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# Influence of different silica fume contents on the leaching resistance of shotcrete

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Shotcrete is a key support material in tunnel engineering, and its durability under underground water decalcification conditions directly affects structural safety and service life. In this study, a 6 mol/L ammonium chloride solution was used to simulate an underground water decalcification environment. The effects of different silica fume (SF) contents (0%, 5%, 7%, 9%) on the leaching resistance of shotcrete were systematically evaluated in terms of compressive strength, porosity, leaching depth, and calcium ion leaching amount. The results show that the physical and mechanical properties of the shotcrete specimens decrease with increasing leaching time. Compared with the specimens without silica fume, the SF-modified specimens exhibit a lower compressive strength loss rate and a smaller increase in porosity after 90 days of leaching. The development of leaching depth is slower, and the calcium ion leaching rate is also significantly reduced. A higher leaching resistance is already observed at early ages. When the SF content is 7%, the shotcrete specimens exhibit the best leaching resistance. Silica fume has high pozzolanic activity. When incorporated into the fresh concrete mixture, it provides an effective micro-filling effect at early ages and increases the density of the concrete. At the same time, the pozzolanic reaction consumes part of the calcium hydroxide, which hinders the further development of leaching and thus improves the leaching resistance.

## KEYWORDS

accelerated leaching, compressive strength, pozzolanic effect, shotcrete, silica fume

## 1 Introduction

Shotcrete is a technique in which a concrete mixture is sprayed at high velocity onto the receiving surface by compressed air to form a concrete structure (Alekseev and Bazhenova, 2020; Mohajerani et al., 2015). Because of its short setting time, high early strength, simple construction process, and flexible operation, it has been widely used in tunnel engineering (Alekseev et al., 2017; Liu et al., 2024; Shalaby et al., 2025; Wang, 2024). However, during production and service, internal pores and microcracks are easily generated in shotcrete due to fluctuations in construction procedures, and its resistance to aggressive environments is relatively weak. The investigation of leaching-resistance methods for shotcrete is of great significance.

Under natural environmental conditions, concrete leaching is a slow process. To better clarify the degradation behavior of concrete after leaching, accelerated leaching tests have been widely adopted by many researchers. The commonly used methods can be divided into the following types: electrochemical accelerated corrosion (Feng et al., 2021;

Saito and Deguchi, 2000), chemical solution immersion (Steindl et al., 2020; Yang et al., 2025) and dry-wet cycling acceleration (Wang et al., 2016). In practical engineering, tunnel shotcrete is subjected to long-term groundwater attack (Garba et al., 2024; Ye et al., 2021). Due to the difference in calcium ion concentration, calcium ions in calcium hydroxide (CH) and calcium silicate hydrate (C-S-H), which are cement hydration products, are dissolved in water and migrate out, and calcium ion leaching occurs (Fu et al., 2024; Tong et al., 2024; Ye et al., 2021). In this study, the chemical solution immersion method was adopted. Prepared shotcrete specimens were immersed in a 6 mol/L ammonium chloride solution for accelerated leaching, by which the ion migration and decalcification leaching of shotcrete in natural groundwater environments were simulated.

With respect to the physical and mechanical properties of concrete after leaching, many studies have been carried out. The dissolution and loss of cement hydration products in concrete, especially the decomposition of CH and C-S-H, have been reported to cause an increase in porosity and a deterioration of the microstructure (Choi and Yang, 2013; Ma et al., 2022; Qi et al., 2024). Shan (Shan et al., 2024) found that the porosity of cement paste increased with leaching time. After 300 days of calcium leaching, the porosity increased from 21.4% to 31.8% and 33.4% in 1 mol/L and 3 mol/L ammonium chloride solutions, respectively, while the porosity in deionized water (DW) remained at 21.4%. Zhang et al. (2023) carried out accelerated leaching tests and three-point bending tests on single-edge notched beam specimens. The results showed that the mechanical properties of concrete were all affected by leaching. The fracture toughness, elastic modulus, tensile strength, and fracture energy decreased rapidly within the first 60 days of leaching, and the residual fracture parameters of fully leached concrete were about 60%–80% of those of unleached concrete. Huang and Qian (2011) investigated the degradation behavior of concrete under coupled chemical and mechanical actions. It was found that the longer the leaching period, the more significant the change in pore volume. After 60 days of leaching, a marked increase in pore volume in the pore size range of 0.002–0.3  $\mu\text{m}$  was observed. Chen et al. (2025) studied various properties of hydraulic concrete after leaching. The results showed that, with increasing leaching time, calcium leaching in concrete became more pronounced, leaching depth increased significantly, and the mass loss rate and porosity of concrete gradually increased. Salvador et al. (2020) reported that, for concrete subjected to sulfate attack, an increase in porosity was induced by rapid setting caused by accelerators.

Previous studies have shown that SF can improve the leaching resistance of concrete. This improvement is attributed to the pozzolanic reaction, in which the reactive silica in SF reacts with  $\text{Ca}(\text{OH})_2$  produced by cement hydration to form additional C-S-H gel (Hamada et al., 2023; Li et al., 2025). The increased amount of C-S-H can fill the pores in the cement paste, refine the pore size distribution, and reduce the porosity and permeability of concrete (Song et al., 2010).

In summary, leaching has been shown to cause degradation of both macroscopic mechanical properties and microscopic properties of concrete. Existing studies have mainly focused on the chemical attack mechanisms and degradation behavior of ordinary concrete, while systematic studies on calcium ion migration and

decalcification leaching of shotcrete in groundwater environments remain relatively limited. In the present study, an ammonium chloride accelerated leaching method was adopted as the main approach. Accelerated leaching tests of shotcrete in ammonium chloride solution were carried out. Compressive strength, porosity, leaching depth, and calcium ion leaching amount of the specimens were measured. On this basis, the degradation behavior of physical and mechanical properties of shotcrete during leaching was systematically analyzed, the leaching resistance mechanism was revealed, and theoretical guidance and technical references were provided for durability enhancement and mix proportion optimization of shotcrete.

## 2 Materials and methods

### 2.1 Materials

#### 2.1.1 Cement and aggregates

P-O 42.5 ordinary Portland cement was used in this study, and tap water was used as the mixing water. Silica fume was provided in the form of microsilica powder produced by Henan Borun Foundry Materials Co., Ltd., with an  $\text{SiO}_2$  content of 98.4%. The properties of the fine aggregate are given in Table 1, and the properties of the coarse aggregate are given in Table 2.

#### 2.1.2 Admixtures

##### 1. Accelerator

The accelerator, as an indispensable admixture for shotcrete, is used to accelerate setting and hardening so that the strength of shotcrete can meet specification requirements within a short time. Various types of accelerators are available, such as sodium silicate accelerators, aluminate accelerators, and alkali-free accelerators. In this study, an alkali-free accelerator was adopted, and its main performance indexes are listed in Table 3.

##### 2. Water-reducing admixture

The water-reducing admixture is a concrete admixture that is used to increase the strength of shotcrete and reduce the amount of mixing water. In this study, a high-range water-reducing admixture FDN-C produced by Shandong Wanshan Chemical Co., Ltd. was used. The test results are given in Table 4.

#### 2.1.3 Mix proportions

The incorporation of SF in shotcrete can effectively reduce the porosity and rebound rate, which is beneficial to the strength and durability of shotcrete. Based on relevant literature and codes, SF replacement ratios of 5%, 7%, and 9% were adopted in this study. The mix proportions of shotcrete with different SF contents are presented in Table 5.

### 2.2 Specimen preparation

Shotcrete specimens were prepared using the wet-mix method, and the spraying process was carried out in accordance with the *Technical Specification for Construction of Highway Tunnels* (JTG/T 3660-2020). The specific preparation procedure was as follows:

TABLE 1 Physical properties of fine aggregate.

Fineness modulus	Mud content (%)	Apparent density (kg/m <sup>3</sup> )	Bulk density (kg/m <sup>3</sup> )	Stone powder content (%)
2.90	0.1	2,701	1,634	7.6

TABLE 2 Physical properties of coarse aggregates.

Crush value (%)	Needle flake content (%)	Apparent density (kg/m <sup>3</sup> )	Water absorption (%)	Mud content (%)	Blocky clay content (%)
11	4.2	2,720	0.2	0.6	0.1

TABLE 3 Alkali-free accelerator main performance index.

Ingredients	Condensation time (min)		1d compressive strength (MPa)	28 days compressive strength ratio (%)
	Initial condensation time	Final condensation time		
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	2:15	9:50	9.0	95

TABLE 4 Test result of water reducing agent.

Water reduction rate (%)	Bleeding rate (%)	Gas content (%)	Condensation time difference (min)		Compressive strength ratio (%)		
			Initial setting	Final setting	3d	7d	28d
23.4	70.5	2.1	207	226	127	132	134

TABLE 5 Mix ratio of shotcrete with different silica fume content (kg/m<sup>3</sup>).

Number	W/b	Cement	SF	Manufactured sand	Stone	Water	Accelerator	Water reducer
S38	0.38	474		918	782	180		2.7
S38G5	0.38*	451	23 (5%)	918	782	180	31.5	2.7
S38G7	0.38*	443	31 (7%)	918	782	180	31.5	2.7
S38G9	0.38*	435	39 (9%)	918	782	180	31.5	2.7

1. Cement, water, and aggregates were added into a mixer according to the designed mix proportion and were mixed continuously for not less than 3 min. After mixing, the fresh mixture was discharged into the shotcreting trolley. Immediately before spraying, a set accelerator and a water-reducing admixture were added to the mixture, and mixing was conducted again for not less than 3 min.
2. The large panel mold was placed on the ground with an inclination of approximately 45° to the horizontal so that the sprayed surface faced the nozzle. A uniform layer of release agent was applied to all inner surfaces of the large panel mold to facilitate smooth demolding at a later stage.
3. During spraying, concrete was first sprayed along the edge region around the perimeter of the large panel mold to form a stable frame. Then the interior of the mold was gradually filled with sprayed concrete until the mold was completely filled. After completion of spraying, the concrete surface exposed in the mold was trowelled so that the surface was smooth and dense.
4. After spraying, the formed specimens were cured for 1 day. After 1 day of curing, the molds were removed. The demolded

specimens were then cut into cube specimens with an edge length of 10 cm. After cutting, these 10 cm cube specimens were placed in a standard curing room and were further cured until an age of 28 days was reached.

## 2.3 Test methods

### 2.3.1 Accelerated leaching method

The chemical reagent acceleration method was adopted as the accelerated leaching method. All specimens used for the leaching tests were specimens cured for 28 days in the standard curing room. To increase the accelerated leaching rate, a 6 mol/L ammonium chloride solution prepared with industrial distilled water was used as the accelerated leaching reagent.

### 2.3.2 Compressive strength and loss rate

An unconfined compressive strength test was used to test the specimens. During the leaching process, specimens meeting the test requirements were taken out and tested in accordance with the Standard for Test Methods of Physical and Mechanical Properties of Concrete (GB/T 50081-2019). The compressive strength was calculated by Equation 1.

$$f = 0.95 \frac{F}{A} \quad (1)$$

In the above equation,  $f$  is the axial compressive strength of the shotcrete, in MPa;  $F$  is the failure load of the specimen, in N; and  $A$  is the bearing area of the specimen, in  $\text{mm}^2$ .

The loss rate of concrete compressive strength was calculated by Equation 2.

$$\Delta f = \frac{f_0 - f_t}{f_0} \times 100\% \quad (2)$$

In the above equation,  $\Delta f$  is the compressive strength loss rate of the shotcrete specimen at time  $t$ ;  $f_0$  is the initial compressive strength of the shotcrete after 28 days of curing under standard curing conditions, in MPa;  $f_t$  is the compressive strength of the shotcrete after leaching for time  $t$ , in MPa; and  $t$  is the leaching time, in days.

### 2.3.3 Porosity

In this study, the saturated surface-dry weighing method was used to determine the porosity of shotcrete specimens during the leaching process, in order to investigate the time-varying behavior of shotcrete porosity. The specific steps were as follows: First, specimens meeting the specified age were taken out, and free water on the surface was wiped off. The specimens were then placed on a high-precision electronic balance and weighed to obtain the saturated mass. Second, the specimens were completely suspended in water and weighed to obtain the apparent mass in water. Subsequently, the weighed specimens were placed in a vacuum drying oven and dried to a constant mass. The drying temperature was set at 105 °C. After drying, the specimens were weighed again to obtain the dry mass. Finally, based on the saturated mass, the apparent mass in water, and the dry mass of the specimens, the porosity was calculated according to Equation 3.

$$\varphi_s = \frac{M_b - M_g}{M_b - M_f} \times 100\% \quad (3)$$

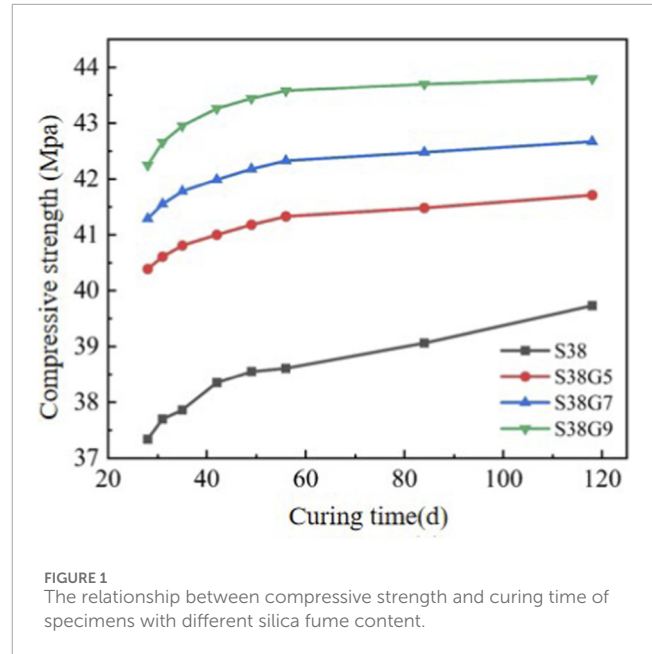


FIGURE 1  
The relationship between compressive strength and curing time of specimens with different silica fume content.

In the above equation,  $\varphi_s$  is the porosity of the specimen;  $M_b$  is the saturated mass of the specimen in kg;  $M_f$  is the apparent mass of the specimen in water in kg; and  $M_g$  is the dry mass of the specimen in kg.

### 2.3.4 Leaching depth

In this study, the leaching depth of the specimens was measured by the phenolphthalein indicator method. First, each specimen was cut along the leaching direction. A prepared phenolphthalein solution was then dropped onto the freshly exposed cross-section. The leached zone appeared colorless, while the unleached zone turned purple-red. The distance from the specimen surface to the boundary of the purple-red area was taken as the leaching depth. Three measurement points were selected on each side along the boundary of the purple-red area, giving a total of 12 points. The leaching depth at each point was measured with a micrometer, and the final leaching depth was taken as the arithmetic mean of the 12 measured values.

## 3 Results and discussion

### 3.1 Compressive strength

The variation of compressive strength with curing time for shotcrete containing 0%, 5%, 7%, and 9% SF under standard curing conditions is shown in Figure 1.

It can be seen from Figure 1 that different SF contents have a clear effect on the evolution of compressive strength of shotcrete with curing time. With increasing curing time, the compressive strength of all specimens was increased. However, the late-age strength growth rate of shotcrete with 5%, 7%, and 9% SF was lower than that of the control group without SF, indicating that the contribution of SF to the later strength was limited. This behavior is mainly because the pozzolanic reaction of SF depends on sufficient free water in the

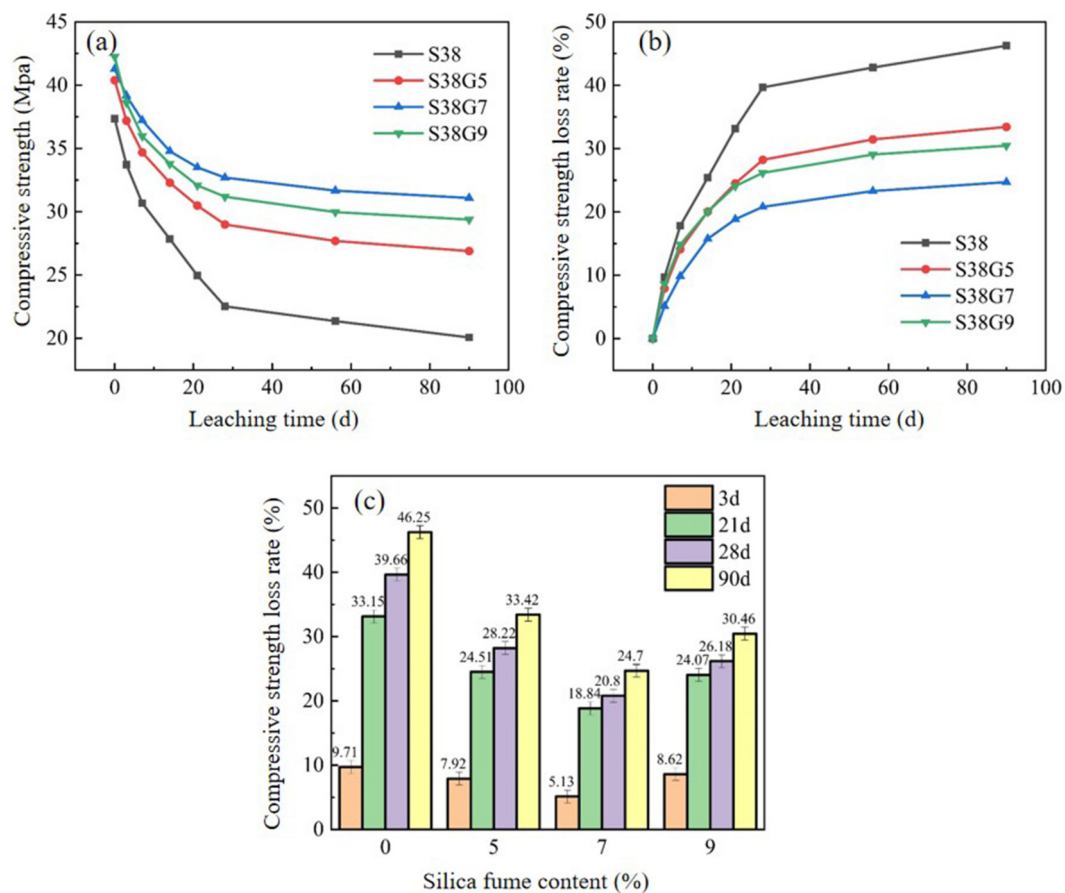


FIGURE 2

The relationship between compressive strength and leaching time of specimens with different silica fume content. (a) Compressive strength; (b) Compressive strength loss rate; (c) Compressive strength loss rate of specimens with different silica fume contents under different corrosion times.

system. As the curing age increases, the capillary pores inside the concrete are gradually filled by hydration products, and the amount of free water is reduced. Under such conditions, it becomes difficult to provide the necessary environment for the secondary reaction between SF and CH, so the reactivity of SF is restricted, and its promoting effect on later strength development is weakened.

With the increase of SF content, the early compressive strength of shotcrete was continuously improved. When the SF contents were 5%, 7%, and 9%, the early strength of the specimens was increased by 8.2%, 10.6%, and 13.1%, respectively, compared with the control group. This trend is different from the effect of fly ash on the compressive strength of shotcrete. The main reason is that SF consists of micron-scale, spherical particles, with an average particle size of about 0.1–0.3  $\mu\text{m}$ , which is much smaller than that of cement particles. These fine particles can effectively fill the internal pores of concrete and increase the density of the matrix. At the same time, the addition of SF increases the number of contact points between solid particles and enhances the internal cohesion of concrete. As a result, the early compressive strength is significantly improved through the combined effects of higher compactness and cohesion.

The variation of compressive strength with leaching time for shotcrete containing 0%, 5%, 7%, and 9% SF under different leaching ages is shown in Figure 2.

It can be seen from Figure 2 that, after SF is incorporated, the variation pattern of compressive strength of shotcrete with leaching time is generally similar. For specimens with different SF contents, the compressive strength gradually decreases with increasing leaching time, and the rate of decrease is progressively reduced. When the leaching time exceeds 28 days, the strength variation of shotcrete with 5%, 7%, and 9% SF becomes relatively small, indicating better mechanical stability.

This behavior is mainly attributed to the high pozzolanic activity of SF. After incorporation, SF can react with the hydration product  $\text{Ca}(\text{OH})_2$  and form a large amount of dense C–S–H gel (Lin et al., 2023). In this process,  $\text{Ca}(\text{OH})_2$  is consumed and the structural compactness of the matrix is improved. In addition, SF can further react with the existing C–S–H gel to form pozzolanic C–S–H gel with a lower Ca/Si ratio. The newly formed C–S–H gel can polymerize with hydroxyl ions and aluminum ions to form a more stable silicate network. As a result, the resistance of the material to leaching is enhanced, and the variation in compressive strength of SF-containing shotcrete during the leaching process is significantly reduced.

By further comparing shotcrete with different SF contents and the shotcrete without SF, it can be observed that the compressive strength of SF shotcrete is always higher than that of the mix without

SF. In contrast to SF shotcrete, the shotcrete without SF shows the most pronounced decreasing trend in compressive strength. With the increase of SF content, the variation range of compressive strength of SF shotcrete first decreases and then increases. When the SF content is between 0% and 7%, the variation range of compressive strength is gradually reduced with increasing SF content. However, when the SF content reaches 9%, the variation range of compressive strength is increased.

From the perspective of different leaching stages, the early compressive strength of shotcrete with different SF contents decreases rapidly, and then begins to decrease more slowly after 28 days of leaching. This behavior is mainly attributed to the following reasons. At the early stage of leaching, the content of  $\text{Ca}(\text{OH})_2$  inside the shotcrete specimens is high, while the concentration of calcium ions in the external solution is low, resulting in a large concentration gradient. In addition, the diffusion path of calcium ions from the concrete to the leaching medium is relatively short, so a high leaching rate is induced. As the leaching depth and porosity increase, the concentration difference of calcium ions between the inside and outside of the specimens is reduced, and the diffusion path of calcium ions becomes longer. Consequently, the leaching rate is gradually decreased.

From the perspective of compressive strength loss rate, the loss rate of shotcrete with different SF contents is gradually increased with the extension of leaching time. At a leaching time of 90 days, the compressive strength loss rates of shotcrete specimens with 0%, 5%, 7%, and 9% SF are 46.25%, 33.42%, 24.70%, and 30.46%, respectively, that is,  $S38 > S38G5 > S38G9 > S38G7$ . This result indicates that the incorporation of SF is beneficial for improving the leaching resistance of shotcrete. From the viewpoint of compressive strength, the optimal SF content is 7%.

### 3.2 Porosity

The variation of porosity with leaching time for specimens with different SF contents, namely, S38, S38G5, S38G7, and S38G9, is shown in Figure 3.

Before leaching, the SF content has a significant influence on the porosity of shotcrete. Specifically, the porosities of shotcrete with 5%, 7%, and 9% SF are all lower than that of shotcrete without SF. In addition, with the increase of SF content, the porosity first decreases and then increases. When the SF content is 7%, the initial porosity of shotcrete reaches the minimum value. This phenomenon is attributed to the small particle size of SF, which allows the SF particles to effectively fill the pores in the concrete and thus improve the pore size distribution and reduce the number of pores. During the leaching process, the porosity of shotcrete specimens with different SF contents shows a similar variation trend with leaching time, that is, the porosity increases with the extension of leaching time. This is because, as leaching proceeds, the hydration products inside the specimens are continuously dissolved and calcium ions are gradually released, which leads to a continuous increase in the porosity of the specimens.

By further comparing the porosity variation rate of shotcrete with different SF contents during leaching, the following observations can be made. For shotcrete without SF, the porosity variation rate reaches 92.59% after 21 days of leaching. In contrast, for shotcrete with 5%,

7%, and 9% SF, the porosity variation rates after 90 days of leaching are 93.88%, 87.47%, and 100.34%, respectively. In terms of the amplitude of porosity variation, after 90 days of leaching, the porosity of specimens with 5%, 7%, and 9% SF increases by factors of 1.98, 1.60, and 1.96, respectively, whereas the porosity of specimens without SF increases by a factor of 4.14, which is approximately twice that of specimens with SF. Therefore, when evaluated from the perspective of porosity, the optimal SF content is 7%.

### 3.3 Leaching depth

The variation of leaching depth with leaching time for shotcrete specimens with different SF contents is shown in Figure 4. It can be seen from Figure 4 that the four groups of specimens with different SF contents exhibit a similar variation law: the leaching depth gradually increases with the extension of leaching time, with a faster increase at the early stage and a slower increase at the later stage. Specifically, the specimen with 0% SF shows the most significant increase in leaching depth, while the specimen with 7% SF shows the smallest increase. Moreover, the differences in leaching depth among the groups become more pronounced as leaching time increases. These results indicate that, under the same water-binder ratio, the leaching resistance of SF shotcrete is significantly higher than that of ordinary shotcrete. The main reasons are as follows: SF provides a micro-filler effect, by which the gel pores and capillary pores in concrete can be effectively filled, and the leaching rate of  $\text{Ca}(\text{OH})_2$  in hydration products can be reduced. At the same time, the active  $\text{SiO}_2$  in SF can react with  $\text{Ca}(\text{OH})_2$  to form pozzolanic C-S-H gel, which optimizes the internal pore structure of concrete, increases its compactness, and consequently retards the development of leaching-induced damage.

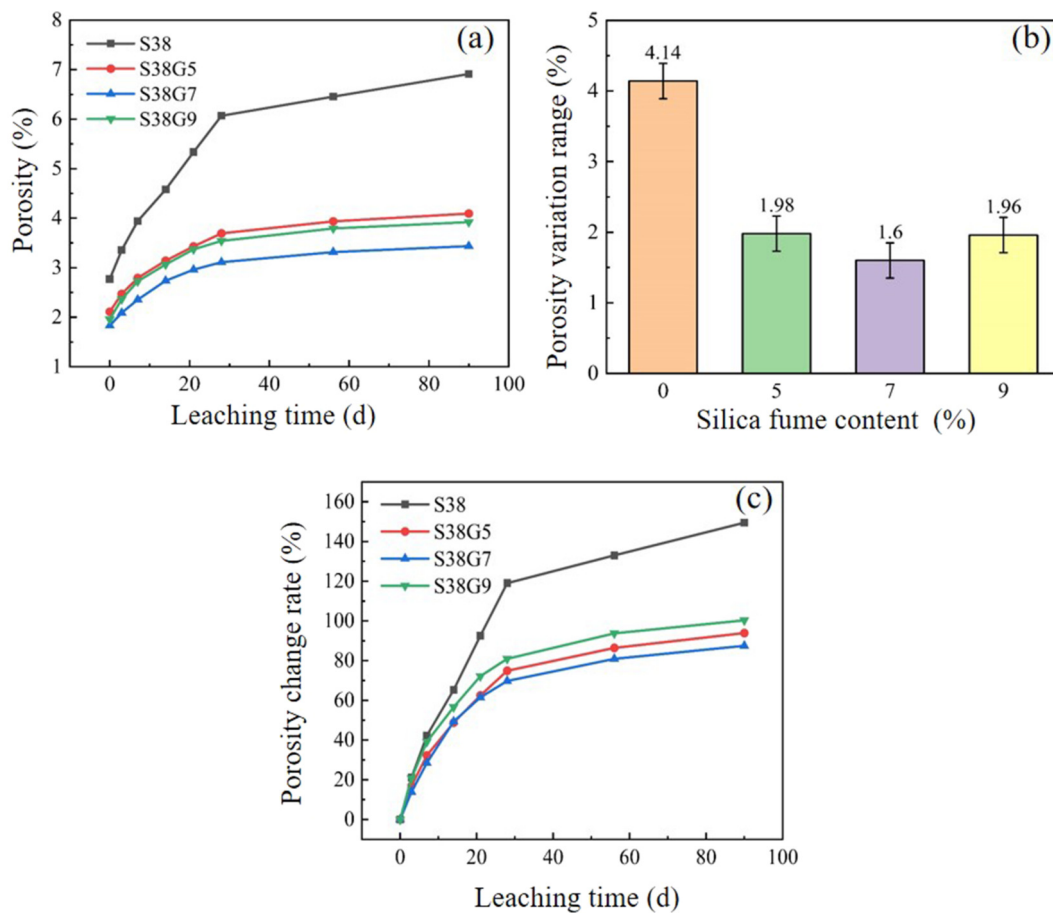
When the leaching time exceeds 28 days, the growth rate of leaching depth in all four groups of specimens is significantly reduced. The leaching depth, from large to small, follows the order  $S38 > S38G5 > S38G9 > S38G7$ . The leaching process can be divided into two stages. The first stage is the leaching of CH, which mainly includes the dissolution, diffusion, and migration of CH. The second stage is the leaching of the cement hydration product C-S-H gel, whose leaching rate is significantly lower than that of CH. Because SF has high pozzolanic activity, a large amount of CH can be consumed, and the CH content in shotcrete can be reduced. As a result, the first leaching stage proceeds relatively quickly, and the second stage is reached earlier. Therefore, in the later period of leaching, the growth rate of leaching depth in SF-containing specimens is clearly slowed down, and better leaching resistance is exhibited.

The relationship between leaching depth and the square root of leaching time for specimens in groups S38G5, S38G7, and S38G9 was fitted using a functional model, as shown in Figure 5. The corresponding fitting equations and correlation coefficients are presented in Table 6.

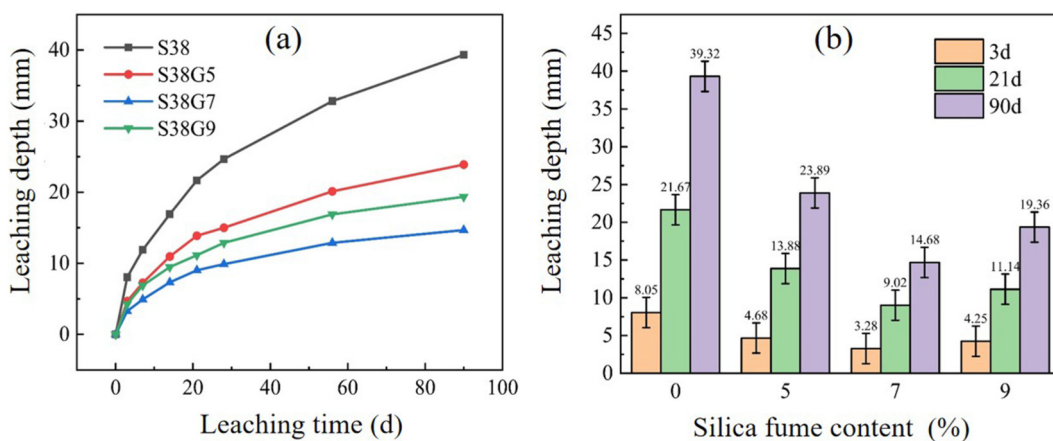
The form of the fitting equations in the above table is expressed as Equation 4:

$$D = k\sqrt{t} \quad (4)$$

In the above equation, denotes the leaching depth of leached shotcrete (Mainguy and Ulm, 2001), in mm; is defined as the diffusion coefficient; and represents the leaching time, in days.



**FIGURE 3** The relationship between porosity and leaching time of specimens with different silica fume content. (a) Porosity; (b) Porosity variation range of specimens after 90 days of leaching; (c) Relationship between porosity variation rate and leaching time.



**FIGURE 4** The relationship between leaching depth and leaching time of specimens with different silica fume content. (a) Leaching depth; (b) Leaching depth after 3, 21, and 90 days.

From Table 6, it can be seen that the leaching depth of shotcrete specimens with different SF contents is linearly related to the square root of leaching time, and the correlation coefficients are satisfactory, all exceeding 0.99.  $k_5 = 2.6877$ ,  $k_7 = 1.7142$ ,  $k_9 = 2.2390$ ,

The diffusion coefficients are  $k_7 < k_9 < k_{20} < k_0$ . It is indicated that the incorporation of SF contributes to improving the leaching resistance of shotcrete. From the perspective of leaching resistance of shotcrete, the optimal SF content is 7%.

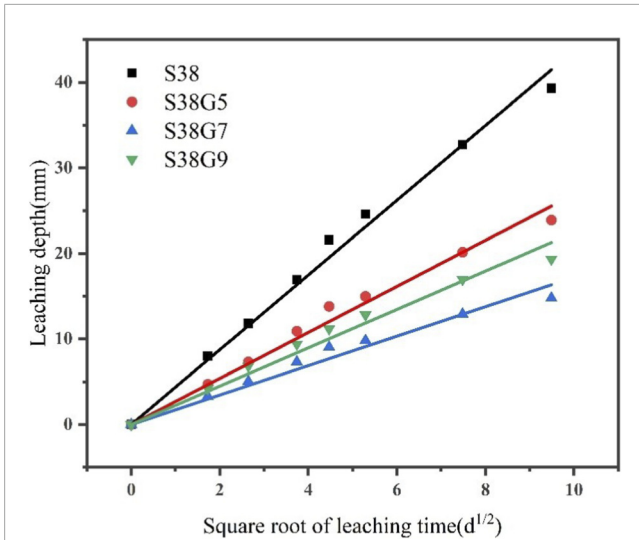


FIGURE 5 The square root fitting curves of leaching depth and leaching time of S38G5, S38G7 and S38G9 specimens were fitted.

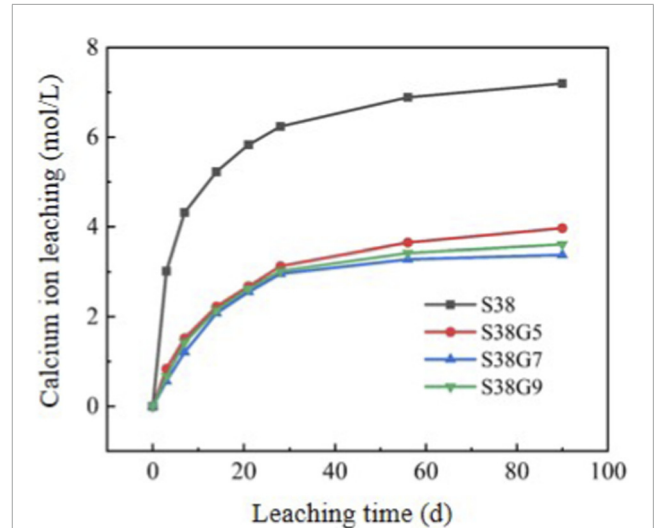


FIGURE 6 The relationship between calcium ion leach and leaching time of specimens with different silica fume content.

TABLE 6 The leaching depth fitting curve equation of S38G5, S38G7 and S38G9 specimens was established.

Specimen	Fitted curve equation	Correlation coefficient
S38	$D_0 = 4.3852\sqrt{t}$	0.99162
S38G5	$D_5 = 2.6877\sqrt{t}$	0.99533
S38G7	$D_7 = 1.7142\sqrt{t}$	0.99014
S38G9	$D_9 = 2.2390\sqrt{t}$	0.99206

### 3.4 Amount of leached calcium ions

The variation of calcium ion leaching amount with leaching time for shotcrete specimens S38G5, S38G7, S38G9 and the control shotcrete specimen S38 is shown in Figure 6.

From Figure 6, it can be observed that the amount of leached calcium ions of shotcrete with different SF contents increases with leaching time. The leaching rate of calcium ions is high at the early stage and gradually decreases at the later stage. The increase rate of calcium ion leaching for the control shotcrete is much higher than that of the shotcrete with 5%, 7%, and 9% SF. When the leached calcium ion amount reaches 3 mol/L, the required leaching times for shotcrete with 0%, 5%, 7%, and 9% SF are 3 days, 28 days, 28 days, and 28 days, respectively. In addition, when the leaching time is between 0 and 28 days, the leached calcium ion amount of SF shotcrete specimens shows an increasing trend within 28 days. When the leaching time exceeds 28 days, the leached calcium ion amount of SF shotcrete specimens stabilizes in the range of 3–4 mol/L. This indicates that the incorporation of SF can significantly improve the leaching resistance of shotcrete.

At the same leaching time, the amount of leached calcium ions from shotcrete with 0% SF is much higher than that from

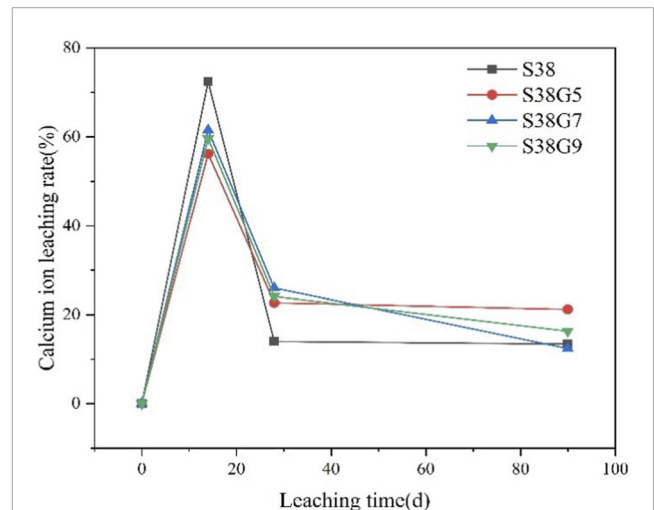


FIGURE 7 Calcium ion leaching rate of S38G5, S38G7 and S38G9 specimens.

shotcrete with 5%, 7%, and 9% SF. When the leaching time is 90 days, the calcium ion leaching amounts of the four groups of shotcrete specimens are 7.20 mol/L, 3.97 mol/L, 3.38 mol/L, and 3.61 mol/L, respectively. From the perspective of calcium ion leaching, an SF content of 7% is the most beneficial for improving the leaching resistance of shotcrete.

The calcium ion leaching rate of shotcrete with different SF contents is shown in Figure 7.

From Figure 7, it can be seen that in the early leaching stage (0–14 days), the calcium ion leaching rate of shotcrete without SF is higher than that of shotcrete with 5%, 7%, and 9% SF. The early leaching rates of calcium ions for the three SF shotcrettes are close to each other, and with increasing SF content, the leaching rate first increases and then decreases. This behavior can be explained as follows. On the one hand, the incorporation of SF reduces

the cement dosage, and thus decreases the amount of cement hydration product  $\text{Ca}(\text{OH})_2$ . On the other hand, SF increases the internal compactness of the shotcrete. The secondary hydration of SF produces cementitious products, which fill internal pores and water-filled spaces. In this way, the transport paths for calcium ions are blocked, and the probability of leaching is reduced. When the SF content is too high, the hydration product  $\text{Ca}(\text{OH})_2$  in shotcrete cannot fully react with the active components of SF. The excess SF particles only play a filler role, and their effectiveness in hindering calcium ion leaching is weakened. In the middle leaching stage (14–28 days), the calcium ion leaching rates of specimens S38, S38G5, S38G7, and S38G9 are 14.0%, 22.7%, 26.0%, and 24.1%, respectively. The leaching rates of SF shotcrete are higher than that of the control shotcrete. However, the corresponding amounts of leached calcium ions for S38, S38G5, S38G7, and S38G9 are 1.01 mol/L, 0.90 mol/L, 0.88 mol/L, and 0.87 mol/L, respectively, and the differences among the four groups are small. This result indicates that SF has little influence on the absolute amount of leached calcium ions in the middle leaching stage. The higher leaching rates of SF shotcrete in this period are mainly due to the smaller total amount of leached calcium ions. In the late leaching stage (28–90 days), the calcium ion leaching rates of shotcrete without SF and shotcrete with 7% SF are similar. This is because, at this time, almost all the pozzolanic activity of SF has been exerted. The internal reactions of SF shotcrete are basically the same as those of the control shotcrete, and only cement hydration continues to occur.

By comparing four indicators, namely, compressive strength, porosity, leaching depth, and the amount of leached calcium ions, it can be found that the presence of SF effectively improves the leaching resistance of shotcrete, and that the optimal SF content is 7%. In practical engineering applications, an appropriate amount of SF can be incorporated to enhance the durability of shotcrete, provided that the safety and economy of the shotcrete are ensured.

## 4 Conclusions and outlooks

In this study, shotcrete was taken as the research object. SF was added at 0%, 5%, 7%, and 9% by mass, and leaching damage of shotcrete was comprehensively evaluated from four aspects: compressive strength, porosity, leaching depth, and calcium ion leaching amount. The leaching damage behavior of shotcrete was investigated, and the following conclusions were obtained:

1. During the leaching process, the changes in compressive strength and porosity, the leaching depth, and the amount of leached calcium ions all showed a trend of first decreasing and then increasing with increasing SF content. To improve the leaching resistance of shotcrete, the optimal SF content is about 7%.
2. SF has high pozzolanic activity. When it is incorporated into fresh concrete, an effective micro-filling effect is provided at an early age, and the compactness of concrete is increased. SF also reacts secondarily with CH, which is a cement hydration product, and consumes a certain amount of CH. In addition, the incorporation of SF reduces the porosity of concrete and hinders the further development of leaching, so that the leaching resistance is improved. The optimal SF content range is 5%–7%.
3. When the SF content is in the range of 5%–9%, the compressive strength of shotcrete first increases and then decreases with increasing SF content, while the porosity first decreases and then increases. A critical turning content of 7% is observed. Due to the small particle size, large specific surface area, high activity, and secondary hydration reaction of SF, the amplitudes of change in compressive strength and porosity during leaching, as well as the leaching depth and the amount of leached calcium ions, are all reduced. Therefore, the incorporation of SF can effectively enhance the leaching resistance of shotcrete.
4. This study investigates shotcrete mixed with SF with different mix proportions and presents the optimal SF dosage. However, this study has certain limitations. For instance, the accuracy of the adopted porosity test method is relatively limited: although the employed saturated-dry weighing method is simple to operate, it suffers from the limitation of being unable to accurately characterize the pore microstructure. In future research, established techniques such as Mercury Intrusion Porosimetry (MIP) or nitrogen adsorption (BET/BJH method) can be adopted to improve the accuracy of porosity measurement.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

XL: Software, Writing – original draft, Writing – review and editing. JaW: Writing – original draft, Writing – review and editing. XZ: Conceptualization, Writing – review and editing. JL: Data curation, Writing – review and editing. JcW: Methodology, Writing – review and editing.

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## Conflict of interest

Authors XL and XZ were employed by Guangxi Guilu Expressway Co., Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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