

Research Article

Experimental Study of a New Concrete Admixture and Its Function in Filling and Reinforcing Granite Fissures

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A concrete admixture with water retention and superhydrophobic properties was developed according to the high tensile strength, fissure resistance, and antiseepage requirements of concrete linings. Capillary water absorption, early-age anticracking, cube compressive strength, and splitting tensile tests were employed to study the effects of the new concrete admixture on the basic performance of concrete. On this basis, a triaxial compression test was conducted on granite fissures filled with concrete containing the admixture; the stress-strain and failure characteristics under different admixture dosages, confining pressures, and fracture widths were analyzed, and the reinforcement effect of the concrete with the admixture on the fractured rock mass was studied. The results show that the admixture can effectively improve the ability of concrete to resist water and fissures, and the concrete with the admixture significantly reinforced the fractured rock mass. Therefore, it can be widely applied in filling and reinforcing fractured rock masses.

1. Introduction

With the increase in the scale and complexity of underground engineering, the performance requirements of concrete lining structures for underground tunnels and caverns are increasingly stringent. Modern tunnel theory focuses on the mechanical evolution of surrounding rocklining systems [1, 2], and many scholars have studied the mechanical properties of concrete linings. Ding et al. [3] studied the influence of lining deterioration on the seismic vulnerability of tunnels through model tests and pointed out that the impact produced by lining deterioration increased over time. Considering the time and spatial effects of sprayed concrete, Xu et al. [4] studied the stress characteristics of shotcrete layers with different rock mass qualities and the response of the surrounding rock and proposed an applicable evaluation method for concrete shotcrete layers. Oreste [5] studied the mechanical properties of sprayed concrete linings and provided a method for calculating the lining safety factor. Gschwandtner and Galler [6] studied the application of the convergence confinement method in concrete linings, considering the time effect. Lu et al. [7] studied the performance of cement grouting in filling rocks. However, damage and failure of concrete linings in engineering projects are still common. For example, the Shiziya Tunnel, which was completed and began use in 2003, experienced a serious collapse of its lining supports and water leakage in 2004 [8]. The lining structures of the Sanchaling Tunnel [9], the Jinjiguan Tunnel [10], and the Liupanshan Tunnel [11] were damaged to varying degrees after these tunnels entered operation, which has had a substantial impact on both engineering safety and social and economic development.

Lining cracking is a common issue for underground caverns. Upon investigation of the tunnels in the Wenchuan earthquake area, Ji et al. [12] found that most of the earthquake damage to the surrounding rock caverns was caused by lining fissures. Many factors are likely to cause lining

fissures in the surrounding rocks of engineering projects, including improper surveys and designs and unsatisfactory construction and maintenance. In particular, the use of unqualified lining materials is a major factor that causes lining fissures. Therefore, the application of new highperformance materials to solve the problem of lining cracking is worthy of further study. High-performance concrete materials have been studied, but there are still a limited number of studies on the use of these materials in the lining supports of the surrounding rocks in underground engineering projects. Through laboratory model tests, Cui et al. [13] found that after becoming deformed, the initial support of steel-fiber concrete may intersect with the characteristic curve of the surrounding rock, thereby enabling the surrounding rock structure to remain stable. Guo [14] studied the concrete used for grouting reinforcement, compared the setting times of phosphoric acid-water glass and cement-water glass with different mix ratios, and proposed relevant design parameters. Li et al. [15] studied the influences of the concrete grain size and nanosilica content on the grouting reinforcement effect in rock fissures. Cui [16] studied the possibility of using geopolymers, which are a type of cementitious material, to treat fissures in tunnel linings. It is generally believed that the addition of fly ash can significantly improve the impermeability of concrete. Naik et al. [17] conducted experiments to study the influence of a large amount of fly ash on the impermeability of concrete. Their results show that as long as the amount of fly ash being substituted for cement does not exceed 50%, the addition of fly ash will reduce the chloride ion permeability of concrete. Yu and Wang [18] developed a concrete admixture that successfully promotes the hydration degree of cement to significantly improve the crack resistance and tensile properties of concrete.

A limited number of high-performance materials have been developed for use in surrounding rock-lining supports in underground engineering projects, so the research and development of new concrete materials with superior antiseepage, fissure resistance, and tensile resistance properties are important for the stabilization of the surrounding rocks in underground engineering projects. In this study, a new concrete admixture for use in the linings of surrounding rocks was developed. Through capillary water absorption, early-age anticracking, cube compressive strength, and splitting tensile tests, the performance of the admixture when added to concrete was investigated in this study. In addition, triaxial compression tests were conducted after filling granite fissures with concrete containing the admixture, and the working performance of this amended concrete in the linings of surrounding rocks was analyzed to determine the reinforcement effect that the concrete with the admixture had on fractured rock masses.

2. Materials and Methods

2.1. Materials. The high-strength (HS) admixture, which has a particle size of $100 \,\mu$ m, is a superhydrophobic powder containing both inorganic and organic materials. It has a floor structure, a flat structure, a spherical structure, and a smooth



FIGURE 1: Microstructure of the HS admixture.

sphere structure (see Figure 1). The thin sheet inorganic substrate has the properties of heat resistance, corrosion resistance, and high strength. The sheet structure, which has a high diameter to thickness ratio, can hinder the penetration of water and other corrosive substances in concrete linings. The chemical bonding between the surfaces of organic compounds and inorganic powders under alkaline conditions gives concrete materials hydrophobic properties.

Adding the HS admixture to concrete materials can improve the separation and seepage of the concrete mixture, strengthen the connection between concrete aggregates, and promote a sufficient reaction between cementitious grouting materials and hydration products to generate a highstrength and highly stable gel, with the HS admixture as the crystal nucleus. Then, many hydrophobic membranes are generated in the capillary channels, and bubbles and thin films with thicknesses of approximately 20 nanometers are introduced to form an impermeable "isolation zone" for permeable materials, which improves the waterproof performance of concrete linings.

To verify its performance, the HS admixture was added to concrete, and capillary water absorption, early-age anticracking, cube compressive strength, splitting tensile, and triaxial compression tests were performed. The materials used in the sample concrete mixtures are as follows: tested Portland cement with a grade of 42.5, in compliance with Chinese national standard GB175-2007 (equivalent to Eurocode CEM I 42.5, ENV197-1: 2000); natural river sand with a fineness of 2.8 as fine aggregate; limestone with a diameter of 5-20 mm as coarse aggregate; water reducing agent; and the HS admixture. Table 1 shows the mix ratio of the concrete used in each test.

2.2. Capillary Water Absorption Test. Cylindrical specimens with diameters of 150 mm each and heights of 300 mm each were prepared, and the HS admixture was added at proportions of 0% and 3%. After 28 days of maintenance, epoxy resin was applied to the top and sides, and then, the bottom of the specimen was placed in a water absorption device with

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HS admixtura dacaga	Quantity of materials used in each cube of concrete (kg/m ³)					
ns admixture dosage	Water	Cement	Fine aggregate	Coarse aggregate	Water reducer	HS admixture
0%	160	320	747	1169	4.16	0.00
1%	160	320	746	1167	4.16	3.20
3%	160	320	743	1163	4.16	9.60
5%	160	320	741	1159	4.16	16.00

TABLE 1: Mix ratios of concrete with different HS admixture dosages.



(a) Vertical fissures

(b) Horizontal fissures

FIGURE 2: Specimens with filled fissures.

a water depth of 3-5 mm to measure the water absorption height at different time points. Three tests were conducted for each specimen.

2.3. Early-Age Anticracking Ability. Under a temperature of 21° and a relative humidity of 60%, an early-age anticracking test [19] was conducted for concrete mixtures with 0% and 3% HS admixture. The size of the testing device was 800 mm \times 600 mm \times 100 mm, and the central wind speed was no less than 5 m/s. Two tests were conducted for each specimen.

2.4. Cube Compressive Strength Test. Cubic specimens 100 $\text{mm} \times 100 \text{ mm} \times 100 \text{ mm} \text{ in size}$ and containing 0%, 1%, 3%, and 5% of the HS admixture were prepared. After 28 days of maintenance, two cube compressive strength tests [19] were conducted for each specimen.

2.5. Splitting Tensile Test. Cubic specimens $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ in size and containing 0%, 1%, 3%, and 5% of the HS admixture were prepared. After 28 days of maintenance, two splitting tensile tests [19] were conducted for each specimen.

2.6. Triaxial Compression Test by Filling Granite Fissures. The tested granite came from Lanzhou, Gansu, China. Cylindrical granite specimens 50 mm in diameter and 100 mm in height were prepared. To simulate the surrounding rocks, specimens containing vertical and horizontal fissures were prepared by cutting, and then, the fissures were



FIGURE 3: Results of the capillary water absorption test.

filled with concrete containing the HS admixture. The specimens are shown in Figure 2.

3. Performance of HS Admixture and Test Results

3.1. Results of the Capillary Water Absorption Test. The results of the capillary water absorption test are shown in



(a) 0% HS

(b) 3% HS

FIGURE 4: Distribution of fissures after 24 h.

TABLE 2: Results of the early-age anticracking test.

HS admixture dosage	Number of fissures per unit area	Cracking area per unit area (1 mm ² /m ²)
0%	12.5	1388
3%	8.3	813

Figure 3. The benchmark specimen (0%) had a high capillary water absorption rate, and the capillary water absorption rate of the concrete with a 3% HS admixture was much less than that of the benchmark specimen for the entire process. The benchmark specimen (0%) absorbed water quickly in the first 1,440 min, then the absorption rate slowed, and finally, the water reached a height of approximately 3.21 mm after the adsorption rate stabilized. For the specimen with a 3% HS admixture, the capillary water absorption height was only 0.88 mm at 1,440 min, and it finally stabilized at a height of approximately 0.92 mm. The analysis showed that adding the HS admixture effectively improved the water absorption resistance of the concrete.

3.2. Results of the Early-Age Anticracking Test. The surface conditions of the specimens after the early-age anticracking test are shown in Figure 4. Table 2 shows the number of fissures and the cracking area on the surface of the specimens with the two admixture dosages. As shown in Figure 4, the benchmark specimen (0%) had a much greater number of fissures than the concrete with a 3% HS admixture. Table 2 shows that the concrete with 3% admixture had a significantly lower number of fissures per unit area and a significantly smaller cracking area compared to the benchmark specimen (0%). Therefore, the HS admixture effectively improved the early-age anticracking ability of the concrete. At the same time, the concrete with the 3% HS admixture performed better in terms of the water retention, while that without the HS admixture lost more water.

The HS admixture improved the early-age anticracking ability of the concrete because it contains a substantial amount of active SiO₂, Al₂O₃, and CaO. These components can react with the substances generated by cement hydration and thereby improve the composition of hydrated cement and reduce both the internal and external migrations of water. Hydrated calcium silicate $Ca_5Si_6O_{16}$ (OH)·4H₂O with a low alkalinity, a high strength, and good stability is generated in this process, which improves the composition of hydrated gelatinous substances. In the early stage of concrete molding, adding the HS admixture can restrict contraction and prevent the loss of water from the concrete, which can reduce the amount of desiccation fissures and thereby decrease the cracking area and the number of fissures in the amended concrete.

3.3. Results of the Cube Compressive Strength Test. The results of the cube compressive strength test are shown in Figure 5, which shows that the cube compressive strength of the specimens declined as the HS admixture dosage increased. The benchmark specimen (0%) had a compressive strength of 48.4 MPa. The cube compressive strength values for the specimens with 1% and 3% HS admixture were 48.0 and 43.5 MPa, respectively, which are 0.8% and 10.1% less than the values of the benchmark specimen; for the specimens with 5% HS admixture, the cube compressive strength was 39.5 MPa, which represents a decrease of 18.4% compared to the benchmark specimen.

In this test, the HS admixture lessened the damage to the concrete specimens. The benchmark (0%) specimen showed vertical fissures and a high degree of crushing. The specimen with 1% HS admixture showed a similar failure mode to the benchmark specimen; however, the occlusions between the fragments were more compact, and the degree of crushing was reduced. The specimens with 3% and 5% HS admixture were more intact, with a further decrease in the amount of crushing.

3.4. Results of the Splitting Tensile Test. The results of the splitting tensile test are shown in Figure 6, which shows that the splitting tensile strength first increased and then



FIGURE 5: Results of the cube compressive strength test.



FIGURE 6: Results of the splitting tensile test.

decreased as the HS admixture amount was increased. The splitting tensile strength of the benchmark specimen (0%) was 2.3 MPa; for the specimen with a 1% HS admixture, the splitting tensile strength was 2.8 MPa, which represents an increase of 21.7% compared to the benchmark specimen; for the specimen with 3% HS admixture, the splitting tensile strength reached a peak of 3.1 MPa, which is 34.8% higher than the value for the benchmark specimen; for the specimen with 5% HS admixture, the splitting tensile strength decreased to 2.3 MPa.

The HS admixture dosage also affected the splitting tensile failure mode of the specimens. The fissure surface of the benchmark specimen (0%) was neat, interface fissures were formed, and the specimen had no crush marks. The specimen with 1% admixture cracked locally, and the cracking surface was more rugged than that of the benchmark specimen. The specimens with 3% and 5% admixture showed uneven fissures.

4. Triaxial Compression Test of Granite Fissures Filled with Concrete Containing the HS Admixture

4.1. HS Admixture Dosage. To study the reinforcement effect of the HS admixture dosage on the rock mass, rock specimens with 4 mm wide vertical fissures were prepared and filled with concrete containing 0%, 1%, 3%, and 5% of the HS admixture. Then, triaxial compression tests were conducted on a TAW-2000 triaxial tester with a confining pressure of 2 MPa. The stress-strain curve and failure mode are shown in Figure 7.

As shown in Figure 7, the damaged benchmark specimen (0%) had one fissure from top to bottom, with a width of 0-2 mm, which was serrated along the depth direction. The entire specimen cracked and peeled off, and the filled layer became fragmented.

The damaged specimen with 1% HS admixture had two fissures from top to bottom on both sides of the filled layer, with depths of 1-2 mm. The specimen cracked and peeled off between the two fissures that were serrated along the depth direction. The surface rock peeled off from the specimen, and the failure surface was characterized by steps.

The specimen with 3% HS admixture had two clear fissures from top to bottom on both sides of the filled layer. The rock and filled layer within these two fissures cracked and peeled off. One serrated fissure was oriented from top to bottom, with a width of 1-1.5 mm, and had pinnate fissures on both sides. The other fissure in the middle was short and oblique, and the entire peeling surface was uneven and had a steep dip angle, with a 2 mm wide crack, which extended upward from the lower part of the specimen through the middle part of the specimen and then gradually



FIGURE 7: Stress-strain curve and typical failure mode of specimens with different HS admixture dosages.



FIGURE 8: Stress-strain curve and typical failure mode under different confining pressures.

ended. In addition, there were longitudinal and transverse cracks and step-like damage in the filled layer.

The damaged specimen with 5% HS admixture had four fissures on the back of the filled layer. In particular, one fissure was a short vertical fissure, two fissures developed obliquely and intersected with the main fissure, and the remaining main fissure was serrated and crescent-shaped on the side face, with a depth of 0.5-2 mm. The rocks between the main fissure and the filled layer cracked and peeled off, and the damaged surface had two steps. The hoop strain at the stress-strain curve was greater than the axial strain.

With the increase in the HS admixture dosage, the overall peak strain decreased, which indicates that adding the HS admixture improved the axial and radial stiffnesses of the specimen with fissures. The specimen with 5% HS admixture showed an evident decrease in the peak strength, while the other specimens had similar peak strength values, which is consistent with the results of the splitting tensile test. Therefore, the concrete containing 3% HS admixture was recommended for filling fissures.

4.2. Confining Pressure. To study how the confining pressure affects the mechanical properties of rocks filled with concrete containing the HS admixture, rock specimens with 6 mm wide vertical fissures were prepared. Samples containing 3% HS admixture were tested under confining pressures of 2, 4, and 6 MPa. The stress-strain curve and failure mode are shown in Figure 8.

Figure 8 shows that under a confining pressure of 2 MPa, the damaged specimen had two inverted Y-shaped fissures and two oblique fissures. One inverted Y-shaped fissure was seriously damaged, and the rocks between this fissure and the filled layer were completely crushed. The rocks between a short oblique fissure in the lower part and the filled layer also peeled off, and the rocks in the upper part of the specimen collapsed. Under a confining pressure of 4 MPa, two small transverse fissures and two small oblique fissures appeared and converged at the filled layer, and the rocks at the upper part were broken. Under a confining pressure of 6 MPa, there was one oblique fissure with a high dip angle on the side of the filled layer, which ran from top to bottom and clearly cracked at the bottom. In addition to the fissure, unclear small closed pinnate fissures appeared.

In conclusion, under different confining pressures, the stress-strain values of the specimens with filled fissures were similar to those of the specimens without fissures. When a specimen was damaged, the filled layer was closely connected to the rock without evident sliding. The broken surface, which ran from top to bottom, appeared on the rock rather than on the filled layer itself, which indicates that concrete containing the HS admixture can effectively fill rock fissures.

4.3. Fissure Width. To study how the concrete containing the HS admixture reinforced rock masses with different fissure widths, rock specimens with vertical fissures of 4 mm and 6 mm were prepared. The HS admixture dosage was 3%, and the confining pressure was 2 MPa. The stress-strain curve and failure mode are shown in Figure 9.

Figure 9 shows that the damaged specimen with a fissure of 4 mm had two fissures that ran from top to bottom on the side of the filled layer, with a depth of approximately 1-1.5 mm. The rocks and filled concrete between the two fissures were broken and peeled off, the fissures showed a zigzag shape, and there were pinnate cracks on the side. There was a damaged fissure with a width of approximately 2 mm on the peeling surface, which extended upward from the lower part of the specimen through the middle part of the specimen and then gradually ended. There were transverse cracks and step-like damages in the filled layer.

The damaged specimen with a fissure of 6 mm had one inverted Y-shaped fissure on the side of the filled layer that ran from top to bottom. The rocks above the fissure were broken and peeled off, and there were more fissures in the specimen. Two inverted Y-shaped fissures were also formed on the side of the filled layer. For one inverted Y-shaped fissure, the rocks at the fissure bifurcation were broken and fell. The Y-shaped fissure on the side gradually diminished and ended at the convergence of the filled layer. The upper part of the filled layer was broken and peeled off due to the broken and peeled rocks. Although there were many longitudinal fissures in the specimen, the overall skeleton of the specimen was intact.

Overall, the damaged specimen with a fissure width of 4 mm was highly intact, while the specimen with a fissure width of 6 mm had many longitudinal fissures. The peak strengths of the specimens with the two different fissure



FIGURE 9: Stress-strain curve and typical failure mode of specimens with different fissure widths.

widths did not significantly change, and the axial strains after damage were also almost the same. In addition, both specimens showed high residual strengths after the peaks, which shows that concrete containing the HS admixture can effectively reinforce fissures of different widths.

5. Conclusions

As a new admixture for the concrete linings of surrounding rocks, the HS admixture showed good water retention and superhydrophobic properties, so it is applicable in the harsh working conditions of the linings of surrounding rocks. Through a triaxial compression test, the ability of concrete containing the HS admixture to fill and reinforce rock fissures was evaluated. The conclusions are as follows:

- (1) The HS admixture greatly lowered the water absorption rate of concrete and significantly improved the water resistance
- (2) The HS admixture effectively prevented the concrete from losing water and reduced the number of desiccation cracks in the concrete

- (3) The HS admixture was cemented in the concrete. As the HS admixture dosage increased, the damaged specimen under cube compressive strength was more intact, and the damaged surface of the specimen under the splitting tensile test was coarser
- (4) The concrete containing the HS admixture was applicable to rock specimens with premade fissures because it effectively reinforced the rock fissures

Data Availability

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

- J. Sulem, M. Panet, and A. Guenot, "An analytical solution for time-dependent displacements in a circular tunnel," *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts*, vol. 24, no. 3, pp. 155–164, 1987.
- [2] A. Graziani, D. Boldini, and R. Ribacchi, "Practical estimate of deformations and stress relief factors for deep tunnels supported by shotcrete," *Rock Mechanics and Rock Engineering*, vol. 38, no. 5, pp. 345–372, 2005.
- [3] Z. Ding, H. Zi, X. Ji, C. Shi, and Z. Ren, "Seismic fragility analysis of mountain tunnels considering lining degradation," *Chinese Journal of Rock Mechanics and Engineering*, vol. 39, no. 3, pp. 581–592, 2020.
- [4] Q. Xu, J. Wu, W. Chu, A. Cao, and J. Liu, "Application of temporal and spatial characteristics of shotcrete mechanics in Middle East pumping storage project," *Chinese Journal of Underground Space and Engineering*, vol. 16, no. 3, pp. 852– 862, 2020.
- [5] P. P. Oreste, "A procedure for determining the reaction curve of shotcrete lining considering transient conditions," *Rock Mechanics & Rock Engineering*, vol. 36, no. 3, pp. 209–236, 2003.
- [6] G. G. Gschwandtner and R. Galler, "Input to the application of the convergence confinement method with time-dependent material behaviour of the support," *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, vol. 27, no. 1, pp. 13–22, 2012.
- [7] Y. Lu, L. Wang, Z. Li, and H. Sun, "Experimental study on the shear behavior of regular sandstone joints filled with cement grout," *Rock Mechanics and Rock Engineering*, vol. 50, no. 5, pp. 1321–1336, 2017.
- [8] G. Xiang, Z. Li, and J. Zhang, "Analysis and treatment for Shiziya Tunnel damage," *Soil Engineering and Foundation*, vol. 1, pp. 5–7, 2008.
- [9] Q. Zhang, "Analysis on engineering geological characteristics of Sanchaling Tunnel," *Railway Investigation and Surveying*, vol. 36, no. 3, pp. 50–52, 2010.
- [10] J. Qi, Z. Hou, and S. Jia, "The research on the characteristics of Jinjiguan Tunnel's water penetration and deformation with defects control," *Journal of Disaster Prevention and Mitigation Engineering*, vol. 2, pp. 222–226, 2005.
- [11] J. Zhang and H. Huang, "Analysis and treatment of lining concrete corrosion failure in Liupanshan Tunnel," *Journal of Highway and Transportation Research and Development*, vol. 11, pp. 228–232, 2007.
- [12] S. JI, Y. TANG, H. U. Degui, J. WANG, and S. TAO, "Analysis of typical seismic damages of highways in Wenchuan earthquake-induced hazard areas in Sichuan Province," *Chinese Journal of Rock Mechanics and Engineering*, vol. 28, no. 6, pp. 1250–1260, 2009.
- [13] G. Cui, D. Y. Wang, S. Z. Ni, and J. X. Yuan, "Model tests on bearing characteristics of steel fiber-reinforced concrete lining of weak surrounding rock tunnel," *Chinese Journal of Geotechnical Engineering*, vol. 39, no. 10, pp. 1807–1813, 2017.
- [14] Y. Guo, Study of Mechanical Model of Reinforced Soils by Pre-Grouting and Its Application in Tunnelling Practices, Beijing Jiaotong University, China, 2016.
- [15] W. Li, F. Shaikh, L. Wang et al., "Experimental study on shear property and rheological characteristic of superfine cement grouts with nano-SiO₂ addition," *Construction and Building Materials*, vol. 228, article 117046, 2019.

- [16] D. Cui, The Research and Performance Test of Type of Tunnel Lining Crack Repairing Material, Chang'an University, China, 2017.
- [17] T. R. Naik, S. S. Singh, and M. M. Hossain, "Permeability of concrete containing large amounts of fly ash," *Cement & Concrete Research*, vol. 24, no. 5, pp. 913–922, 1994.
- [18] Y. Yu and J. Wang, "The influence of WHDF crack resistance agent on improving crack resistance characteristics of concrete face-slab," *Journal of Hydroelectric Engineering*, vol. 19, no. 3, pp. 112–116, 2006.
- [19] "Test code for hydraulic concrete (China)(DL/T5150-2017)".