

Article

Synergistic Self-Healing and Seepage Resistance of Basalt Fiber-Reinforced Microbial Concrete for Pressurized Diversion Tunnel Linings

Xianqi Xu ¹, Wanpeng Mu ², Ruigang Xu ³, Junqian He ⁴, Junfu Lu ^{4,*} and Yunpeng Hu ⁴¹ Sinohydro Bureau 14 Co., Ltd., Kunming 650041, China² Banda Hydropower Project Construction Management Bureau, Huaneng Lancang River Upstream Hydropower Co., Ltd., Qamdo 854300, China³ Banda Hydropower Station Supervision Center, China Northwest Water Conservancy & Hydropower Engineering Consulting Co., Ltd., Qamdo 854300, China⁴ College of Environment and Civil Engineering, Chengdu University of Technology, Chengdu 610059, China

* Correspondence: lujunfu11@cdut.edu.cn

Abstract

Concrete linings in pressurized diversion tunnels are susceptible to cracking and seepage under sustained hydraulic pressure and saturated service conditions, threatening their long-term durability, water-conveyance reliability, and operational safety. To improve the autonomous repair and seepage-control capacity of cracked linings, basalt fiber-reinforced microbial self-healing concrete was developed using modified basalt fibers as both reinforcing components and microbial carriers. Four fiber volume fractions of 0%, 0.1%, 0.2%, and 0.3% were investigated. Mechanical properties, impermeability, crack closure, internal structural recovery, and healing products were evaluated through mechanical tests, water-permeability tests, ultrasonic pulse velocity measurements, crack morphology observations, and microstructural analyses. A normalized integrated self-healing index was further established by combining the crack area healing ratio, ultrasonic pulse velocity recovery ratio, and reduction ratio of water penetration height. The results showed that an appropriate basalt fiber content enhanced the mechanical performance, crack-healing capacity, and seepage resistance of the concrete. The specimen containing 0.2% basalt fiber exhibited the best overall performance, with a 57.6% reduction in permeability coefficient relative to the reference group, a crack area healing ratio of 84%, successful healing of cracks up to 0.65 mm in width, and an integrated self-healing index (SEI) of 1.000 under the adopted internal normalization. Microstructural observations revealed dense CaCO₃-rich deposits within the cracks, with preferential mineral accumulation on and around the basalt-fiber surfaces. These features, together with the mineralogical evidence, were consistent with an MICP-related contribution to crack filling. However, the 0.3% group exhibited markedly poorer impermeability recovery despite relatively high crack closure, indicating that apparent surface healing did not ensure complete functional sealing. These findings demonstrate that apparent crack closure alone is insufficient to characterize self-healing effectiveness and that impermeability recovery provides a more sensitive indicator of internal healing quality. Among the investigated mixtures, the 0.2% basalt fiber formulation exhibited the most favorable overall performance under the continuously saturated laboratory conditions adopted in this study, providing a basis for subsequent validation under representative pressurized seepage conditions.

Keywords: microbial self-healing concrete; basalt fiber; pressurized diversion tunnel lining; extreme hydraulic environment; crack healing; seepage resistance



Academic Editor: Yi Man

Received: 3 August 2026

Revised: 4 September 2026

Accepted: 14 September 2026

Published: 21 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

With the continuous advancement of hydraulic and hydropower infrastructure construction in China, large-scale hydropower hubs, high-dam flood discharge systems, and cross-basin water diversion projects are increasingly developing toward deep-buried, high-head, high-ground-temperature, and geologically complex environments [1]. As a key hydraulic structure responsible for water conveyance and energy regulation, the long-term operational safety of pressurized diversion tunnels has attracted growing attention [2]. Unlike conventional underground tunnels, pressurized diversion tunnels operate under complex service conditions involving the coupled effects of high internal hydraulic pressure, surrounding rock stress, seepage fields, and other environmental effects associated with deep burial [3]. Consequently, the lining concrete must withstand not only sustained hydraulic loading, but also the combined influence of fracture seepage, hydraulic pressure fluctuation, and hydraulic erosion [4]. Under prolonged high-pressure seepage conditions, microcracks are prone to initiate within the lining concrete and progressively develop under the combined effects of cyclic hydraulic loading and stress redistribution. The accumulation of environmental and mechanical damage can weaken the load-bearing capacity and deformation resistance of the lining while promoting further crack propagation. As damage continues to evolve, localized deterioration and interconnected fracture paths may develop, thereby increasing the risk of seepage concentration, structural instability, and progressive degradation of the lining system [5]. Therefore, the effective prevention and long-term repair of cracks in pressurized diversion tunnel linings have become critical scientific and engineering issues for improving the durability and lifecycle safety of hydraulic tunnel structures.

To address cracking problems in pressurized diversion tunnel linings, conventional repair technologies mainly rely on passive remediation methods such as epoxy resin grouting, surface sealing, impermeability reinforcement, and steel lining strengthening. Although these methods can temporarily restore crack sealing and local impermeability, their long-term effectiveness under high hydraulic pressure and saturated service environments is often limited by interfacial aging, hydraulic scouring, and restricted construction space. As a result, it remains difficult to achieve continuous repair of internal microcracks and effective suppression of crack re-propagation [6]. Moreover, for deep-buried pressurized diversion tunnels, shutdown maintenance and secondary repair operations are associated with extremely high economic and operational costs. Consequently, the traditional “damage–repair” strategy can no longer satisfy the long-term service requirements of modern hydraulic structures. In recent years, with the rapid development of smart cementitious materials and biomimetic repair technologies, microbial self-healing concrete with autonomous crack-healing capability has gradually become a major research focus [7]. By incorporating functional microorganisms into cement-based materials, microbial-induced calcium carbonate precipitation (MICP) can be activated after crack formation, thereby promoting autonomous crack closure and structural performance recovery. This technology provides a promising approach for active crack regulation and long-term durability enhancement of hydraulic lining structures. Owing to its excellent interfacial compatibility with cementitious matrices, environmental friendliness, and targeted crack-filling capability, MICP-based repair technology has shown considerable application potential in hydraulic concrete crack remediation. Hu et al. [8] investigated the application of *Sporosarcina pasteurii* in hydraulic concrete crack repair and confirmed the effectiveness of MICP in crack sealing and impermeability restoration. Wang et al. [9] studied the healing behavior of microbial self-healing concrete under saturated conditions and clarified the influence of water-curing

environments on the mineralization process. Zhang et al. [10] evaluated the enhancement of erosion resistance induced by MICP treatment and revealed the optimization effect of mineral precipitation on the pore structure of concrete. Existing studies indicate that microbial mineralization can effectively refine the internal pore structure of concrete and exhibit excellent autonomous healing performance within a limited crack width range.

However, although microbial mineralization can effectively achieve crack sealing and local impermeability recovery, relying solely on post-crack mineralization remains insufficient for pressurized diversion tunnel linings subjected to long-term high hydraulic pressure and cyclic loading conditions. Even when cracks are subsequently filled with mineralized products, the overall toughness and long-term structural stability of the concrete may still be restricted. In recent years, basalt fiber has been widely employed to improve the crack resistance and toughness of concrete due to its high strength, high elastic modulus, excellent corrosion resistance, and good compatibility with cementitious matrices. Li et al. [11] systematically investigated the influence of basalt fibers on the mechanical properties and impermeability of hydraulic concrete, confirming that the three-dimensional fiber network can effectively bridge cracks and inhibit crack propagation. Song et al. [12] conducted flexural performance tests on basalt fiber-reinforced concrete with different fiber contents and clarified the mechanism by which fibers improve the brittleness characteristics of concrete. Li et al. [13] further evaluated the enhancement effect of basalt fibers on the hydraulic fracturing resistance of concrete under high-water-pressure conditions, providing experimental support for their application in hydraulic engineering structures. Previous studies have demonstrated that basalt fibers can form an effective three-dimensional bridging network within concrete due to their excellent mechanical properties, alkali resistance, and favorable interfacial bonding performance, thereby significantly suppressing crack propagation. In addition, fiber incorporation can improve the internal pore structure of concrete and provide potential attachment sites for microbial adhesion and mineral deposition. Therefore, integrating basalt fiber reinforcement technology with MICP self-healing technology is regarded as an important strategy for achieving the synergistic regulation of “active crack resistance and toughening during crack initiation” and “autonomous healing after crack formation.”

With the continuous development of this field, fiber–microbe synergistic self-healing systems have gradually become a research frontier. In terms of microbial immobilization, Kanwal et al. [14] proposed the use of porous carriers for microbial fixation, which effectively improved bacterial survival in highly alkaline cementitious environments. Amjad et al. [15] explored the feasibility of natural fibers as microbial carriers and proposed the concept of an integrated “bacteria-laden fiber” self-healing system. Shaheen et al. [16] systematically analyzed immobilization carrier materials and preparation methods, providing theoretical guidance for functional carrier optimization. Regarding fiber–matrix interfacial synergy, Vijay et al. [17] first investigated the synergistic enhancement effect of basalt fibers and bacteria in self-healing concrete and demonstrated that their combined incorporation could simultaneously improve mechanical performance and crack-healing capability. Zhang et al. [18] optimized fiber interfacial properties through nanomodification technology, thereby improving the compatibility between microbial mineralization products and the cement matrix. Mardani et al. [19] further revealed the influence of fiber surface modification on the performance evolution of composite systems from the perspective of interface regulation. In addition, concerning mineralization reaction mechanisms, Tao et al. [20] investigated the influence of different calcium sources on the MICP reaction rate and precipitation characteristics, indicating that organic calcium sources exhibit better adaptability in saturated environments. Jiang et al. [21] analyzed the mineralization behaviors of different bacterial species and found that *Sporosarcina pasteurii* exhibits

higher mineralization efficiency and environmental adaptability in urea hydrolysis systems. Wu et al. [22] further clarified the evolution behavior of microbial mineralization under low-oxygen saturated conditions, providing theoretical support for microbial repair applications in complex hydraulic environments. Overall, current studies have preliminarily established the theoretical foundation of fiber-reinforced microbial self-healing systems from the perspectives of microbial immobilization, fiber interface regulation, and mineralization reaction mechanisms. These findings demonstrate the strong synergistic potential between fiber bridging effects and MICP crack-healing mechanisms, providing new research ideas and technical pathways for the integrated regulation of crack resistance, toughness enhancement, and autonomous healing in hydraulic concrete.

Nevertheless, despite the substantial progress achieved in fiber reinforcement and microbial mineralization repair, significant limitations still exist regarding their application to pressurized diversion tunnel lining structures. On the one hand, most existing studies focus primarily on the individual mechanisms of fiber reinforcement or microbial healing, while systematic investigations into synergistic toughening and self-healing design under long-term high-pressure saturated environments remain limited. Consequently, a comprehensive material system capable of simultaneously satisfying mechanical performance, impermeability, and long-term healing stability requirements has not yet been established. On the other hand, for bacteria-laden fiber composite systems, the healing behavior and toughening mechanisms under prolonged saturated service conditions are still not fully understood. Previous studies have shown that moisture and oxygen transport efficiency are important boundary conditions affecting microbial mineralization reactions. However, under high hydraulic pressure and saturated environments, the influence of fiber dosage on microbial survival, mineral precipitation characteristics, and crack-healing efficiency remains unclear, and the intrinsic synergistic mechanisms have not yet been fully elucidated. Furthermore, whether a synergistic coupling relationship exists between fiber-bridging toughening effects and mineralization-based repair mechanisms, as well as the optimal fiber dosage range for simultaneously maximizing mechanical enhancement and crack-healing performance, still lacks systematic experimental and theoretical verification. Therefore, investigating the synergistic mechanisms of fiber reinforcement and microbial self-healing in pressurized diversion tunnel linings under long-term saturated conditions is of considerable engineering significance for improving the durability and operational safety of hydraulic structures.

Based on the above research background and engineering demands, this study developed a basalt fiber-reinforced microbial self-healing concrete system with reference to the performance requirements of pressurized diversion tunnel linings. Modified basalt fibers were employed to achieve the integrated functions of crack inhibition, structural toughening, and microbial immobilization, thereby establishing a full-cycle regulation mechanism combining passive crack resistance and active autonomous healing. Four basalt fiber volume fractions of 0%, 0.1%, 0.2%, and 0.3% were designed as the primary control variables. Mechanical properties, impermeability performance, and crack-healing behavior were systematically investigated through macroscopic performance tests and crack observation experiments. Meanwhile, UPV testing, SEM, and XRD analyses were conducted to characterize the evolution of microstructure, interfacial morphology, and mineralized products. From the perspectives of macroscopic performance evolution, interfacial structural development, and mineral precipitation characteristics, the toughening mechanisms and crack self-healing behavior of the composite system under saturated conditions were comprehensively revealed. The findings of this study provide an experimental reference for material optimization and subsequent validation of self-healing concrete for pressurized diversion tunnel linings.

2. Engineering Background and Experimental Program

2.1. Engineering Background

This study was conducted based on a diversion tunnel project of a hydropower station located in Chaya County, Tibet Autonomous Region, China. The diversion tunnel has a total length of approximately 2.3 km and adopts a horseshoe-shaped cross-section with a lining thickness ranging from 0.4 to 0.6 m. Designed to withstand high internal hydraulic pressure, the structure is representative of a typical deep-buried pressurized tunnel. The surrounding rock mass in the engineering area is mainly classified as Grade III–IV rock, characterized by well-developed fractures and abundant groundwater. Consequently, the lining concrete is continuously exposed to a complex service environment involving long-term water saturation, hydraulic erosion, and repeated internal water pressure effects. After crack initiation in the lining structure, groundwater and pressurized internal water can continuously penetrate along the crack paths, forming localized hydraulic pressure zones and seepage channels within the cracks. This process further accelerates crack propagation and structural deterioration. Therefore, the long-term saturated seepage environment surrounding cracked regions can be regarded as one of the most significant service characteristics of pressurized diversion tunnels. Engineering practice and operational observations indicate that, after approximately 5–10 years of service, pressurized diversion tunnels are prone to developing penetrating cracks with widths ranging from 0.3 to 0.6 mm [23]. These cracks provide preferential pathways for high-pressure water intrusion and subsequently induce a series of deterioration phenomena, including hydraulic fracturing, cement paste dissolution, and interfacial debonding.

2.2. Materials

Sporosarcina pasteurii (ATCC 11859) was employed as the functional microorganism in this study to induce calcium carbonate precipitation through urea hydrolysis, thereby enabling autonomous crack healing in concrete. The bacterial culture was incubated at 30 °C for 24 h to obtain a bacterial suspension with a cell concentration of approximately 1×10^8 cells/mL, which was subsequently used for bacterial immobilization on the basalt fibers. Short-cut basalt fibers were completely immersed in a 2 wt.% NaOH solution and treated at 80 °C for 12 h. After alkali treatment, the fibers were thoroughly rinsed with deionized water until a neutral pH was reached and then dried at 80 °C for 10 h to constant mass to obtain surface-modified basalt fibers. The modified fibers were mixed with the bacterial suspension at a fiber-to-suspension ratio of 1 g:50 mL and subjected to constant-temperature shaking adsorption for 7 h, followed by vacuum infiltration for 15 min. Accordingly, the nominal bacterial dose was estimated to be approximately 5×10^9 cells/g fiber; this value represents the theoretical initial bacterial input rather than the actual viable loading after immobilization. After removal of the excess bacterial suspension, the fibers were dried at 40 °C for 12 h and subsequently sealed and stored at 4 °C until use.

The cementitious material used in this study was P.O 42.5R ordinary Portland cement, and its chemical composition is presented in Table 1. The basalt fibers used in this study were BFC813-5 fibers produced by Sichuan Aerospace Tuoxin (Chengdu, China), and their physical and mechanical properties are listed in Table 2. Four basalt fiber volume fractions were designed, namely 0% as the control group, 0.1%, 0.2%, and 0.3%. All fiber-reinforced groups incorporated the prepared bacteria-laden microbial fibers. The experimental design was established to compare the overall performance of bacteria-loaded basalt fiber formulations with different fiber contents, with A0 serving as the matrix reference.

Table 1. Chemical composition of the cement.

Component	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	MgO	K ₂ O	Loss
Content	18.6	6.2	4.76	66.2	0.2	1.74	1	1.3

Table 2. Physical properties of the basalt fibers.

Fiber	Diameter (μm)	Length (mm)	Density (g/cm ³)	Tensile Strength (MPa)	Modulus of Elasticity (Gpa)	Elongation at Break (%)
Basalt fiber	17.4	12	2.65	3257	93	3.0

2.3. Specimen Preparation

The key objective in the preparation of fiber-reinforced microbial self-healing concrete was to achieve the uniform dispersion of microbial carriers, nutrient substances, and cementitious materials without impairing microbial activity. The designed concrete strength grade was C30. The experimental conditions and mix proportions were determined according to the representative engineering parameters of pressurized diversion tunnels, and the detailed mix design is presented in Table 3. All specimens were prepared using a forced-action mixer. Prior to concrete mixing, the bacteria-laden basalt fibers were maintained in a dry state and stored in sealed containers at 4 °C to minimize environmental effects on the activity of the immobilized microorganisms. Before use, the fibers were allowed to equilibrate to room temperature and were then directly incorporated into the concrete mixture. Before mixing, the inner wall of the mixing drum was pre-wetted with a small amount of water. The coarse aggregate, fine aggregate, cement, and fly ash were first dry-mixed for 60 s. Subsequently, mixing water containing 80% of the total water content and the polycarboxylate superplasticizer was added for wet mixing over 90 s. The bacteria-laden basalt fibers were then gradually dispersed into the mixture together with the remaining water, followed by continuous mixing for an additional 120 s until no visible fiber agglomeration was observed. The fresh concrete mixture was poured into molds coated with a release agent in layered batches and compacted on a vibration table for 60 s. Secondary filling was performed during vibration to ensure adequate compaction, after which the specimen surfaces were leveled and finished. The specimens were demolded after being stored at room temperature for 24 h and subsequently transferred into a constant-temperature water-saturated tank maintained at 20 ± 2 °C for continuous immersion curing, ensuring that the specimens remained in a long-term saturated state throughout the curing period (Figure 1). Considering that cracks in pressurized diversion tunnel linings are commonly exposed to sustained moisture supply and saturated seepage environments, continuous immersion curing was adopted to provide a stable saturated boundary condition for crack healing. This curing regime was intended to reproduce moisture availability and ion transport under saturated conditions. No external hydraulic pressure was applied in the present tests; therefore, the experimental condition should not be regarded as a direct simulation of high-pressure hydraulic loading.

Table 3. Mix ratios of the specimens.

Group	Fiber Content	Fine Aggregate 5–20 mm (kg/m ³)	Coarse Aggregate 20–40 mm (kg/m ³)	River Sand <5 mm (kg/m ³)	Cement (kg/m ³)	Fly Ash (kg/m ³)	Water (kg/m ³)	Water-Reducing Agent (kg/m ³)	Urea (kg/m ³)	Calcium Lactate (kg/m ³)
A0	0%	555	555	740	281	94	165	3.56	0	0
A1	0.1%	555	555	740	281	94	165	3.56	10.73	33.46
A2	0.2%	555	555	740	281	94	165	3.56	10.73	33.46
A3	0.3%	555	555	740	281	94	165	3.56	10.73	33.46

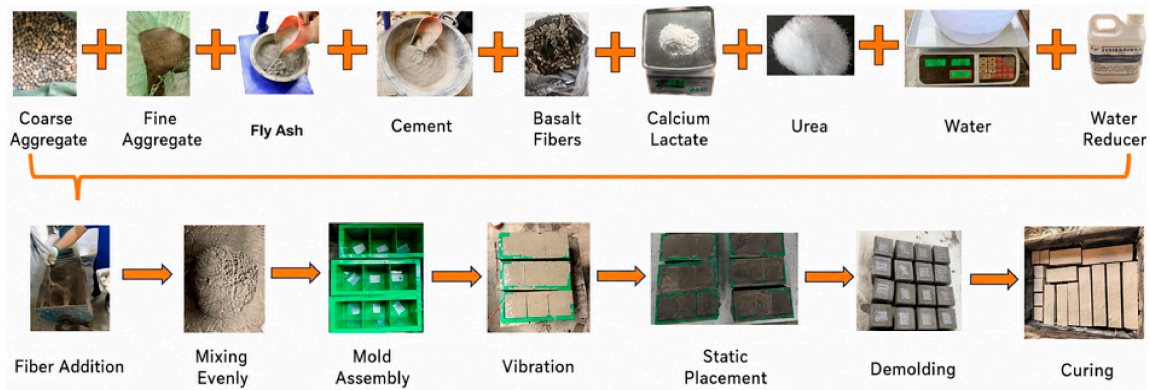


Figure 1. Preparation of test specimens.

2.4. Experimental and Testing Methods

2.4.1. Macroscopic Mechanical and Impermeability Testing

Mechanical and impermeability tests were carried out in strict accordance with the Standard for Test Methods of Hydraulic Concrete [24]. Compressive, splitting tensile, and flexural strengths were measured using cubic and prismatic specimens, respectively. Water impermeability was evaluated using truncated conical specimens, and the permeability coefficient was calculated from the water penetration height. For each test type, three parallel specimens were prepared to obtain the average value, minimizing experimental variability and data dispersion. The testing setups and procedures are schematically illustrated in Figure 2.

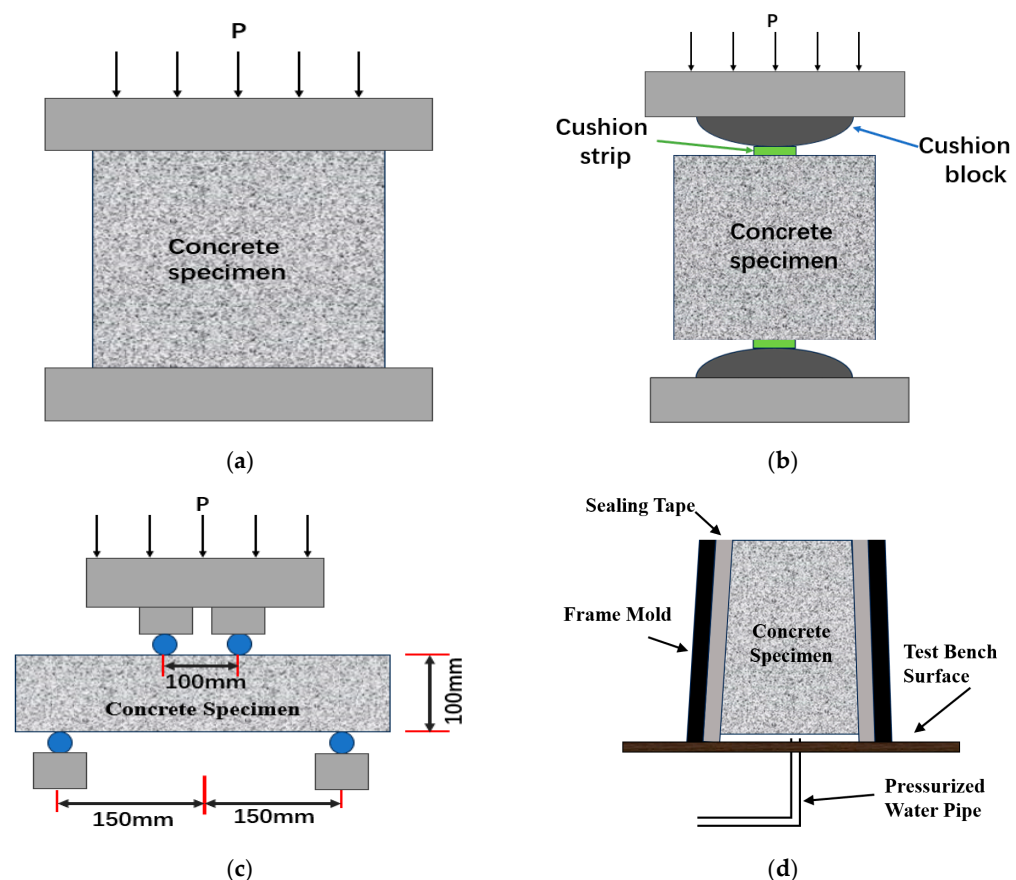


Figure 2. Schematic diagrams of mechanical and water impermeability tests: (a) compressive strength test; (b) splitting tensile strength test; (c) flexural strength test; (d) water impermeability test.

The compressive strength was measured using 100 mm cubic specimens (Figure 2a) at curing ages of 3 d, 7 d, and 28 d under water-saturated conditions to evaluate the effect of the bacteria-loaded basalt fiber formulations on the compressive performance of concrete. The splitting tensile strength was tested using 100 mm cubic specimens (Figure 2b) at curing ages of 3 d, 7 d, and 28 d with a loading rate of 0.3 kN/s to quantify the improvement in tensile resistance and crack resistance provided by the fibers. The flexural strength was determined using 100 mm × 100 mm × 400 mm prismatic specimens (Figure 2c) after 28 d of water-saturated curing to simulate practical flexural tensile conditions and investigate the influence of the composite system on the flexural strength and resistance to bending-induced cracking of concrete. The impermeability performance was evaluated using frustum specimens with dimensions of $\phi 175$ mm × $\phi 185$ mm × 150 mm (Figure 2d) after 28 d of water-saturated curing. The permeability coefficient was calculated based on the measured water penetration height to assess the effect of fibers on the impermeability performance of concrete.

2.4.2. Crack Pre-Cracking and Healing Methodology

To systematically evaluate the autonomous self-healing performance of concrete containing bacteria-laden modified basalt fibers, pre-cracking was induced in 100 mm cubical specimens using the splitting tensile method. Specimens were subjected to this procedure after 28 d of saturated curing to generate reproducible cracks. A controlled post-cracking curing regime was then implemented to simulate a stable saturated environment. The loading apparatus and crack preparation procedure are shown in Figure 3.

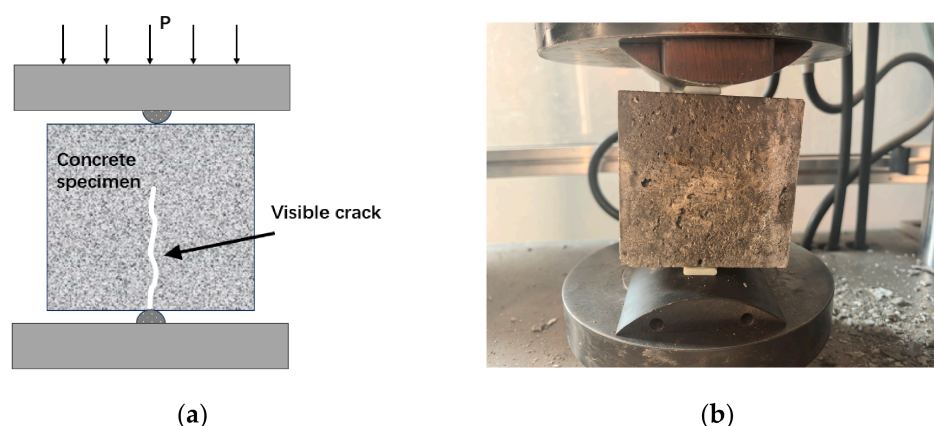


Figure 3. Crack preparation procedure: (a) schematic diagram of crack preparation; (b) experimental operation.

The pre-cracking procedure was executed using a WAW-1000F electro-hydraulic servo-controlled universal testing machine. Linear splitting loads were applied to the 100 mm cubical specimens at a continuous loading rate of 0.3 kN/S until a through-body macro-crack initiated. The loading was precisely terminated at the critical threshold of failure to achieve a controlled residual crack width ranging from 0.1 to 0.8 mm, thereby successfully replicating the typical cracking morphology observed in operational tunnel linings. The mean initial residual crack widths of groups A0, A1, A2, and A3 were 0.47 ± 0.17 , 0.46 ± 0.14 , 0.48 ± 0.16 , and 0.47 ± 0.15 mm, respectively (mean $\pm$ standard deviation, $n = 3$). The close mean values and comparable data dispersion indicate that the four groups had generally comparable initial crack geometries before the healing stage. Immediately following crack induction, the damaged specimens were secured and tightly bound using adjustable stainless steel hose clamps (Figure 3). This configuration effectively restricted subsequent crack propagation and elastic rebound closure, thereby helping

to maintain the measured initial crack geometry during the subsequent healing process. Upon completion of the pre-cracking process, the specimens were chronically submerged in a constant-temperature water bath for the self-healing incubation. Because the interconnected cracks served as preferential conduits linking the matrix core to the external hydraulic environment, moisture continuously infiltrated the crack channels to establish a localized, fully saturated hydraulic environment. This setup provided a continuously saturated crack environment relevant to the moisture boundary conditions of pressurized diversion tunnel linings, but did not reproduce the actual hydraulic-pressure level experienced during service. Under this continuous moisture supply, the crack environment may provide favorable conditions for the potential reactivation of immobilized *Sporosarcina pasteurii* and subsequent ureolysis-induced CaCO_3 precipitation, thereby facilitating progressive crack filling and structural restoration. To systematically track the macroscopic evolution of the healing process, fixed-point visual monitoring and quantitative tracking were conducted at specific healing intervals of 0 d, 7 d, 14 d, 21 d, and 28 d post-cracking. Microscopic crack features and the morphological evolution of the mineralized precipitates were tracked via a $100\times$ digital optical crack microscope at identical target regions. The holistic healing efficacy was subsequently quantified through key engineering benchmarks, including the maximum healable crack width and the total crack area healing rate. Crack images were processed using ImageJ software. Before analysis, image scale calibration was performed using a standard reference scale. The crack region was extracted through grayscale threshold segmentation, and the crack area healing ratio was calculated based on the reduction in projected crack area before and after healing. Each image was analyzed three times to minimize measurement uncertainty. Combined with non-destructive UPV monitoring and subsequent multi-scale microstructural characterizations, the long-term self-healing kinetics and evolution laws of the microbial fiber-reinforced concrete were comprehensively unveiled.

2.4.3. Ultrasonic Pulse Velocity Test

In this study, the UPV test was employed to quantitatively evaluate the recovery of the internal structure of concrete during crack healing. This method is based on the principle that stress-wave propagation velocity varies with the compactness and continuity of the material, thereby reflecting the evolution of internal defects within the crack region. The presence of cracks inside concrete leads to ultrasonic scattering and attenuation, resulting in a reduction in wave velocity. As the cracks are progressively filled by mineral deposits, the structural continuity of the material is gradually restored, leading to an increase in wave velocity. Therefore, the recovery degree of the internal structure can be quantitatively assessed through changes in UPV. The test was conducted using an HC-U91 concrete ultrasonic detector (Figure 4). The specimens were 100 mm cubic samples, and the testing stages included the uncracked state after 28 d of water-saturated curing, the initial pre-cracked state (0 d), and the healed states after 7 d, 14 d, 21 d, and 28 d of healing. Prior to testing, a medical coupling agent was applied to the center of the opposite testing surfaces of each specimen. The transducers were then placed tightly against the surface and aligned coaxially to ensure stable signal transmission. The ultrasonic propagation velocity was recorded in km/s. Each group was tested three times, and the average value was used for analysis. By comparing the UPV variation at different healing ages, the structural recovery effect of the cracks was quantitatively evaluated. A higher UPV recovery degree indicates a more complete crack filling and better restoration of internal continuity [25,26]. The UPV results were further correlated with crack observation and impermeability tests to establish a multi-parameter evaluation system for self-healing performance.

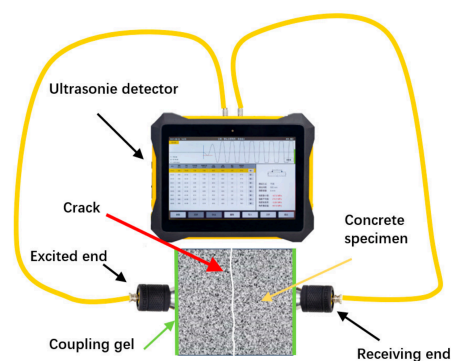


Figure 4. Ultrasonic pulse velocity testing setup.

2.4.4. Microstructural Analysis and Product Characterization

To characterize the crack-filling morphology of mineral precipitates and their interfacial bonding with the cementitious matrix at the microscopic scale, SEM and XRD were employed to observe the microstructure and determine the phase composition of the healed specimens. The microstructural observations were integrated with macroscopic mechanical properties, water impermeability, and UPV measurements to establish a comprehensive multi-scale evaluation framework for the self-healing performance of the microbial fiber-reinforced concrete [19]. The microstructural testing equipment used in this study is shown in Figure 5.

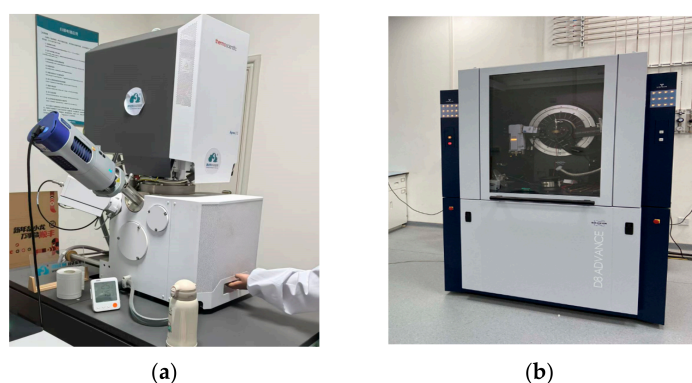


Figure 5. Microstructural characterization instruments: (a) scanning electron microscope; (b) X-ray diffractometer.

Following a 28-day healing period, specimens for microstructural analysis were carefully prepared. Cubic samples approximately 1 cm in edge length, containing the healed products, were extracted from the crack regions of each experimental group. During sampling, the original morphology of the crack interfaces was preserved to prevent mechanical disturbance and avoid damage to the mineralized products. In addition, fragments from the cracked regions of specimens after compressive testing were collected and dried together with the primary samples. Micro-morphology and elemental composition were characterized using a Thermo Fisher Apreo field emission scanning electron microscope (Figure 5a), with imaging performed at multiple magnifications and EDS data acquired. The phase composition of the mineralized products was determined using a Rigaku Ultima IV X-ray diffractometer (Figure 5b). White precipitate powders were carefully scraped from the crack surfaces and interiors, with any loose cement particles removed. The powders were then homogenized in an agate mortar, packed into sample holders, and compacted prior to analysis. XRD measurements were performed using Cu-K α radiation at a tube voltage of 40 kV and a tube current of 40 mA. The diffraction patterns were collected over a 2θ range of 10–80° with a scanning step size of 0.02°.

3. Results and Analysis

3.1. Effect of Microbial Fibers on Macroscopic Mechanical Properties of Concrete

3.1.1. Compressive Strength

The compressive strength of the concrete under varying fiber dosages exhibited a non-linear enhancement characteristic with the progression of curing ages (Figure 6a). The strength of all experimental groups monotonically increased as the curing period extended. From the baseline group A0 to group A2, a progressive strength increment was observed, with the A2 group achieving the optimal strength across all testing ages. Specifically, at 7 d, the compressive strength of the A2 group reached approximately 33.5 MPa, representing a 9.1% increase over the A0 group; by 28 d, this margin expanded to 15.1%, demonstrating a sustained strengthening trend. The strength of the A1 group was consistently higher than that of the A0 group, yet its enhancement magnitude remained lower than that of the A2 group throughout the curing period. For the A3 group, the 28 d strength exhibited a 12.3% increase compared to the A0 group, maintaining a performance advantage, but the growth rate receded relative to the A2 group, failing to sustain the latter's peak reinforcement level. From the perspective of chronological development, the strength discrepancies among the groups were relatively marginal at 3 d. However, as the curing age extended, the gaps between different dosage groups progressively widened, with the divergence becoming particularly pronounced from 7 d to 28 d. For instance, the strength increment of the A2 group during this specific stage was approximately 11.6%, higher than the 5.9% observed for the A0 group, which reflects the distinct strength development kinetics of the different composite systems. Overall, the compressive strength exhibited a characteristic trend of “initial enhancement followed by a subsequent deceleration” with increasing fiber content, wherein the 0.2% volume fraction exhibited the best strengthening performance among the investigated dosages.

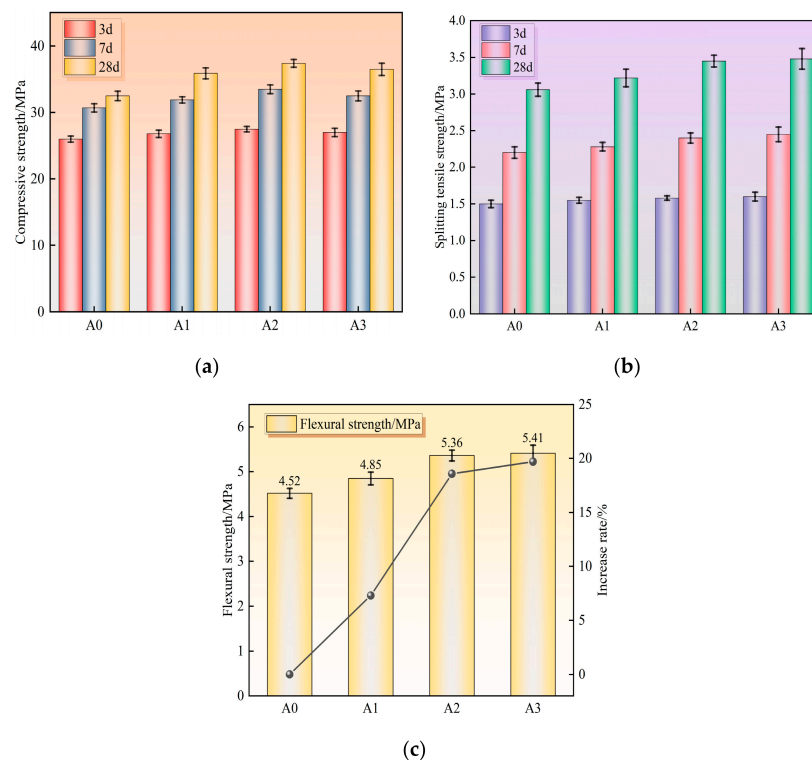


Figure 6. Mechanical properties of concrete with different basalt fiber contents: (a) compressive strength; (b) splitting tensile strength; (c) flexural strength. Error bars represent ± 1 standard deviation of three parallel specimens ($n = 3$).

3.1.2. Splitting Tensile Strength

The splitting tensile strength of concrete increased continuously with curing age under different fiber contents and showed a clear response to fiber dosage (Figure 6b). Overall, tensile strength rose with increasing fiber content, although the rate of enhancement slowed at higher dosages. The A2 and A3 groups exhibited higher strengths during the mid-to-late curing stages. At early ages, differences among groups were small but already indicated that higher fiber content corresponded to higher tensile strength. At 7 days, the A2 and A3 groups increased by approximately 9.1% and 11.4% compared to the control group A0, higher than the 3.6% increment of A1. By 28 days, all groups continued to gain strength. The A2 group reached 3.45 MPa, 12.7% higher than A0, while the A3 group attained 3.48 MPa, an increase of 13.7%, with growth slowing relative to the 7-day value. From 7 to 28 days, the strength of A0 increased by about 39.1%, whereas A2 rose by 43.8%, indicating stronger late-stage development. Although A3 achieved a slightly higher ultimate strength, its late-stage growth rate was lower than A2. These results indicate that basalt fibers effectively enhance tensile strength and crack resistance, with the 0.2% dosage achieving an optimal balance between strength level and sustained late-age development.

3.1.3. Flexural Strength

Different fiber dosages markedly improved the 28-day flexural strength of concrete, showing a trend of rapid initial increase followed by a gradual plateau (Figure 6c). The control group A0 exhibited a flexural strength of 4.52 MPa. The A1 group increased to 4.85 MPa, an improvement of about 7.3%. The A2 group reached 5.36 MPa, with a notable enhancement of 18.6%. Although the A3 group attained the highest strength of 5.41 MPa, the increase relative to A2 was minimal, indicating a clear deceleration in growth. Overall, the 0.1% to 0.2% dosage range represents the stage of rapid strength increase, while the 0.2% to 0.3% range corresponds to a slowing growth phase. This indicates that flexural strength responds to fiber content in a staged manner. Moderate fiber content provides the optimal reinforcement effect, while higher dosages result in saturation, with 0.2% approaching the upper limit of strength enhancement.

3.2. Evolution of Concrete Impermeability

The water impermeability and degradation behavior of concrete under different fiber contents are presented in Figure 7. The A2 group exhibited the best overall performance. From the baseline A0 to A2, both water penetration height and permeability coefficient decreased continuously. In contrast, the A3 group showed a notable rebound. Specifically, the A0 group had a water penetration height of 21.5 mm and a permeability coefficient of 2.83×10^{-7} cm/h, indicating the lowest impermeability. The A1 group showed a reduced penetration height of 15.1 mm, a decrease of 29.8%, and a permeability coefficient of 1.80×10^{-7} cm/h, a reduction of 36.4%, reflecting a clear improvement. The A2 group reached a minimum penetration height of 12.9 mm, 40.0% lower than A0, and the lowest permeability coefficient of 1.20×10^{-7} cm/h, a reduction of 57.6%. When the fiber content increased to 0.3% in the A3 group, impermeability declined: the penetration height increased to 21.2 mm, and the permeability coefficient rose to 3.30×10^{-7} cm/h, approaching the baseline level. The results indicate that the 0% to 0.2% dosage range corresponds to an optimum stage of impermeability enhancement, while higher fiber contents induce performance deterioration. Overall, fiber content affects concrete impermeability in an “optimization followed by degradation” pattern, with 0.2% achieving the minimum penetration height and permeability coefficient and the best resistance to water flow.

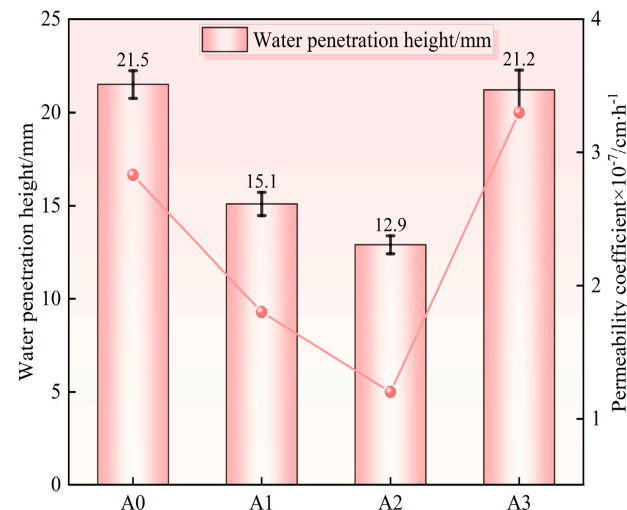


Figure 7. Water penetration height and permeability coefficient of concrete with different basalt fiber contents. Error bars represent ± 1 standard deviation of three parallel specimens ($n = 3$).

3.3. Evaluation of Crack Self-Healing Effect

3.3.1. Ultrasonic Pulse Velocity Analysis

The ultrasonic pulse velocity of each experimental group was measured at different healing intervals, and the results are summarized in Table 4. Compared with the intact specimens, wave velocity decreased significantly after cracking, indicating that the cracks extended the propagation path and increased internal defects. During the healing process, pulse velocity gradually increased with time, reflecting progressive mineral deposition within the cracks and partial restoration of material continuity. The baseline group A0 showed minimal change during the healing period. The average velocity after cracking was 3.163 km/s and increased only to 3.218 km/s after 28 days, corresponding to a recovery rate of 4.5%, indicating limited crack repair through natural hydration and carbonation alone. The addition of bacteria-laden basalt fibers improved recovery substantially. In the A1 group, the 28-day velocity reached 3.679 km/s with a recovery rate of 31.7%, showing stable structural recovery in the bacteria-loaded fiber formulation. The A2 group achieved the highest recovery. The post-cracking velocity was 3.275 km/s and increased to 4.343 km/s after 28 days, yielding a recovery rate of 85.8%. Recovery accelerated after 14 days, indicating enhanced late-stage mineral deposition and the formation of a dense and continuous internal structure. For the A3 group, the 28-day velocity reached 4.264 km/s with a recovery rate of 79.0%, close to that of A2. However, the A3 group showed slower early-stage recovery than A2. Overall, the A2 group exhibited the most favorable UPV recovery among the investigated mixtures, indicating a comparatively high degree of structural recovery under the present healing conditions. It should be noted that UPV recovery reflects the overall change in wave transmission characteristics, which may also be influenced by continued hydration, carbonation, moisture variation, and surface mineral deposition. Therefore, UPV recovery was interpreted together with crack observation and impermeability results rather than considered as an independent indicator of healing quality.

Table 4. Ultrasonic pulse velocity of microbial self-healing concrete (km/s).

Specimen	28-Day Intact	28-Day Cracked	Healing at 7 d	Healing at 14 d	Healing at 21 d	Healing at 28 d
A0-1	4.373	3.135	3.153	3.169	3.183	3.197
A0-2	4.358	3.191	3.203	3.218	3.230	3.243
A0-3	4.409	3.163	3.175	3.189	3.203	3.215
A1-1	4.554	3.268	3.307	3.353	3.492	3.642
A1-2	4.587	3.253	3.294	3.338	3.509	3.679
A1-3	4.529	3.294	3.331	3.372	3.523	3.715
A2-1	4.526	3.305	3.376	3.529	3.852	4.355
A2-2	4.537	3.253	3.331	3.501	3.820	4.333
A2-3	4.497	3.268	3.347	3.511	3.843	4.340
A3-1	4.452	3.253	3.287	3.347	3.671	4.270
A3-2	4.587	3.305	3.336	3.388	3.709	4.244
A3-3	4.529	3.320	3.349	3.406	3.743	4.277

3.3.2. Crack Healing Observation

To systematically evaluate the autonomous self-healing capacity of the basalt fiber-microbial composite system, fixed-point observations of crack surface morphology were conducted on specimens from all groups at healing ages of 0 d, 7 d, and 28 d. The residual crack width was measured, and the crack area healing ratio was calculated concurrently. The corresponding results are presented in Figure 8. The observations indicate that the composite system exhibits effective autonomous crack healing, and the fiber volume fraction strongly influences the healing performance. The healing response generally increases with fiber content up to an optimal level and then gradually plateaus. All groups showed progressive crack closure over time, but the extent of convergence varied. The baseline group A0 showed the weakest healing, with a maximum healable width of 0.14 mm and an area healing rate of 12%, indicating limited mineral deposition under natural hydration and carbonation. The A1 group achieved a maximum width of 0.57 mm and an area healing rate of 73%, indicating that the bacteria-loaded fiber formulation exhibited substantially greater superficial mineral backfilling than the matrix reference. The A2 group showed the best performance, with a maximum observed healed crack width of 0.65 mm and an area healing rate of 84%. The fiber network provided favorable interfaces for mineral precipitation while maintaining pathways for mass transport. This allowed thorough mineralization, producing a dense, continuous backfill within the cracks. For the A3 group, the maximum healable width was 0.62 mm with an area healing rate of 81%, slightly lower than A2. Here, the maximum observed healed crack width refers to the largest initial crack width among the monitored cracks that achieved surface closure after 28 d of healing under the present experimental conditions. It represents an observed extreme value rather than a group-average value, a statistical upper confidence limit, or a universal healing threshold of the material. This result indicates that increasing the fiber dosage from 0.2% to 0.3% did not further improve crack-healing performance under the present experimental conditions. Healing efficiency was positively correlated with curing time. Between 0 d and 7 d, rapid mineral deposition reduced crack widths quickly. By 28 d, mineralized crystals continued to grow and interconnect, forming a dense internal structure. Overall, the 0.2% fiber dosage provided the best balance among fiber bridging, mineral precipitation, and mass transport under the present experimental conditions. The maximum observed healed crack width of 0.65 mm in the A2 group falls within the typical crack-width range reported for pressurized diversion tunnel linings, indicating its potential relevance for such applications. However, its healing performance under actual hydraulic-pressure conditions requires further experimental validation.

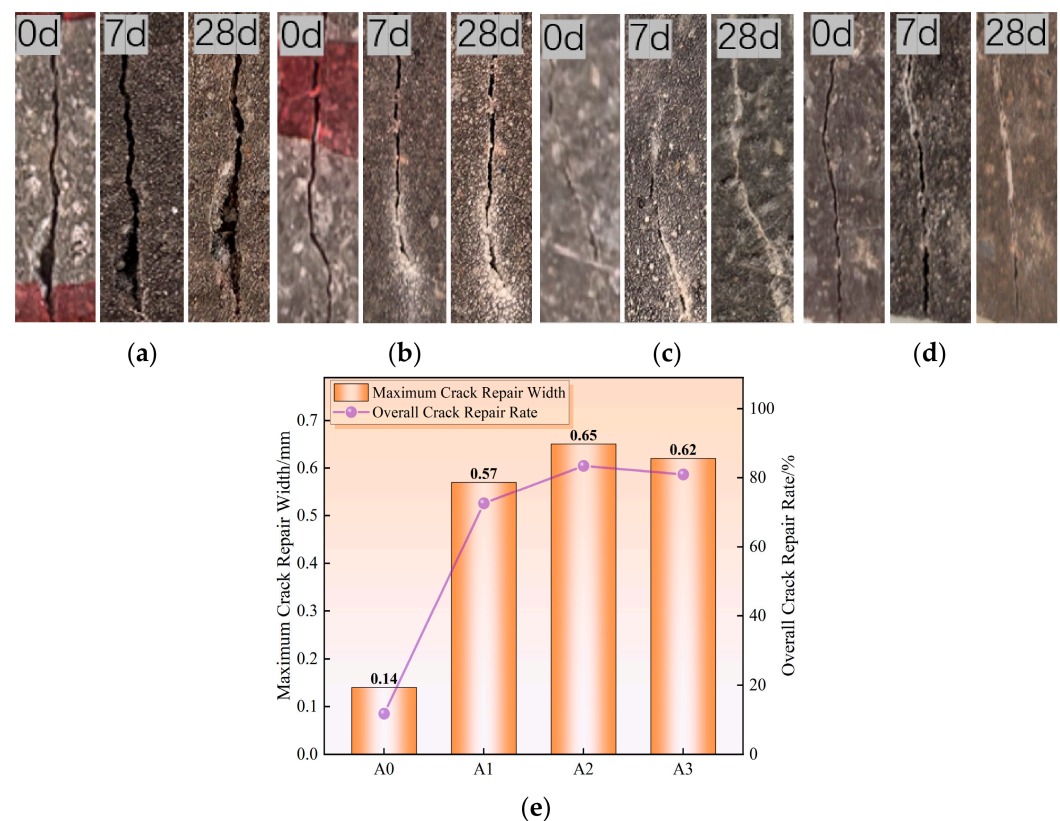


Figure 8. Evolution of crack self-healing in concrete with different basalt fiber contents: (a) group A0; (b) group A1; (c) group A2; (d) group A3; (e) crack area healing rate and maximum healed crack width after 28 days.

3.4. Microstructural Characterization and Healing Mechanism

3.4.1. SEM Morphology and EDS Elemental Characterization of Deposits

The fiber-matrix interfaces and crack-filling regions of the A2 group after 28 days of healing were examined using scanning electron microscopy. Although detailed SEM observations were mainly conducted for the A2 group, differences among the investigated mixtures were further interpreted by combining XRD results with macroscopic performance indicators. Figure 9 presents the micro-morphology and interfacial characteristics of the healing deposits. Figure 9a shows the interfacial transition zone (ITZ) between basalt fibers and the cement matrix. Unlike conventional fiber-reinforced concrete, no continuous debonding or pore concentration was observed. The fiber surface was covered with irregular crystalline particles interwoven with surrounding C-S-H gels. This indicates that mineral deposits effectively filled and densified the originally loose ITZ, enhancing mechanical interlocking and stress transfer [25] while reducing local interconnected porosity [26], which is consistent with the macroscopic improvements in tensile, flexural, and impermeability performance of the A2 group.

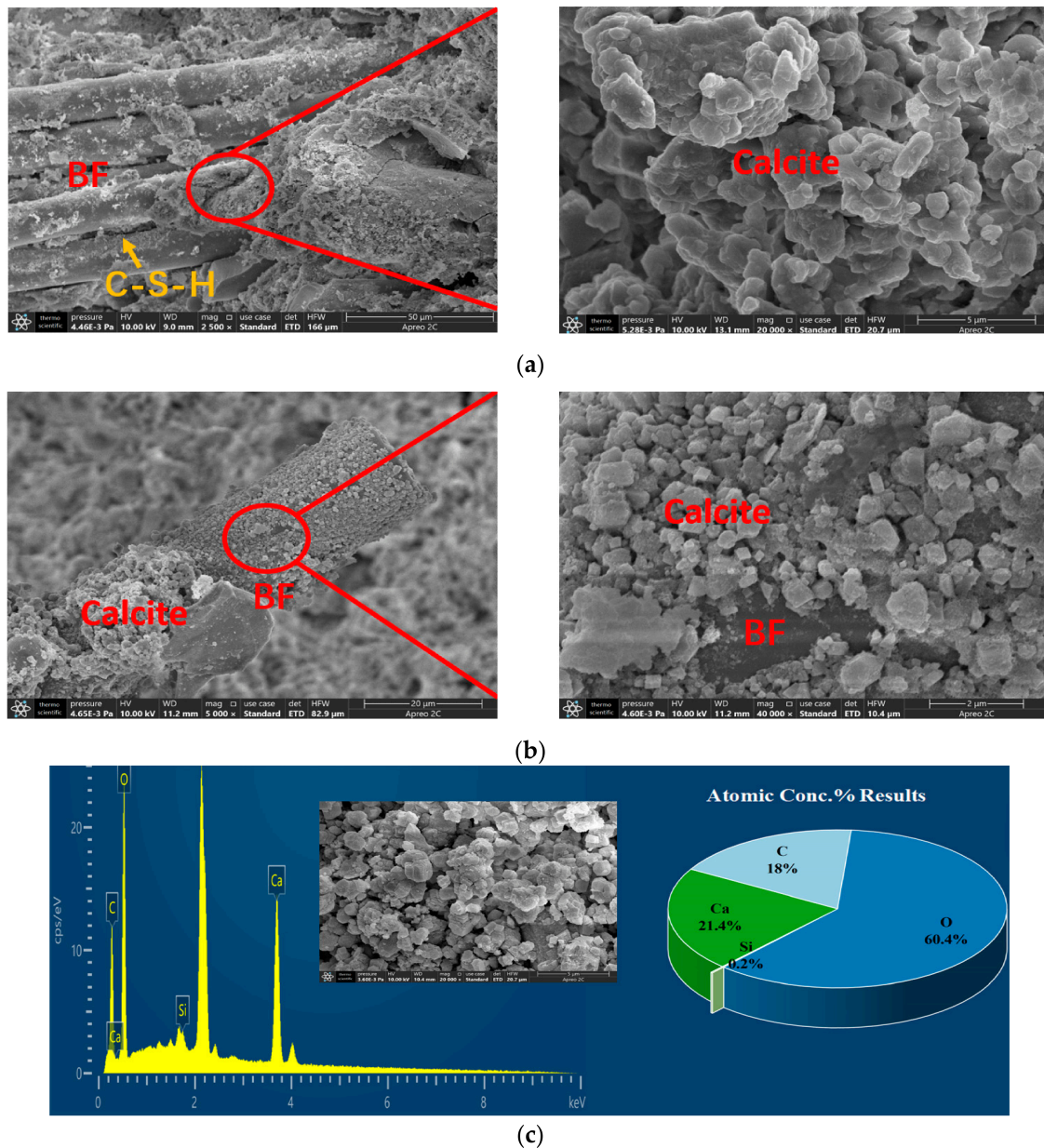


Figure 9. SEM micrographs and EDS spectrum of the healing products: (a) microscopic bonding morphology between the basalt fibers and concrete matrix; (b) mineralized precipitate morphology on the basalt fiber surfaces; (c) EDS spectrum of the mineralized products.

Figure 9b illustrates the mineral deposits on the fiber surface and their interaction within the cracks. The fiber surfaces were covered by dense mineral precipitates forming locally continuous layers, and the crystals extended outward from the fibers into adjacent voids. This fiber-associated deposition morphology supports the interpretation that, in addition to their conventional mechanical bridging role, the modified basalt fibers provided favorable substrates and preferential nucleation interfaces for mineral precipitation. When cracks form, moisture and oxygen may provide favorable conditions for the potential reactivation of immobilized bacteria on the fiber surfaces. If metabolically active, the bacteria can promote urea hydrolysis and carbonate generation, thereby facilitating CaCO_3 nucleation along the fiber and crack interfaces. Continued deposition progressively fills the cracks, restoring structural continuity, consistent with known microbial self-healing mechanisms [26].

Figure 9c presents EDS results for the region. Ca, C, and O dominate, with atomic ratios near 1:1:3, matching the stoichiometry of CaCO_3 [27]. Minor Si signals indicate the presence of C-S-H gel from the matrix. Compared with the bulk matrix, the stronger Ca signal was consistent with the presence of Ca-rich mineral deposits in the examined region. Combined with the dense crystalline morphology observed by SEM, these findings are consistent with MICP-related calcium carbonate precipitation and support its contribution to crack sealing and interfacial densification. However, the mineralogical and morphological evidence alone does not directly verify bacterial viability after concrete mixing and curing.

3.4.2. XRD Mineral Phase Composition Evolution

To further characterize the mineral phase composition of crack-healing products under different fiber contents, X-ray diffraction analysis was conducted on specimens after 28 days of healing, and the results are shown in Figure 10. Distinct diffraction peaks of calcium carbonate were detected in all groups, accompanied by minor phases of calcium hydroxide and quartz. The strong diffraction peak near 29.4° corresponds to the characteristic diffraction peak of calcite-type CaCO_3 . This result is consistent with previous studies on MICP-treated materials and indicates that calcite was a prominent crystalline phase in the collected healing products. Differences in CaCO_3 -related peak intensity were observed among the groups. The A2 group exhibited the strongest calcite-related diffraction characteristics among the investigated mixtures, which was consistent with its favorable crack-healing, structural-recovery, and impermeability performance. This result agrees with the superior crack healing rate, structural recovery, and impermeability performance observed in the A2 group, further demonstrating the advantage of the 0.2% fiber dosage. The A1 group showed moderate calcite-related peak intensity. Although the A3 group also exhibited relatively strong calcite-related diffraction characteristics, its poorer impermeability recovery indicates that mineral precipitation did not necessarily translate into complete functional sealing. Therefore, peak intensity alone could not fully reflect the effectiveness of crack closure in this group. The baseline group A0 showed only weak CaCO_3 -related peaks, which were consistent with natural carbonation of the cement matrix and its limited healing response. In addition, the Ca(OH)_2 -related peaks were comparatively weaker in A2, accompanying its stronger calcite-related diffraction characteristics. Similar behavior has been reported in previous studies of MICP-induced carbonation reactions. Among the investigated mixtures, A2 exhibited the strongest calcite-related diffraction characteristics, which were consistent with its favorable crack-healing and impermeability performance.

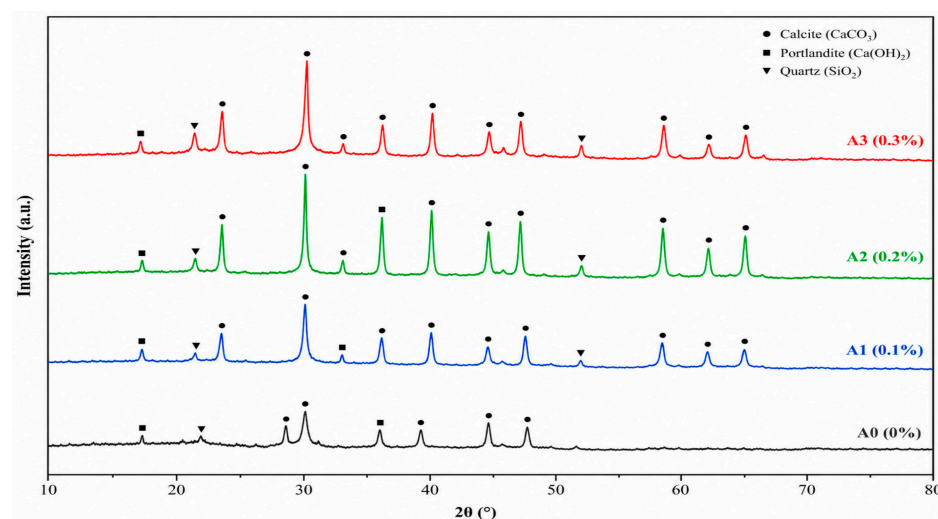


Figure 10. X-ray diffraction patterns of the healing products in different experimental groups.

4. Discussion

4.1. Synergistic Mechanism of MICP in Crack Self-Healing, Toughening, and Impermeability Enhancement

To discuss the possible mechanisms associated with crack healing, toughening, and impermeability improvement in bacteria-laden basalt fiber concrete, the crack-evolution behavior and mineral-deposition observations were considered together. Based on the available evidence, the observed response may involve the combined effects of basalt fiber bridging, mineral precipitation, and progressive sealing of crack channels. Accordingly, the mechanistic interpretation presented below concerns the integrated response of the bacteria-loaded fiber formulation rather than the isolated contributions of individual nutrient and microbial components. The corresponding mechanism is illustrated in Figure 11.

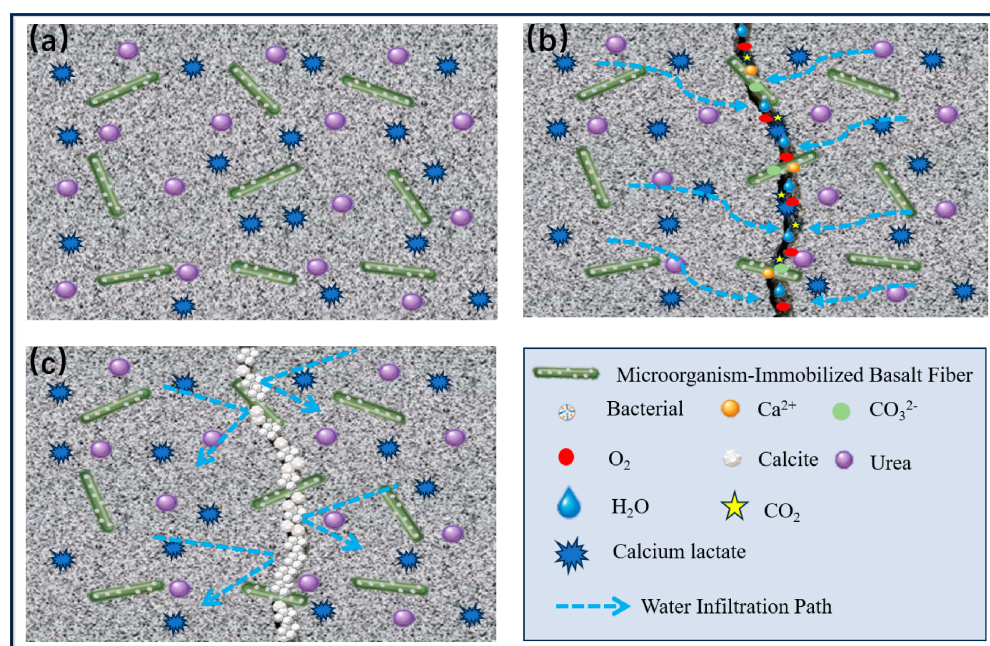


Figure 11. Synergistic self-healing and impermeability enhancement mechanism of fiber-reinforced MICP concrete: (a) initial stabilization stage; (b) crack activation and microbial mineralization stage; (c) mineralization sealing stage.

As illustrated in Figure 11, the self-healing process of the bacteria-laden basalt fiber-reinforced concrete can be divided into three successive stages: the initial stabilization stage, the crack activation stage, and the mineralization sealing stage. Prior to crack initiation (Figure 11a), the bacteria-laden modified basalt fibers, urea, and calcium sources are uniformly distributed throughout the concrete matrix. The alkali treatment increases the surface roughness of the basalt fibers, which enhances the mechanical interlocking with the cement matrix and simultaneously provides stable attachment sites for bacterial spores. In addition, the randomly distributed fiber network forms an internal bridging structure that restrains microcrack propagation, reduces pore connectivity, and improves the compactness of the concrete matrix. After cracking occurs under external loading (Figure 11b), the generated cracks become transport channels connecting the external environment with the concrete interior, allowing water, oxygen, and part of the CO_2 to penetrate into the crack region. At this stage, the basalt fibers first exert a bridging effect across the crack surfaces, limiting further crack propagation, alleviating stress concentration at the crack tip, and improving the deformation compatibility of the damaged zone. Meanwhile, the infiltrated moisture may provide favorable conditions for the potential reactivation of *Sporosarcina pasteurii* immobilized on the fiber surfaces. If the immobilized bacteria

remained metabolically active after concrete mixing and curing, urea hydrolysis could generate carbonate ions, which could subsequently react with Ca^{2+} to promote CaCO_3 precipitation. Owing to the rough and active fiber surfaces, the fibers serve as preferential nucleation sites for mineral deposition, gradually forming mineralized regions centered around the fibers. In terms of healing performance, the A2 group exhibited the best crack closure effect, with a maximum healed crack width of 0.65 mm and a crack healing ratio of 84%. The UPV recovery rate reached 85.8%, indicating that the internal structural continuity of the crack region was effectively restored. As the healing process further proceeds (Figure 11c), Ca^{2+} and CO_3^{2-} continuously combine within the crack region to generate CaCO_3 crystals. These crystals progressively deposit, grow, and interconnect along the crack walls and fiber surfaces, eventually forming a dense and continuous filling structure. Simultaneously, the mineralized products fill the micropores at the fiber–matrix interface, reducing the connectivity of internal seepage channels and thereby improving the impermeability of the concrete. The impermeability results showed that the water penetration height of the A2 group decreased by 40.0% compared with the control group, while the permeability coefficient decreased by 57.6%. Moreover, the A2 group exhibited stronger calcite-related diffraction characteristics near 29.4° , which were consistent with its favorable crack-healing and impermeability performance. Overall, basalt fibers provide crack-bridging and toughening effects while also offering favorable interfaces for mineral precipitation. The resulting CaCO_3 -rich deposits further facilitate crack filling and pore sealing. Through the combined effects of fiber bridging, mineral deposition, and crack sealing, the composite system exhibited coordinated improvements in crack self-healing, structural recovery, and impermeability. It should be noted that the continuous water-immersion curing regime adopted in this study primarily simulates the long-term saturated and localized seepage conditions within cracks in pressurized diversion tunnel linings, with emphasis on moisture transport and mineral deposition within the crack channels. The effects of dynamic hydraulic pressure under higher hydraulic heads require further investigation using specialized high-pressure seepage simulation systems.

4.2. Self-Healing Efficacy Evaluation Indexes and Comprehensive Evaluation Framework

4.2.1. Selection of Core Evaluation Indexes and Their Physical Significance

The healing performance of microbially self-healing concrete exhibits distinct multi-scale and multi-dimensional characteristics. Different evaluation indices reflect different physical implications and engineering sensitivities. In this study, crack closure refers to the morphological reduction in the visible crack area, whereas UPV recovery is used as an auxiliary indicator of the restoration of internal structural continuity. Functional self-healing, in contrast, refers primarily to the recovery of crack-sealing and water-transport resistance, which is evaluated through water penetration and permeability-related indicators. Therefore, morphological closure and structural recovery should not be directly equated with functional self-healing. Previous studies have demonstrated that the crack surface closure ratio alone cannot comprehensively characterize the actual healing state of MICP-based systems. Particularly under complex service environments, apparent crack closure at the surface does not necessarily indicate that internal seepage pathways have been completely blocked. In some cases, an incomplete healing condition characterized by “surface closure with internal connectivity” may still exist [28]. Therefore, the evaluation of self-healing performance should not only consider the degree of crack filling, but also focus on the recovery of internal structural continuity and long-term impermeability durability [27]. Based on the experimental results of this study, a comparative analysis was carried out from four aspects, including crack morphology recovery, structural restoration, impermeability performance, and mechanical property recovery, in order to identify the core evaluation

parameters suitable for pressurized diversion tunnel lining conditions. To further assess the applicability of different evaluation indices under the service environment of pressurized diversion tunnels, the physical significance and engineering sensitivity of various self-healing evaluation parameters were systematically compared, and the corresponding results are summarized in Table 5.

Table 5. Physical significance and applicability of different self-healing evaluation metrics.

Indicator Category	Specific Metric	Main Representation	Advantage	Limitation	Engineering Sensitivity
Morphological	Crack Area Healing Rate (R)	Overall filling degree of crack voids	Directly quantifies crack closure, sensitive to the healing process	Cannot fully reflect internal densification	High
Morphological	Maximum Healed Crack Width	Maximum recoverable crack width of the system	Captures the ultimate healing capacity	Strongly influenced by initial crack geometry and local deposition, high variability	Medium
Physical	Wave Velocity Recovery Rate (U)	Restoration of internal structural continuity	Non-destructive evaluation, reflects internal defect repair	Sensitive to superficial deposition, may overestimate internal healing quality	High
Functional	Water Penetration Height Reduction/Permeability Coefficient (P)	Sealing capability of seepage channels and durability recovery	Provides a functional measure of impermeability performance	Requires relatively long testing duration	Very High
Mechanical	Compressive/Splitting/Flexural Strength	Overall load-bearing capacity	Reflects macroscopic structural enhancement	Insensitive to localized crack repair	Medium

The sensitivity classification was determined based on the combined consideration of experimental response characteristics, engineering relevance, and previous studies. As shown in Table 5, the crack area healing rate, UPV recovery rate, and water penetration height reduction rate correspond to three key aspects of the healing process, namely the quantitative extent of crack filling, the recovery of internal structural continuity, and the quality of impermeability restoration. Together, these indexes can comprehensively characterize the actual healing state of the microbial self-healing system. Among them, the crack area healing rate directly reflects the overall filling degree of mineralized products within the crack space and has become one of the most widely adopted evaluation indexes in current MICP self-healing studies [22]. In this study, the crack area healing rate of the A2 group reached 84% after 28 d of healing, which was higher than those of the A1 and A3 groups. This result indicates that, among the tested formulations, the 0.2% fiber dosage was associated with more favorable crack filling and mineral deposition. However, using the crack area healing rate alone as the evaluation criterion still presents certain limitations. To unify the evaluation basis and ensure consistency in the interpretation of experimental data throughout this study, the core derived indices for self-healing evaluation are defined as follows:

The crack area healing rate (R) is defined as the percentage of the healed crack area after 28 d relative to the initial crack area before healing. This parameter was obtained through fixed-point crack imaging combined with digital image processing analysis. The UPV recovery rate (U) is defined as the ratio between the recovered wave velocity after 28 d of healing and the velocity loss caused by cracking. This index reflects the degree of internal structural continuity restoration after the crack region is filled by mineralized products, which effectively shortens the ultrasonic transmission path and improves material

integrity. The water penetration height reduction rate (P) was calculated by taking the water penetration height of the fiber-free control group A0 as the unified reference baseline and determining the reduction in penetration height of each group after 28 d of healing relative to the A0 group. Similarly, the permeability coefficient reduction rate was calculated using the permeability coefficient of group A0 as the reference value to quantify the reduction in permeability coefficient after healing for each experimental group. When the permeability coefficient of a specific group exceeded that of the A0 group, the reduction rate became negative, indicating deterioration rather than improvement in impermeability performance.

Based on these definitions, the measured values of the core self-healing indices for the four experimental groups are summarized in Table 6 to further quantify the response differences in each evaluation parameter under different fiber volume fractions.

Table 6. Comparative analysis of self-healing metrics for different experimental groups.

Group	Crack Area Healing Rate (%)	Maximum Heal Width (mm)	Wave Velocity Recovery Rate U (%)	Water Penetration Height Reduction (%)	Permeability Coefficient Reduction (%)	Comprehensive Healing Characteristics
A0	12	0.14	4.5	0	0	Limited autogenous healing of the matrix
A1	73	0.57	31.7	29.8	36.4	Initial formation of mineralized crack infill
A2	84	0.65	85.8	40.0	57.6	Continuous and dense mineralized layer formed within cracks
A3	81	0.62	79.0	1.4	−16.6	High apparent crack closure and UPV recovery, but limited functional self-healing as reflected by poor impermeability recovery

Further analysis of Table 6 indicates that the variations in different evaluation indices are not completely consistent, and this discrepancy is particularly evident in the A3 group. The crack area healing rate of the A3 group reached 81%, which was very close to the 84% obtained by the A2 group. Its UPV recovery rate reached 79.0%, corresponding to 92.1% of that of the A2 group, while the maximum healed crack width reached 0.62 mm, remaining at a relatively high level. Judging only from the crack morphology and wave velocity indices, the healing performance of the A3 group appeared comparable to that of the A2 group. However, the water penetration height reduction rate of the A3 group was only 1.4%, and the permeability coefficient reduction rate reached −16.6%, indicating that the internal seepage channels were not effectively sealed. Possible explanations for the poor impermeability recovery of A3 include less uniform fiber distribution, interfacial heterogeneity, and spatially non-uniform mineral deposition at the higher fiber dosage. This distinct phenomenon of “high morphological recovery but low impermeability restoration” demonstrates that crack surface closure does not necessarily represent actual functional recovery. The observed discrepancy suggests that relatively high surface healing did not correspond to complete sealing of deeper seepage pathways. Therefore, impermeability indices can more accurately reflect the true internal healing quality of cracks. Previous studies have similarly reported that permeability recovery is generally more representative of the long-term service reliability of MICP-based healing systems than crack closure rate alone. A comparison between the core evaluation indices established in this study and the corresponding results reported in the previous literature is summarized in Table 7.

Table 7. Comparison of the core self-healing metrics obtained in this study with those reported in the literature.

Reference	Healing System	Core Evaluation Metrics	Key Findings
Wang et al. [9]	Microbially induced self-healing concrete	Crack closure rate, Water penetration height reduction	Moisture conditions directly influence the completeness of internal mineralization
Tan et al. [28]	Bacteria-based self-healing cementitious materials	Crack closure rate, Oxygen supply level	Superficial crack closure does not guarantee complete internal repair
Bashaveni et al. [25]	Bacterial concrete	UPV, Compressive strength	UPV can be used to predict the internal repair degree
Zhang et al. [18]	Nano-SiO ₂ modified fiber MICP system	Overall Crack Repair Rate, Water impermeability	Fiber–matrix interface promotes CaCO ₃ deposition and crack sealing
This study	Basalt fiber-MICP system	R, U, P comprehensive evaluation	A2 group achieves optimal synergy among superficial healing, structural restoration, and water impermeability

Compared with previous microbial self-healing studies, the present results generally agree that water availability promotes mineralization [9] and that surface crack closure does not necessarily represent complete functional recovery [28]. In particular, although A3 exhibited relatively high crack-area healing (81%) and UPV recovery (79.0%), its impermeability performance remained poor, indicating that UPV and morphological healing should be interpreted together with permeability-related indicators. This finding also supports the use of a multi-index evaluation combining morphological, structural, and functional recovery. Direct numerical comparison across studies should be made cautiously because differences in crack width, healing conditions, and evaluation methods can substantially affect the reported healing efficiency. Based on the above analysis, it can be concluded that different evaluation indices correspond to different physical levels of crack healing. The crack area healing rate reflects the degree of apparent spatial filling, the UPV recovery rate represents the restoration of internal structural continuity, and the water penetration height reduction rate directly characterizes the sealing ability of seepage channels and provides a functional indicator of impermeability recovery under the saturated conditions investigated in this study.

For pressurized diversion tunnel lining structures, relying solely on superficial crack closure is insufficient to accurately evaluate the actual healing performance. The recovery of impermeability and internal structural continuity should instead be regarded as the key evaluation criteria. Therefore, the R–U–P multi-index framework provides a combined characterization of morphological, structural, and functional recovery under the saturated conditions investigated in this study. It may serve as a preliminary reference for subsequent evaluation of self-healing lining materials.

4.2.2. Multi-Metric-Based Comprehensive Evaluation of Self-Healing Efficacy

The preceding analysis indicates that different evaluation indices exhibit distinct response characteristics toward microbial self-healing behavior. A single evaluation parameter generally reflects only localized features of the healing process and cannot comprehensively characterize the overall repair capacity of materials under practical service conditions. Particularly for pressurized diversion tunnel lining structures, crack remediation should not only achieve superficial closure, but also establish a continuous and dense mineralized structure within the crack interior to ensure long-term impermeability and structural durability. Therefore, this study integrates crack morphology recovery,

internal structural restoration, and impermeability recovery to establish a comprehensive evaluation model based on multi-index coupling.

(1) Formulation of the Comprehensive Self-Healing Efficacy Index (SEI)

To quantitatively compare the overall self-healing performance of different experimental groups, a Comprehensive SEI was established based on three core evaluation parameters, including the crack area healing rate R , wave velocity recovery rate U , and water penetration height reduction rate P . Considering the engineering-oriented priorities adopted in this study, a weighted aggregation methodology was used to assign provisional weights to the three evaluation parameters, with greater emphasis placed on impermeability-related performance. The mathematical formulation of the SEI for each group is expressed in Equation (1):

$$SEI = \omega_R \cdot R^* + \omega_U \cdot U^* + \omega_P \cdot P^* \quad (1)$$

where R^* , U^* , and P^* represent the normalized values of each evaluation index using the A2 group as the reference baseline. The A2 group was selected as the internal normalization reference because it exhibited the best overall performance among the investigated mixtures. Because A2 serves as the normalization reference, its normalized R^* , U^* , and P^* values are all equal to 1.0 by definition, yielding an SEI of 1.000. Accordingly, the SEI is used primarily for relative comparison among the investigated mixtures. At the present stage, the proposed SEI should therefore be regarded as a preliminary engineering-oriented evaluation framework that requires further validation across a broader range of mixture designs, crack geometries, and service conditions. ω_R , ω_U , and ω_P denote the weighting coefficients of the corresponding parameters, satisfying: $\omega_R + \omega_U + \omega_P = 1$. Considering the engineering service priorities of pressurized diversion tunnel linings, the weighting coefficients were provisionally assigned as $\omega_R = 0.25$, $\omega_U = 0.35$, and $\omega_P = 0.40$, corresponding, respectively, to crack morphology recovery, internal structural continuity recovery, and impermeability recovery. The weighting scheme follows the engineering-oriented principle of “impermeability priority, structural continuity emphasis, and morphological reference.” These weights are intended for relative comparison among the investigated mixtures rather than as universally applicable weighting constants. To examine the influence of the assigned weighting coefficients on the SEI results, a sensitivity analysis was performed by varying the individual weights by ± 0.05 while maintaining the sum of the three coefficients equal to 1. Five weighting scenarios were considered: (0.25, 0.35, 0.40), (0.30, 0.35, 0.35), (0.20, 0.35, 0.45), (0.25, 0.40, 0.35), and (0.25, 0.30, 0.45) for (ω_R , ω_U , ω_P), respectively. The resulting SEI rankings remained $A2 > A1 > A3 > A0$ under all five scenarios. The SEI of A2 remained 1.000, whereas the values of A1 and A3 varied within 0.626–0.663 and 0.531–0.624, respectively. These results indicate that the relative ranking of the investigated mixtures is stable under moderate variations in the weighting scheme. Nevertheless, the weighting coefficients remain preliminary and should be further calibrated using broader experimental datasets and independent engineering validation.

(2) Comparative Analysis of Comprehensive Self-Healing Efficacy among Different Groups

To quantitatively compare the relative differences in self-healing performance among the experimental groups, the standardized values and the Comprehensive SEI of each group were calculated using the A2 group, which exhibited the best overall performance among the investigated mixtures, as an internal normalization reference. The corresponding results are presented in Figure 12.

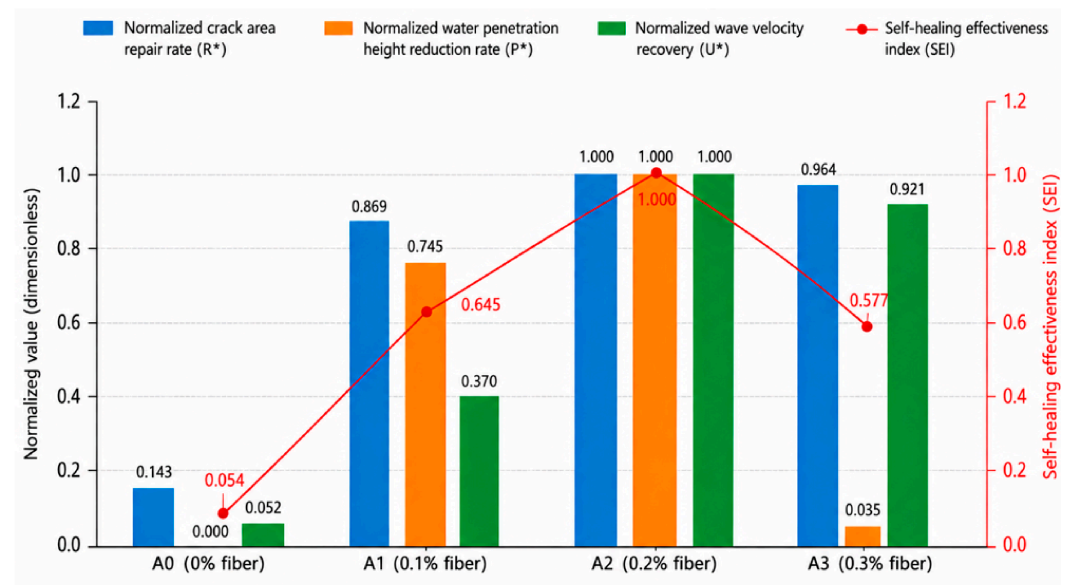


Figure 12. Normalized comparison of the core self-healing indices and comprehensive SEI values under different basalt fiber contents.

The analytical results are presented in Figure 12. Under the standardized evaluation framework using the A2 group as the internal normalization reference, the differences in comprehensive SEI among the experimental groups can be clearly identified. Accordingly, A2 has an SEI value of 1.000 by definition because it serves as the internal normalization reference. Its favorable overall performance is supported by the underlying measured R , U , and P indicators, while the SEI is used to compare the relative performance of the investigated formulations.

In contrast, the A1 group exhibited relatively lower standardized values across all evaluation indices ($R^* = 0.869$, $U^* = 0.370$, $P^* = 0.745$), resulting in an SEI value of only 0.645. Although the impermeability recovery performance of this group remained at an acceptable level ($P^* = 0.745$), the wave velocity recovery rate was comparatively low ($U^* = 0.370$). Although A1 showed a moderate impermeability index ($P^* = 0.745$), its UPV recovery index was substantially lower ($U^* = 0.370$), indicating less complete internal structural recovery than A2.

It is noteworthy that the A3 group exhibited a pronounced imbalance among the evaluation indices. Although its crack area healing rate ($R^* = 0.964$) and wave velocity recovery rate ($U^* = 0.921$) were both close to the A2 reference level, the impermeability index (P^*) sharply decreased to 0.035, resulting in an SEI value of only 0.577. This reflects a typical non-coordinated phenomenon characterized by “high morphological healing but poor impermeability recovery.” The water penetration height reduction rate of the A3 group was only 3.5% of that of the A2 group, while its permeability coefficient increased by 16.6% compared with the control group. These results indicate that the higher fiber dosage did not translate into improved functional sealing, despite the relatively high morphological healing and UPV recovery of A3. Previous studies by Tan et al. [28] also demonstrated that when mass transport within the MICP healing system is restricted, superficial crack closure does not necessarily indicate complete sealing of internal seepage pathways. Therefore, impermeability-related indices exhibit higher engineering sensitivity for evaluating healing quality. The A3 results further show that relatively high morphological healing did not translate into a continuous functional sealing response. Consequently, its comprehensive self-healing efficacy remains lower than that of the A2 group, while the deterioration of impermeability performance greatly limits its engineering applicability.

For the baseline group A0, all three standardized indices remained at extremely low levels ($R^* = 0.143$, $U^* = 0.052$, $P^* = 0$), resulting in an SEI value of only 0.054. This indicates that in the absence of a fiber-supported microbial mineralization system, the concrete matrix relies mainly on the natural carbonation of cement hydration products, which cannot effectively achieve crack filling or seepage channel sealing. Consequently, the overall self-healing performance remains at the lowest level.

The standardized evaluation results further demonstrate that relying solely on superficial crack closure can easily overestimate the actual healing capability of the material, whereas the multi-index coupled SEI can comprehensively reveal the deficiencies and limitations of each system relative to the internal normalization reference. In particular, the performance of the A3 group highlights the potential separation between “morphological healing” and “functional recovery.” This finding provides a quantitative basis for relative multi-index comparison and preliminary classification within the present dataset and further emphasizes the engineering principle of “impermeability priority” in the design and optimization of lining materials for pressurized diversion tunnels.

(3) Preliminary Classification of Self-Healing Levels and Engineering-Oriented Interpretation

Based on the calculated SEI values and corresponding healing characteristics of each experimental group, and with reference to the durability requirements of pressurized diversion tunnel lining structures and relevant standards [29,30], a preliminary five-grade classification framework was proposed for the investigated mixtures. The classification follows the engineering evaluation principle of “impermeability priority, structural continuity emphasis, and morphological reference.” The detailed classification results are presented in Table 8.

Table 8. Preliminary SEI-based classification framework for the investigated mixtures.

Healing Grade	SEI Range	Description of Healing Characteristics	Engineering Applicability Recommendation
Grade A	$0.85 \leq \text{SEI} \leq 1.00$	High relative coordination among superficial healing, internal structural continuity, and impermeability recovery under the present test conditions	Promising candidate for further validation under hydraulic-pressure and long-term service conditions
Grade B	$0.70 \leq \text{SEI} < 0.85$	Relatively favorable coordination among superficial healing, internal structural continuity, and impermeability recovery, with minor local deficiencies	Superficial healing and internal continuity are satisfactory, with relatively favorable impermeability recovery; minor local improvements remain possible
Grade C	$0.50 \leq \text{SEI} < 0.70$	Superficial healing is acceptable, but internal continuity or water impermeability shows noticeable deficiencies	Moderate relative performance; additional optimization and validation are required
Grade D	$0.30 \leq \text{SEI} < 0.50$	Low coordination among superficial healing, internal structural continuity, and impermeability recovery	Limited superficial healing, significant internal defects, and relatively weak impermeability recovery
Grade E	$0 \leq \text{SEI} < 0.30$	Very low relative SEI and weak overall healing response under the present test conditions	Lowest relative performance among the investigated mixtures; not recommended as a preferred candidate without redesign

Based on the preliminary SEI classification and the corresponding measured indicators, the performance and potential engineering applicability of the investigated mixtures are discussed below. The A2 group was assigned to Grade A within the proposed preliminary classification. Its measured R, U, and P indicators showed the most favorable overall coordination among the investigated mixtures, supporting its identification as the most promising candidate for further validation under pressurized diversion tunnel service conditions. The A1 group exhibited an SEI value of 0.645 and was classified as Grade C. Although its

crack closure and impermeability recovery were relatively favorable compared with A0, the restoration of internal structural continuity remained insufficient. This indicates that the overall healing performance of A1 remained limited by its comparatively low internal structural recovery. Therefore, further optimization of fiber dispersion, moderate dosage adjustment, or extension of the healing curing period, along with additional validation, is required before practical engineering application. The A3 group obtained an SEI value of 0.577 and was also classified as Grade C. Despite its relatively high crack healing rate and wave velocity recovery performance, its impermeability performance deteriorated significantly. Thus, although A3 exhibited relatively high crack-healing and UPV-recovery indicators, its poor impermeability recovery indicates that the higher fiber dosage did not improve functional sealing under the present conditions. Further optimization is required before engineering application. The baseline group A0 yielded an SEI value of only 0.054 and was classified as Grade E. Its self-healing performance was the lowest among the investigated mixtures, indicating that substantial improvement or additional repair measures would be required before further engineering consideration.

Particularly noteworthy is that although the A3 group achieved a crack area healing rate as high as 81%, its comprehensive SEI remained only 0.577, placing it within the same Grade C category as the A1 group. This finding further indicates that, within the present evaluation framework, water penetration height reduction provides an important functional indicator for distinguishing differences in healing quality among the tested mixtures. The pronounced phenomenon of “high morphological healing but low impermeability recovery” observed in the A3 group indicates that superficial crack closure cannot be directly equated with complete functional sealing, suggesting that internal seepage pathways may not have been completely sealed. This conclusion is highly consistent with the findings reported by Tan et al. [28], who emphasized that “superficial crack closure does not necessarily indicate complete internal restoration” in MICP-based healing systems. It also agrees with the review perspective proposed by Wong et al. [6], which highlighted that the evaluation of self-healing concrete should focus more on the “quality of healing” rather than merely the “quantity of healing.” Therefore, the multi-metric synergistic evaluation framework (R-U-P-SEI) established in this study effectively integrates crack closure, internal structural restoration, and impermeability recovery into a unified assessment system, enabling a more comprehensive characterization of both the quantitative and qualitative aspects of crack remediation. Consequently, the proposed framework shows potential utility as a preliminary engineering-oriented tool for the relative evaluation of microbial self-healing systems, although further independent validation is required before broader engineering applications.

4.3. Limitations and Future Perspectives

Although the present study demonstrates clear differences among the investigated bacteria-loaded basalt fiber formulations in crack closure, structural recovery, and impermeability performance, several limitations should be acknowledged. First, the experimental design did not include a sterile nutrient-only control group with the same urea and calcium lactate contents as A1–A3; therefore, the independent contributions of the nutrient components and microbial activity cannot be fully separated in the present study. Accordingly, the observed differences between A0 and A1–A3 are interpreted as combined formulation effects, while the respective contributions of nutrient components and bacterial activity require further clarification using dedicated control groups. In addition, the bacterial loading efficiency on the modified basalt fibers and the bacterial viability after fiber immobilization, concrete mixing, and long-term curing were not quantitatively evaluated. Consequently, the actual viable bacterial loading per unit mass of fiber and the effective

bacterial concentration in each hardened-concrete mixture could not be directly determined in the present study. Although *Sporosarcina pasteurii* spores possess strong resistance to alkaline environments and have been widely used in microbial self-healing concrete, future studies should further quantify bacterial immobilization efficiency, survival, and activation behavior using methods such as plate counting and fluorescence-based viability staining. Accordingly, the MICP-based healing pathway proposed in this study should be interpreted as a mechanism consistent with the observed healing behavior and mineralogical evidence, rather than as a directly verified post-curing microbial activity pathway.

Second, the SEI weighting coefficients and grading boundaries adopted in the present study remain preliminary and require further calibration using broader experimental datasets. Because A2 serves as the internal normalization reference, its SEI is 1.000 by definition, and the current SEI framework is therefore primarily used for relative comparison among the investigated mixtures. In addition, the microstructural origin of the poorer impermeability observed in A3 was not directly quantified; variations in fiber distribution, interfacial heterogeneity, and spatially non-uniform mineral deposition are considered possible explanations that require further verification.

Third, the continuous water-immersion curing adopted in this study represents a continuously saturated condition and does not fully reproduce the variations in saturation state or actual hydraulic-pressure conditions experienced by tunnel linings during long-term service. The effects of wetting–drying or saturation fluctuations, hydraulic-pressure variations, and repeated cracking–healing processes therefore require further investigation under representative pressurized seepage conditions.

Fourth, the 28-day healing period used in this study represents a relatively short-term evaluation. Long-term bacterial viability and mineralization activity, the durability of healing products, and the evolution of healing performance under repeated environmental exposure should be further investigated to evaluate the long-term stability of the proposed system.

5. Conclusions

1. This study evaluated a bacteria-laden basalt fiber-reinforced microbial self-healing concrete system under continuously saturated laboratory conditions relevant to sustained moisture availability in cracked tunnel linings. The experimental results showed that an appropriate basalt fiber dosage improved internal structural continuity, crack-healing performance, and impermeability under the saturated boundary conditions investigated. Performance under actual hydraulic-pressure loading requires further experimental validation.
2. The basalt fiber dosage exerted a pronounced nonlinear effect on the mechanical properties of the concrete. The compressive strength reached its maximum at a fiber dosage of 0.2%, while the improvements in splitting tensile and flexural strengths gradually diminished and approached a plateau as the dosage increased from 0.2% to 0.3%. Overall, the A2 group containing 0.2% basalt fiber exhibited the best comprehensive mechanical performance. Compared with the baseline group, its 28-day compressive strength, splitting tensile strength, and flexural strength increased by 15.1%, 12.7%, and 18.6%, respectively. These findings demonstrate that an appropriate basalt fiber dosage can effectively enhance the strength and crack resistance of concrete through fiber bridging and interfacial reinforcement. However, the reinforcing efficiency showed a reduced growth rate at the higher fiber dosage.
3. The impermeability performance of the concrete exhibited a characteristic evolution trend of “initial improvement followed by subsequent deterioration” with increasing basalt fiber dosage. Compared with the baseline group, the A2 group showed the

optimum impermeability performance, with the water penetration height and permeability coefficient reduced by 40.0% and 57.6%, respectively, indicating the strongest hydraulic barrier capacity. In contrast, when the fiber dosage increased from 0.2% to 0.3%, the A3 group exhibited poorer impermeability recovery despite relatively high crack-healing and UPV-recovery indicators. This result indicates that increasing the fiber dosage beyond the level represented by A2 did not further improve functional sealing and was accompanied by a decline in impermeability performance under the present test conditions.

4. After 28 d of healing, the A2 group exhibited the most favorable crack-healing performance among the investigated mixtures, with a crack area healing ratio of 84%, a maximum observed healed crack width of 0.65 mm, and a UPV recovery ratio of 85.8%. SEM and EDS observations revealed dense CaCO_3 -rich mineral deposits within the crack regions, with preferential accumulation on and around the basalt-fiber surfaces, while XRD showed pronounced calcite-related diffraction characteristics. These morphological and mineralogical features support the role of modified basalt fibers as favorable interfaces for mineral deposition and are consistent with an MICP-related contribution to crack filling and structural continuity recovery.
5. Based on the core evaluation indices of crack area healing rate (R), wave velocity recovery rate (U), and water penetration height reduction rate (P), a preliminary engineering-oriented multi-index evaluation framework was proposed to facilitate relative comparison among the investigated mixtures. The results showed that superficial crack closure could not fully represent the recovery of internal functionality, while impermeability-related indices provided a more sensitive measure of functional sealing quality. Among the investigated formulations, the 0.2% mixture exhibited the most favorable overall combination of the measured indicators under the present laboratory conditions, providing a basis for subsequent validation under representative pressurized seepage and long-term service conditions.

Author Contributions: Writing—review and editing, X.X. and J.L.; Methodology, R.X.; Software, Y.H.; Formal analysis, W.M.; Data curation, J.H.; Writing—original draft, J.H.; Project administration, X.X. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Key Technologies for Intelligent and Green Construction of Super-Large Underground Caverns in Ecologically Fragile Plateau Regions (BDa-2025-KY01) and Sichuan Provincial Science and Technology–Education Joint Fund (Grant No. 2026NSFSC1961).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Authors Xianqi Xu, Wanpeng Mu, and Ruigang Xu were employed by Sinohydro Bureau 14 Co., Ltd., Huaneng Lancang River Upstream Hydropower Co., Ltd., and China Northwest Water Conservancy & Hydropower Engineering Consulting Co., Ltd., respectively. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Hu, Y.; Wang, Q.; Wang, M.; Liu, D. A study on the thermo-mechanical properties of shotcrete structure in a tunnel, excavated in granite at nearly 90 °C temperature. *Tunn. Undergr. Space Technol.* **2021**, *110*, 103830. [[CrossRef](#)]
2. Jin, J.; Jing, L.; Song, Z.; Su, K.; Yang, F.; Zhai, Y. Hydraulic-mechanical interaction of pervious concrete lining considering lining cracking in pressure tunnels. *Int. J. Non-Linear Mech.* **2025**, *173*, 105044. [[CrossRef](#)]
3. Zhang, Y.; Ma, C.; Zou, M.; Li, T.; Zeng, P.; Zhao, Y.; Fan, H. Thermomechanical failure analysis of sandstone subjected to high ground temperature. *J. Rock Mech. Geotech. Eng.* **2025**, *17*, 3524–3545. [[CrossRef](#)]

4. Simanjuntak, T.D.Y.F.; Marence, M.; Mynett, A.E.; Schleiss, A.J. Mechanical-hydraulic interaction in the lining cracking process of pressure tunnels. *Int. J. Hydropower Dams*. **2013**, *20*, 48–54.
5. Zhang, C.; Zhu, Z.; Ma, B.; Su, G.; Zhu, D.; Zhou, H.; Cao, W. Generalized damage constitutive model for rock based on residual strength characteristics subjected to multi-environmental factors cycles and loading. *Cold Reg. Sci. Technol.* **2026**, *247*, 104909. [\[CrossRef\]](#)
6. Wong, P.Y.; Mal, J.; Sandak, A.; Luo, L.; Jian, J.; Pradhan, N. Advances in microbial self-healing concrete: A critical review of mechanisms, developments, and future directions. *Sci. Total Environ.* **2024**, *947*, 174553. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Nodehi, M.; Ozbakkaloglu, T.; Gholampour, A. A systematic review of bacteria-based self-healing concrete: Biomineralization, mechanical, and durability properties. *J. Build. Eng.* **2022**, *49*, 104038. [\[CrossRef\]](#)
8. Hu, Y.; Liu, W.; Zhang, Y.; Hu, X. Optimizing *Bacillus pasteurii* spore germination and unveiling impermeability mechanisms in microbial self-healing concrete. *Front. Microbiol.* **2025**, *16*, 1653557. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Wang, J.; De Belie, N. Effect of water availability On microbial self-healing of concrete. In Proceedings of the 1st Concrete Innovation Conference (CIC 2014), Oslo, Norway, 11–13 June 2014; pp. 1–8.
10. Zhang, W.; Li, J.; Chen, Z.; Tan, Y. Durability evaluation of MICP-repaired concrete exposed to the freeze–thaw process. *J. Mater. Civ. Eng.* **2024**, *36*, 04024420. [\[CrossRef\]](#)
11. Li, W.; Zou, Y.; Lu, Y.; Ren, X.; Wang, P.; Ke, L.; Wu, H.; Kai, M. Basalt macro fiber (BMF)-based cementitious materials: A comprehensive review of recent advances. *Adv. Struct. Eng.* **2025**, *28*, 2133–2156. [\[CrossRef\]](#)
12. Song, K.; Yu, Y.; Liu, Y.; Zhao, J. Flexural performance study of basalt-fiber-reinforced polymer Bar basalt-fiber-reinforced concrete beams. *Buildings* **2023**, *13*, 2583. [\[CrossRef\]](#)
13. Li, Y.; Shen, A.; Guo, Y. Influence of basalt fibre on cracking behaviour and flexural toughness of concrete under the coupled effect of fatigue load and hydrodynamic pressure. *Int. J. Pavement Eng.* **2023**, *24*, 2147521. [\[CrossRef\]](#)
14. Kanwal, M.; Khushnood, R.A.; Khaliq, W.; Wattoo, A.G.; Shahid, T. Synthesis of pyrolytic carbonized bagasse to immobilize *Bacillus subtilis*; application in healing micro-cracks and fracture properties of concrete. *Cem. Concr. Compos.* **2022**, *126*, 104334. [\[CrossRef\]](#)
15. Amjad, H.; Khushnood, R.A.; Memon, S.A. Biomimetic robust self-healing of *Bacillus Subtilis* immobilized through sisal fiber for next-generation concrete infrastructure. *Constr. Build. Mater.* **2023**, *368*, 130299. [\[CrossRef\]](#)
16. Shaheen, N.; Khushnood, R.A.; Khaliq, W.; Murtaza, H.; Iqbal, R.; Khan, M.H. Synthesis and characterization of bio-immobilized nano/micro inert and reactive additives for feasibility investigation in self-healing concrete. *Constr. Build. Mater.* **2019**, *226*, 492–506. [\[CrossRef\]](#)
17. Vijay, K.; Murmu, M. Self-repairing of concrete cracks by using bacteria and basalt fiber. *SN Appl. Sci.* **2019**, *1*, 1344. [\[CrossRef\]](#)
18. Zhang, G.-Z.; Liu, C.; Cheng, P.-F.; Li, Z.; Han, Y.; Wang, X.-Y. Enhancing the interfacial compatibility and self-healing performance of microbial mortars by nano-SiO₂-modified basalt fibers. *Cem. Concr. Compos.* **2024**, *152*, 105650. [\[CrossRef\]](#)
19. Mardani, A.; Eren, S.; Akarsu Özenc, A. A comprehensive review on fiber surface modifications and their impact on concrete properties. *J. Adhes. Sci. Technol.* **2025**, *40*, 1839–1867. [\[CrossRef\]](#)
20. Tao, H.; Sun, C.; Qu, J.; Huang, Y. Study on the effect of cementation solution concentration on sand fixation by fiber reinforced MICP. *PLoS ONE* **2025**, *20*, e0329673. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Jiang, L.; Wang, Q.; Hu, S.; Zhao, X.; Wang, W.; Zhang, Y.; Liu, Y. Expanded perlite immobilization enhances long-term survival and mineralization activity of microbial spores in cementitious environments. *Appl. Environ. Microbiol.* **2026**, *92*, e02456-25. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Wu, D.; Zhang, J.; Wang, P.; Gao, P.; Liu, Y.; Zhou, A. Optimizing the self-healing of concrete cracks under actual service oxygen conditions via mineralization of facultatively aerobic microbial consortia. *Cem. Concr. Compos.* **2025**, *165*, 106319. [\[CrossRef\]](#)
23. Li, Q.; Fan, C. Evaluation of Hydraulic-Tunnel-Lining Durability Based on ANP and Cloud-Model-Improved Matter–Element Theory. *Sustainability* **2022**, *14*, 11801. [\[CrossRef\]](#)
24. SL/T 352-2020; Test Code for Hydraulic Concrete. Ministry of Water Resources of the People’s Republic of China: Beijing, China, 2020.
25. Bashaveni, B.; Pannem, R.M.R. Prediction of self-healing ability and compressive strength of bacterial-based self-healing concrete using direct method of ultrasonic pulse velocity test. *Nondestruct. Test. Eval.* **2026**, *41*, 1157–1173. [\[CrossRef\]](#)
26. Huang, W.; Fan, L.; Peng, S.; Qi, Y.; Chen, G.; Liu, X. Experimental study on the principal factors influencing the effectiveness of microbial-induced calcium carbonate precipitation in asphalt concrete crack repair based on response surface methodology. *Road Mater. Pavement Des.* **2025**, *27*, 989–1011. [\[CrossRef\]](#)
27. Ahmad, I.; Shokouhian, M.; Jenkins, M.; McLemore, G.L. Factors influencing bacterial-based precipitation, assessment of crack inducing, durability and characterization methods: A comprehensive review. *Innov. Infrastruct. Solut.* **2025**, *10*, 107. [\[CrossRef\]](#)
28. Tan, L.; Reeksting, B.; Justo-Reinoso, I.; Ferrandiz-Mas, V.; Heath, A.; Gebhard, S.; Paine, K. The effect of oxygen and water on the provision of crack closure in bacteria-based self-healing cementitious composites. *Cem. Concr. Compos.* **2023**, *142*, 105201. [\[CrossRef\]](#)

29. *SL 775-2018*; Standard for Durability Assessment of Hydraulic Concrete Structures. Ministry of Water Resources of the People's Republic of China: Beijing, China, 2018.
30. *JGJ/T 193-2009*; Standard for Test and Evaluation of Concrete Durability. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2009.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.