore structure is optimal when PVA fiber content is 0.2%, where the total pore volume is 0.911 cm³/g. The pore structure is optimal when basalt fiber content is 0.6%, where the total pore volume is 0.726 cm³/g. The macropores of the solidified body are completely filled at this point and the pore size distribution includes mainly mesopores and micropores.

(2) The volume resistivity of the solidified sample is positively correlated with its compressive strength, which first increases and then decreases as fiber content increases. Compressive strength and volume resistivity are the highest when PVA fiber addition is 0.2% at 35.49 MPa and 1937.33 $\Omega \cdot m$ respectively. When basalt fiber content is 0.6%, the compressive strength and volume resistivity are 36.91 MPa and 1815.67 $\Omega \cdot m$, respectively.

(3) The radon exhalation rate of the solidified sample is positively correlated with the pore volume, which first increases and then decreases as fiber content increases. Radon exhalation rate is lowest when PVA addition is 0.2%, at 0.0776 Bq·m²·s⁻¹ and 0.0401 Bq·m²·s⁻¹ for single- and double-exposed samples, respectively. Radon exhalation rate is lowest when basalt fiber content is 0.6%, at 0.0765 Bq·m²·s⁻¹ and 0.0397 Bq·m²·s⁻¹ for single- and double-exposed samples,

respectively, which is far lower than the national standard *Technical Regulations on the Environmental Management of Decommissioning of Uranium Mining and Metallurgical Facilities GB 14586-1993*, $0.74 \text{ Bq}\cdot\text{m}^2\cdot\text{s}^{-1}$.

Author contributions

Fuliang Jiang put forward the experimental scheme, guided the experiment, and guided the writing of the thesis. Biao Tan and Zhe Wang carried out the field experiments and completed the draft paper. Yong Liu guided the formulation and modification of the experimental scheme. Yuying Hao, Chao Zhang, Haonan Wu, Changshou Hong participated in the field experiment. All authors contributed to the writing of the manuscript and approved the final manuscript.

Funding

This research was supported by the Research Foundation of Education Bureau of Hunan Province, China (grant no. 20A422), National Natural Science Foundation of China (grant nos. 11475081 and 11875164), Double First Class Construct Program of USC (grant no. 2019SLY05), Project Approved by the Hunan Province Engineering Research Center of Radioactive Control Technology in Uranium Mining and Metallurgy and Hunan Province Engineering Technology Research Center of Uranium Tailings Treatment Technology (grant no. 2018YKZX1004), Open Fund Project of the Hunan Cooperative Innovation Center for Nuclear Fuel Cycle Technology and Equipment (grant no. 2019KFZ01).

Data availability

All data generated or analyses during this study are included in this published article.

Compliance with ethical standards

Competing interests

The authors declare that they have no competing interests.

Ethical approval

Since this study did not recruit any human and/or animal subjects, this section does not apply.

Consent to participate

Since this study did not recruit any human subjects, this section does not apply.

Consent to publish

Since this study is not attempting to re-publish/ publish any third party or author's previously published material, this section does not apply

Reference

- Bo Liu, Hongjuan Sun, Tongjiang Peng, Tao Duan (2020) Transport and transformation of uranium and heavy metals from uranium tailings under simulated rain at different pH. Environmental Chemistry Letters 18(2): 495-503. DOI: 10.1007/s10311-019-00951-4
- Bin Guo, Dean Pan, Bo Liu, Volinsky, Alex A., Fincan, Mustafa, Jinfeng Du, Shengen Zhang (2017) Immobilization mechanism of Pb in fly ash-based geopolymer. Construction and Building Materials 134:123-130. DOI: 10.1016/j.conbuildmat.2016.12.139
- Chuiyun Tang, Juan Zhong, Ying Lv, daozi Ma, Mingjiang Zhang, Jianlei Wang, Xingyu Liu (2021) The microbial community composition and population change during bioremediation of uranium tailings. IOP Conference Series: Earth and Environmental Science 621(1). DOI: 10.1088/1755-1315/621/1/012096

368 GB/T 1410-2006 (2006) Test method for volume resistivity and surface resistivity of solid insulating
369 materials.

370 Juliana Aparecida Galhardi, Rafael García-Tenorio, Daniel Marcos Bonotto, Inmaculada Díaz Francés;
371 João Gabriel Motta (2017) Natural radionuclides in plants, soils and sediments affected by U-rich
372 coal mining activities in Brazil. *Journal of Environmental Radioactivity* 177: 37-47. DOI:
373 10.1016/j.jenvrad.2017.06.001

374 Fuliang Jiang, Zhe Wang, Guan Chen, Yong Liu, Haonan Wu, Biao Tan, Caiwu Luo (2021) Experimental
375 study of pore characteristics and radon exhalation of uranium tailing solidified bodies in acidic
376 environments. *Environmental Science and Pollution Research* 28(16): 20111-20120. DOI:
377 10.1007/s11356-020-12039-6

378 Fuliang Jiang, Haonan Wu, Jintao Guo, Yong Liu, Zhe Wang, Biao Tan, Caiwo Luo (2021) Experimental
379 study of the damage evolution and radon exhalation characteristics of quasi-uranium ore under
380 constant amplitude cyclic loading and unloading. *Journal of Radioanalytical and Nuclear Chemistry*
381 327(1): 373-384. DOI: 10.1007/s10967-020-07516-8

382 Kang Hyun Woo, Lee Ki Rak, Choi Jung Hoon, Park Hwan Seo (2021) Aerosol processing of glass for
383 radioactive salt waste immobilization. *Annals of Nuclear Energy* 151. DOI:
384 10.1016/j.anucene.2020.107951

385 K. S. W. Sing (2013) Reporting physisorption data for gas/solid systems with special reference to the
386 determination of surface area and porosity (Provisional). *Pure and Applied Chemistry* 54(11). DOI:
387 10.1351/pac198254112201

388 Matthew Isaacs, Steve Lange, Guido Deissmann, Dirk Bosbach, Antoni E. Milodowski, David Read
389 (2020) Retention of technetium-99 by grout and backfill cements: Implications for the safe disposal

390 of radioactive waste. *Applied Geochemistry* 116. DOI: 10.1016/j.apgeochem.2020.104580

391 Mingtao Zhang, Changhui Yang, Min Zhao, Kai Yang, Rui Shen, Yujia Zheng (2017) Immobilization
 392 potential of Cr(VI) in sodium hydroxide activated slag pastes. *Journal of Hazardous Materials* 321:
 393 281-289. DOI: 10.1016/j.jhazmat.2016.09.019

394 Ramanathan Sivakumar, Benzecry Vanessa, Suraneni Prannoy, Nanni Antonio (2021) Condition
 395 assessment of concrete and glass fiber reinforced polymer (GFRP) rebar after 18 years of service
 396 life. *Case Studies in Construction Materials* 14. DOI: 10.1016/J.CSCM.2021.E00494

397 R.O. Abdel Rahman, A.A. Zaki (2020) Comparative analysis of nuclear waste solidification performance
 398 models: Spent ion exchanger-cement based wastefoms. *Process Safety and Environmental*
 399 *Protection* 136: 115-125. DOI: 10.1016/j.psep.2019.12.038

400 Saloni, Parveen, Thong M. Pham (2020) Enhanced properties of high-silica rice husk ash-based
 401 geopolymer paste by incorporating basalt fibers. *Construction and Building Materials* 245. DOI:
 402 10.1016/j.conbuildmat.2020.118422

403 S. Petlitckaia, Y. Barré, T. Piallat, O. Grauby, D. Ferry, A. Poulesquen (2020) Functionalized geopolymer
 404 foams for cesium removal from liquid nuclear waste. *Journal of Cleaner Production* 269. DOI:
 405 10.1016/j.jclepro.2020.122400

406 Sawada, Enokida, Tsukada (2020) Oxidation and vitrification of aluminum with lead borate glass for low
 407 level radioactive waste treatment. *Journal of Nuclear Science and Technology* 57(6): 671-677. DOI:
 408 10.1080/00223131.2019.1710615

409 Shengyang Feng, Hanqing Wang, Yu Cui, Yong-jun Ye, Xiang-yang Li, Dong Xie, Zhengzhong He, Rong
 410 Yang (2019) Monte Carlo method for determining radon diffusion coefficients in porous media.
 411 *Radiation Measurements* 126. DOI: 10.1016/j.radmeas.2019.106130

412 Valeria Cuccia, Carolina Braccini Freire, Ana Cláudia Queiroz Ladeira (2020) Radwaste oil
413 immobilization in geopolymer after non-destructive treatment. Progress in Nuclear Energy 122.
414 DOI: 10.1016/j.pnucene.2020.103246

415 Wei Xu, Guoyi Zhuang, Zhengxiong Chen, Jintao Wei (2020) Experimental Study on the
416 Micromorphology and Strength Formation Mechanism of Epoxy Asphalt During the Curing
417 Reaction. Applied Sciences 10(7). DOI: 10.3390/app10072610