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Impact and mechanism of multi-strain composite microbial mineralized coating on concrete impermeability

Jinpeng Dai¹²³⁴, Yuhu Qi¹⁴, Yan Wang¹⁴, Song Mu²³, Kai Yang¹, Tong Liu⁵

¹ National and Provincial Joint Engineering Laboratory of Road & Bridge Disaster Prevention and Control, Lanzhou Jiaotong University, Lanzhou, P.R. China

² National Key Laboratory of Materials for Major Infrastructure Engineering, Jiangsu Research Institute of Building Science Co., Ltd, Nanjing, P.R. China

³ School of Materials Science and Engineering, Southeast University, Nanjing, P.R. China

⁴ School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou, P.R. China

⁵ Faculty of Engineering, Cardiff University, Cardiff, UK

Corresponding authors: daijp@mail.lzjtu.cn; 12231302@stu.lzjtu.edu.cn

Abstract

This study developed eco-friendly microbial mineralized coatings to mitigate chloride ingress and water absorption in concrete. Three alkali-acclimated strains *Bacillus pasteurii* (B), *Bacillus cohnii* (K), and *Clavispora lusitaniae* (J) were optimally combined. The ternary coating (K:B:J = 3:2:1) achieved synergistic effects via EPS carrier from K, CaCO₃ pore filling by B, and low-hydrophilicity modification by J, reducing open porosity to 4.40% and increasing water contact angle to 55.9°. The binary coating (K:B = 7:3) showed superior chloride resistance with a migration coefficient of 2.72×10^{-10} m²/s, reaching P-V impermeability grade. Microscopic analyses confirmed dense biogenic CaCO₃ filled pores and strengthened interfaces. This work provides a quantitative framework for designing sustainable high-performance coatings to extend concrete service life in aggressive environments.

Keywords: Microbial mineralized coating; chloride penetration resistance; multi-strain compound combination; water impermeability; microscopic mechanism

1. Introduction

Concrete, the most widely employed civil engineering material worldwide, is extensively applied in critical infrastructure, such as buildings, hydraulic engineering, and transportation networks, owing to its excellent compressive strength, favorable formability, and superior cost-effectiveness [1–3]. Despite these advantages, concrete's inherent porosity and microcracks make it vulnerable to deterioration when exposed to environmental factors, such as chloride ions, sulfate ions, carbon dioxide, and water over time, potentially compromising its structural integrity and leading to failure [4,5]. Notably, chloride ion erosion is a primary contributor to premature damage in reinforced concrete structures [6], particularly in marine environments, on deicing salt roads, and in coastal regions. Upon ingress into concrete, they react chemically with cement hydration products to form Friedel's salts [7], while also causing dissolution of the hydration phase and deterioration of the matrix pore structure and microstructure. When the chloride ion concentration at the interface between the steel bars and concrete reaches the critical threshold for

passivation, the passivation film on the surface of the steel bars is damaged, thereby causing passivation failure and electrochemical corrosion, resulting in significant economic losses and safety risks [8,9].

Therefore, improving the impermeability of concrete and enhancing its durability have become key scientific and engineering problems that must be urgently addressed in the current civil engineering field. Surface coating protection is widely used in engineering for its simplicity, low cost and excellent protective performance [10,11]. Despite its popularity, the durability of its protective effect remains a major challenge. Traditional polymer coatings (epoxy resins, polyurethanes, acrylic resins) form dense films on concrete surfaces. However, they suffer from easy aging, poor substrate adhesion and volatile organic compound emissions during application [10,12,13].

Polymer nanocomposite coatings incorporate SiO_2 or TiO_2 nanoparticles to fill pores. This significantly improves coating density and mechanical strength [13]. Nevertheless, nanoparticle agglomeration and high production costs limit their large-scale application in concrete protection [14,15]. Polymer-modified cement coatings show better substrate compatibility and UV aging resistance. But their performance is highly dependent on curing conditions, and they lack autonomous crack healing ability [16,17].

Developing new green concrete protective coatings with environmental friendliness, durability and high compatibility aligns with the ‘dual carbon’ goals and green building principles. This represents the mainstream development direction of concrete protection technology. Microbial-induced calcium carbonate precipitation (MICP) technology is eco-friendly, has active repair capabilities, and is compatible with cement-based materials. It has become a key research focus for concrete protection and self-repair systems [18–20]. The essence of MICP is to induce in-situ mineralization and calcium carbonate deposition through microbial metabolism.

This effectively fills cracks, densifies the matrix structure, and improves durability [21,22]. By combining MICP mineralization mechanism with surface protection techniques, we have developed a novel microbially mineralized self-healing coating. This provides a new solution to traditional coating problems: premature aging, cracking, limited self-healing, and poor long-term waterproofing [23]. This innovative coating achieves two key functions. First, it consolidates the substrate using microbial mineralization products to block the intrusion of aggressive media such as chloride ions.

Second, it autonomously repairs cracks through microbial in-situ mineralization deposition, demonstrating intelligent self-healing capabilities [24–27]. While MICP technology has shown great potential in concrete self-healing and has been tested in preliminary engineering applications [28–31], in-depth research on microbially mineralized coatings is still in its infancy. Systematic and application-oriented studies remain scarce. Qin et al. [32] applied a bacteria-nutrient solution composite system to concrete surfaces. They controlled urea concentration and bacteria liquid ratio, achieving effective pore filling and improved impermeability.

Zhao et al. [33] used urease-positive fungi to induce a biological mineralization film on concrete surfaces. This film effectively prevented sulfate, chloride ion and water erosion, significantly enhancing concrete hydrophobicity. Lou et al. [34] immersed metals in a medium containing L-aspartic acid calcium. They prepared a dense and flat microbial mineralization coating on the surface, which showed excellent anti-corrosion properties. A major research gap remains in this field.

This is primarily because microbially mineralized coatings require complex performance synergy, presenting greater technical challenges than internal MICP technology. Furthermore, most existing

studies focus on crack repair rather than preventive surface protection. Even among the limited surface coating studies, systematic investigations of bacteria-fungi multi-species combinations for concrete surfaces are extremely rare. Nevertheless, this technology offers significant potential advantages. Once technical bottlenecks are overcome, it will enable green and low-carbon active anti-permeation protection, aligning with China's dual-carbon goals and sustainable construction trends.

To address the aforementioned critical research gaps and technical bottlenecks in MICP-based concrete protective coatings, this study systematically investigated the anti-permeation performance and protective mechanism of microbial mineralized coatings for concrete. The research scope covered the screening and rational compounding of functional microbial strains, formulation optimization and preparation of biomineralized coatings, systematic evaluation of protective efficacy, and multi-scale mechanism investigation. By combining macroscopic and microscopic experiments, this study aims to clarify the anti-permeation protection mechanism and microscopic repair principles of microbially mineralized coatings. It will establish a theoretical foundation and provide technical support for enhancing the durability and service life of concrete infrastructures.

2. Materials and methods

To systematically investigate the impermeability performance and underlying regulation mechanism of concrete modified by a multi-strain composite microbial mineralized coating, a complete full-chain experimental scheme was designed in this study. The specific technical route is illustrated in Figure 1.

2.1. Microbial species and cultivation

Bacillus pasteurii (CGMCC 1.3687, denoted as B) was purchased from the China General Microbiological Culture Collection Center (CGMCC). This strain exhibits excellent stress tolerance to high temperature and high salinity, as well as robust urease-producing activity. The micromorphology of the strain is presented in Figure 2a. *Bacillus cohnii* (BNCC 132592, denoted as K) and *Clavispora lusitaniae* (BNCC 340928, denoted as J) were purchased from Beina Biotechnology Co., Ltd (BNCC, China). *Bacillus cohnii* is characterized by rod-shaped vegetative cells and superior adaptability to alkaline environments, as shown in Figure 2b.

In contrast, *Clavispora lusitaniae* features spherical vegetative cells, as shown in Figure 2c. All culture media were sterilized by high-pressure steam at 121 °C for 30 min, then immediately transferred to a Class II aseptic laminar flow cabinet for ultraviolet disinfection and natural cooling to ambient temperature prior to inoculation. Since the surface pH of the ordinary Portland cement concrete specimens can reach around 11–13 after complete hydration [35]. To simulate this high-alkaline microenvironment of the concrete matrix surface, the initial pH of the culture medium was adjusted using 1 mol/L sodium hydroxide (NaOH) solution to establish a pH gradient of 8.0, 9.0, 10.0, 11.0, 12.0 and 13.0. The three target strains were first inoculated onto solid agar plates with the corresponding pH values for alkali domestication.

Subsequently, the acclimated strains were inoculated into liquid culture media at an inoculation volume ratio of 2% (v/v). All inoculated conical flasks were incubated in a constant-temperature shaking incubator at 30 °C and 180 rpm for 48 h. To characterize the growth and proliferation characteristics of

the microorganisms under alkaline stress, the optical density at 600 nm (OD₆₀₀) of the bacterial/fungal suspension was measured every 6 h using a visible spectrophotometer.

2.2. Preparation of microbial mineralized coating

In this study, polyvinyl alcohol (PVA) and sodium alginate (SA) were selected as the composite coating matrix. PVA exhibits excellent film-forming performance and interfacial bonding strength, which can form a dense coating to enhance the mechanical properties and impermeability of the protective layer. In contrast, SA is a natural, nontoxic polymer with outstanding biocompatibility; its three-dimensional porous gel network can effectively buffer the harsh stress from high alkalinity, low temperature, and chloride ions, thus maintaining the long-term metabolic activity of functional microorganisms. The combination of PVA and SA balances the protective performance of the coating and the survival environment of microorganisms, and preliminary compatibility tests verified no adverse reaction between the matrix components and functional strains. A silane coupling agent was used to enhance the interfacial bonding between the inorganic and organic phases in the coating system and to inhibit the agglomeration of nanofillers. nano-alumina (nano-Al₂O₃) was incorporated to refine the pore structure, improve the mechanical strength of the coating, and enhance its resistance to chloride ion penetration.

All operations were performed in a Class II aseptic laminar flow cabinet under sterile conditions. A sterile inoculation loop was used to harvest bacterial cells from a solid agar plate cultured with pre-acclimated target strains. The collected cells were then resuspended in 100 mL of sterile distilled water in a sterile conical flask. The flask was subsequently placed in a constant-temperature shaking incubator to ensure complete dispersion and a homogeneous suspension of the bacterial cells. The concentration of the microbial suspension was adjusted to an optical density (OD₆₀₀) of 2.0 using a visible spectrophotometer for subsequent coating preparation.

For the fabrication of the microbial coating, 4.0 g of PVA and 4.0 g of SA were simultaneously weighed and added to a beaker containing 100 mL of distilled water, after which the mixture was heated in a thermostatic water bath. The water bath temperature was maintained at 80–90 °C, and the mixture was continuously stirred until a transparent and homogeneous solution was obtained; heating was then terminated. The mixed matrix solution was cooled to ambient temperature and then slowly added to 100 mL of the standardized microbial suspension. A magnetic stirrer was used to mix the two components at 200 rpm for 10 min to ensure complete blending. Subsequently, 1.0 g of glucose and 4.0 g of a silane coupling agent were added to the mixture and stirred for 15 min.

Finally, 4.0 g of nano-Al₂O₃ was incorporated and the mixture was stirred for an additional 20 min to obtain a homogeneous microbial coating solution. The detailed formulation of the microbial mineralized coating is listed in Table 1.

2.3. Preparation of concrete specimens and microbial mineralized coating application

Ordinary Portland cement (P·O 42.5), compliant with Chinese Standard GB 175–2023, was used in this study which was produced by Gansu Qilian Mountain Cement Group Co., Ltd. The oxide composition of the cement was characterized by X-ray fluorescence (XRF) spectrometry, and the detailed results are listed in Table 2. Natural river sand with a fineness modulus of 3.29 was sourced from the Xiahe Yellow River sand quarry. Crushed limestone with a gap-graded particle size distribution (5–10 mm: 10–20 mm mass ratio = 2:8) was used as the coarse aggregate, which was derived from the same rock formation and

featured a rough surface texture and high mechanical strength. The experimental mix employed a ratio of cement: sand: stone: water = 488:528:1176:195.

For specimen preparation, the weighed cement, fine aggregate, and coarse aggregate were sequentially added to a 60 L single-shaft horizontal mixer and pre-mixed for 300 s to ensure homogeneous blending of all solid components. Mixing water was then added, and the mixture was stirred for an additional 120 s to obtain fresh concrete with uniform workability. The fresh concrete was cast into standard cubic molds (100 mm × 100 mm × 100 mm) and cylindrical molds (Ø100 mm × 50 mm). All specimens were compacted on a vibrating table for 60 s to eliminate entrapped air, then covered with polyethylene film and cured at ambient temperature for 24 h prior to demolding. After demolding, all specimens were transferred to a standard curing chamber (20 ± 2 °C, relative humidity 95%) for a 28-day standard curing period.

Concrete specimens cured for 28 d were removed from the standard curing chamber, and dried in an electric thermostatic drying oven at 60 °C for 48 h. The detailed experimental procedures were adopted according to Yang et al. [36]. All non-test surfaces of the specimens were sealed with paraffin wax. Only two pairs of parallel test surfaces were reserved for chloride ion penetration resistance testing. The test surfaces were thoroughly cleaned with a high-pressure water jet, then dried with a hair dryer.

Apply the coating solution uniformly on the prepared test surfaces using a brush. The thickness of each single coating layer was controlled at 0.1–0.15 mm. A second coating layer was applied after the first layer was completely dried. A calcium acetate-urea composite nutrient solution was sprayed on the coating surface immediately after each layer application. After the coating process, all specimens were cured at 20 ± 2 °C for 3 d.

This period ensured sufficient coating curing and initial calcium carbonate mineralization deposition. Specimens coated with different bacterial composite systems were labeled with the corresponding bacterial abbreviations. The uncoated blank control group was labeled as C. Cubic concrete specimens (100 mm × 100 mm × 100 mm) were used to evaluate the surface protective performance of the microbial mineralized coating on concrete. Cylindrical concrete specimens (Ø100 mm × 50 mm) were dedicated to the Rapid Chloride Migration (RCM) test.

2.4. Surface open porosity of concrete

The surface open porosity test was performed on 100 mm × 100 mm × 100 mm cubic concrete specimens following the vacuum saturation method specified in the Chinese Standard GB/T 50010-2010. First, the surface of each specimen was thoroughly cleaned. The specimens were dried in an oven at 105 ± 5 °C until a constant mass was achieved, then cooled to ambient temperature in a desiccator and weighed. Subsequently, the specimens were placed on a dedicated support in a vacuum chamber. The chamber was sealed, and a vacuum pump was activated to evacuate air for a minimum of 3 h.

The absolute pressure inside the chamber was monitored with a pressure gauge and maintained below 2000 Pa to fully remove air from the open pores of the specimens. The vacuum condition was maintained, and deaerated water was gradually introduced through a guide pipe until the specimens were completely submerged. The water injection valve was closed, the vacuum pump was turned off, and the specimens were immersed in deaerated water for 24 h to ensure full saturation of the open pores. After saturation, the specimens were removed from the chamber. Surface moisture was gently wiped off with a damp cloth, and the saturated mass of each specimen was weighed.

The Archimedes mass of the specimens was determined using a static hydrostatic balance. The surface open porosity was calculated using formulas (1) – (4), with the density of water (ρ) taken as 1000 kg/m³.

$$V = (m_3 - m_2) / \rho \quad (1)$$

$$w_{\text{sat}} = w_0 p = (m_2 - m_1) / V \quad (2)$$

$$\rho_1 = m_1 / V \quad (3)$$

$$\rho_{\text{mat}} = m_1 / [V(1 - w_0)] \quad (4)$$

Among them, m_1 denotes the dry mass of the concrete specimen after drying to a constant mass and cooling to ambient temperature (g). ρ_1 denotes the apparent density of the concrete specimen (g/cm³). m_2 denotes the saturated surface-dry mass of the specimen (g). where m_3 denotes the hydrostatic mass of the saturated specimen measured using a static hydrostatic balance (g). w_0 denotes the surface open porosity of the concrete specimen (%), and ρ_{mat} denotes the matrix density of the concrete specimen (g/cm³).

2.5. Static water contact angle measurement of concrete surfaces

The cylindrical concrete specimens (Ø100 mm × 50 mm) for the Rapid Chloride Migration (RCM) test were axially split into two halves using a precision cutting machine. The concrete surfaces were thoroughly cleaned and dried at ambient temperature and then placed under a micro-injection needle of a video-based optical contact angle measuring instrument (OCA25, DataPhysics Instruments GmbH, Germany). The needle was adjusted to be close to the specimen surface, and a 5 µL droplet of deionized water was dispensed onto the surface. The droplet was allowed to stabilize for 5 s, then its side profile was captured by a high-speed camera with backlighting. The droplet profile was manually calibrated and fitted with an elliptical model to calculate the static water contact angle.

To minimize random errors, five independent test points on the same surface were selected for replicate measurements.

2.6. Capillary water absorption coefficient of concrete

Cubic concrete specimens (100 mm × 100 mm × 100 mm) were used after 28 days of standard curing. All samples were divided into two groups: the experimental group with uniform microbial coating on the bottom surface, and the untreated blank control group. All specimens were oven-dried at 60 ± 5 °C to constant mass. The weighing interval was no less than 24h, and the mass variation was controlled within 0.1% to remove evaporable internal water. After cooling to ambient temperature, the four side surfaces were fully sealed with molten paraffin.

Only the top and bottom surfaces were reserved, and the bottom surface was defined as the capillary absorption interface. Once the paraffin solidified, the initial dry mass of each specimen was recorded as m_1 . The samples were placed on a wooden support with the absorption surface facing downward in a water tank. The water level was kept 3–5 mm above the specimen bottom. At scheduled time intervals, the specimens were taken out, and free surface water was gently wiped with a damp cloth for subsequent weighing.

$$w = w_{\text{sat}} \times S = (A \times \sqrt{t}) / h \quad (5)$$

Among them, w denotes the water content (kg/m³), S denotes the saturation degree, w_{sat} denotes the vacuum-saturated water content (kg/m³), A denotes the water absorption coefficient, h denotes the height

of the water level above the bottom of the specimen (mm), and t denotes the square root of the weighing time (s).

2.7. Chloride ion penetration resistance test of concrete

The chloride ion penetration resistance of concrete was evaluated using the Rapid Chloride Migration (RCM) method with an RCM-8F analyzer. A 10% sodium chloride (NaCl) solution was used as the cathodic electrolyte for chloride ions. A 0.3 mol/L sodium hydroxide (NaOH) solution served as the anodic electrolyte to ensure ionic conductivity. A stable direct current (DC) electric field of 30V was applied to drive chloride ions toward the anode, thereby shortening the test duration. After the test, the cylindrical concrete specimens were axially split.

A 0.1 mol/L silver nitrate (AgNO₃) solution was immediately sprayed onto the fresh fracture surface. The reaction between chloride ions (Cl⁻) and silver ions (Ag⁺) formed a white silver chloride (AgCl) precipitate, which was used to determine the chloride ion penetration depth boundary.

$$D_{RCM} = [0.0239(273 + T)L / ((U - 2)t)] \times [X_d - 0.0239\sqrt{((273 + T)LX_d / (U - 2))}] \quad (6)$$

Among them: t denotes the energization time (h), T denotes the average temperature of the anode solution (°C), U denotes the applied voltage (V), L denotes the thickness of the concrete specimen (mm) and X_d denotes the depth of chloride ion penetration (mm).

3. Results and discussion

3.1. Microbial cultivation

Figure 3 presents the growth curves of *Bacillus pasteurii* (B), *Bacillus cohnii* (K) and *Clavispora lusitaniae* (J), revealing distinct pH tolerance differences among them. Strain K grew rapidly within the first 10 h across all pH groups, and its OD600 stabilized at 2.0–2.3 over pH 7–13 after 20 h of incubation, demonstrating outstanding alkali resistance even at pH ≥ 12 . This adaptability stems from the unique cell wall structure and intracellular pH homeostasis of Gram-positive spore-forming bacteria. In contrast, strain J had a narrow alkaline adaptation range, with optimal growth at pH 8–10 (OD600 > 1.8). Its growth was restricted at pH 11–12 and weak at pH 7 (final OD600 $\approx$ 1.5), indicating a preference for weakly alkaline environments.

Its poor alkali tolerance was due to fungal cell wall composition and limited pH regulation capacity. Strain B grew best at pH 10–11 (final OD600 $\approx$ 2.5), but severe inhibition occurred at pH 13 (OD600 $\approx$ 1.0). Extremely alkaline conditions greatly suppress its metabolism, particularly urease activity, thus restraining cell proliferation. Figure 4 presents the growth curves of dual-strain and three-strain combinations at different mixing ratios, revealing obvious differences in optimal proportions and growth traits among various mixed systems. For the B-J binary system, the 8:2 ratio achieved the best growth with rapid entry into the logarithmic phase, driven by metabolic interactions: J secreted active substances to promote bacterial proliferation, while B's metabolic by-products provided essential precursors for J, forming a stable symbiosis with slow cell decay in the late stage.

The J-K system reached maximum OD600 at a 3:7 ratio, showing strong metabolic complementarity: J created a local anaerobic microenvironment and provided attachment sites/nutrients via EPS, while K degraded complex organics into small molecules for J. The B-K system grew synergistically early and

stabilized due to nutrient limitation at a 3:7 ratio, with complementary metabolic demands and no obvious competitive inhibition. In the ternary mixed system (K:B:J = 3:2:1), the OD600 increased rapidly and remained at a high level, achieving fast and stable microbial reproduction. The low proportion of J effectively reduced nutritional competition and growth suppression. The dominant proportion of K provided sufficient metabolic support by degrading organic pollutants and improving the microenvironment, thereby producing a synergistic growth effect with B.

Such favorable inter-strain cooperation can continuously supply abundant viable bacteria for subsequent microbial-induced calcium carbonate precipitation.

3.2. Regulation effect of microbial coating solution on surface open porosity of concrete

Figure 5 compares the surface open porosity of concrete coated with single-strain and composite microbial systems, showing distinct modification effects on concrete surface pore characteristics by different microbial systems. The uncoated control group had abundant original surface pores with an open porosity of 7.60%. Among single-strain coating groups, Group J exhibited the lowest porosity (4.53%), significantly lower than Groups B and K. Strain J effectively refined surface pores through pore filling and interface reinforcement, producing low-porosity precipitates to strengthen particle bonding and reduce pore connectivity. In contrast, single treatments of B and K only achieved limited internal pore structure optimization.

For binary composite groups, the open porosity of K + B (5.81%) and K + J (5.86%) was lower than that of B + J (6.11%), mainly due to the interface activation of strain K, which improved B's pore-filling efficiency and promoted dense crosslinked structures with J's products. However, the B + J system failed to achieve satisfactory synergistic regulation due to insufficient reaction compatibility. Notably, the ternary group (K + B + J) had the minimum open porosity (4.40%) across all specimens. This excellent performance originated from the synergistic effects of interface activation, pore filling and structural crosslinking. The coordinated action of the three strains greatly inhibited surface open pore development and achieved optimal pore refinement.

The results of this study are highly consistent with Qian et al. [37], who experimentally confirmed that calcium carbonate mineralization products formed by microorganisms on the surface of cement-based materials can effectively fill the connected pores in the surface of the material, thereby reducing its surface open porosity.

3.3. Surface contact angle of concrete with microbial coating

Figure 6 compares the surface contact angles of concrete coated with single-strain and composite microbial systems, showing that microbial mineralized coatings from different strain systems significantly alter concrete surface wettability, resulting in distinct contact angle differences among groups. The uncoated control group had the lowest contact angle (11.3°), demonstrating the strong hydrophilicity of ordinary concrete. This is mainly attributed to abundant hydrophilic functional groups (e.g. hydroxyl [-OH] and silanol [Si-OH]) on the concrete surface combined with high open pore density [23], which facilitate water wetting, spreading and rapid penetration. Among single-strain coating groups, Group K showed only a slightly higher contact angle than the control, with limited improvement. This is because the extracellular polymeric substances (EPS) produced by strain K partially cover surface

hydrophilic groups, but EPS itself contains hydrophilic components, leading to modest waterproofing enhancement.

Group J had the highest contact angle among single-strain groups, indicating its superior surface waterproofing regulation ability. Binary composite systems exhibited significant performance differences. Group K + B achieved a higher contact angle than all single-strain groups, showing a notable synergistic enhancement effect. Strain K's EPS acts as a carrier for strain B's calcium carbonate crystallization, forming a composite surface structure that optimizes both chemical composition and microscopic roughness. In contrast, Group B + J had the lowest contact angle among composites, as the reaction between B's urease products and J's metabolites impairs the low-hydrophilicity surface structure.

Notably, the ternary group K + B + J exhibited the highest contact angle (55.9°). The K + B synergism effectively offsets J's antagonistic effect. The three strains form an efficient regulation system: K provides EPS carriers, B induces calcium carbonate crystallization to roughen the surface, and J produces metabolites to reduce hydrophilicity. These mechanisms coordinately optimize surface properties, maximizing water impermeability and holding significant engineering application value.

3.4. Effects of different bacterial strains coating solutions on capillary water absorption coefficient of concrete

Figure 7 and Table 3 present the capillary water absorption coefficient test results of concrete with different microbial mineralized coatings, showing significant performance differences among groups. The uncoated control group exhibited a significantly higher initial capillary water absorption coefficient than all coated groups, attributed to its original pore structure with abundant interconnected channels that provide continuous water transport paths. Among single-strain coating groups, Group J maintained a consistently low capillary water absorption coefficient throughout the test, indicating that J effectively blocks and seals interconnected pore channels, reducing effective capillary paths and inhibiting water transport. Notably, the ternary composite group K + B + J achieved the largest reduction in capillary water absorption coefficient. Strain K activates the concrete matrix and improves the bonding interface between B-induced precipitates and the matrix, while strain J reduces pore wall hydrophilicity via surface modification.

Their synergistic effect realizes multi-dimensional regulation including pore blocking, structural densification and low-hydrophilicity interface formation, imposing dual inhibition on both the driving force and transport channels of capillary water absorption. The results of this study are highly consistent with Wang et al. [38] and Zheng et al. [39], who applied *Sporosarcina pasteurii* bacterial solution to the surface of cement mortar and confirmed that MICP mineralization treatment could significantly reduce the capillary water absorption coefficient of the specimens. With prolonged test time, the capillary water absorption coefficient of all groups gradually stabilized as internal pores became saturated and effective capillary channels decreased, conforming to Darcy's law. In summary, all microbial coating treatments regulate the capillary water absorption behavior of concrete by modifying the pore structure and interface characteristics. These treatments simultaneously affect the water transport channels and the driving force of capillary absorption.

This dual-dimensional regulation is the core reason for the significant differences in capillary water absorption coefficients among different groups.

3.5. Effect of different microbial mineralized coatings on chloride penetration resistance of concrete

Figure 8 compares the chloride ion migration coefficients and penetration depths of concrete coated with single and composite microbial systems, evaluating their chloride penetration resistance using these two key indicators. The uncoated control group showed the poorest performance, with a chloride penetration depth of 4.9 mm and a migration coefficient of $6.54 \times 10^{-10} \text{ m}^2/\text{s}$. Among single-strain coating groups, Group K outperformed Groups B and J, but remained significantly less effective than the K + B binary composite group, which exhibited superior chloride penetration resistance with a minimum penetration depth of 2.243 mm and a migration coefficient of $2.72 \times 10^{-10} \text{ m}^2/\text{s}$ (calculated by RCM method formula 6). The exceptional performance of the K + B group stems from efficient synergistic mineralization and multi-level pore-sealing effects. *Bacillus pasteurii* (B) has high urease activity, rapidly catalyzing urea hydrolysis to produce nanoscale crystals that fill micropores (<50 nm) and block chloride diffusion channels.

Bacillus cohnii (K) secretes EPS as an efficient nucleation carrier, facilitating uniform calcite crystal growth and forming a dense precipitation layer to seal mesopores (50–200 nm) and interconnected pores. Their complementary advantages in mineralization pathways, product morphology and pore-filling scales collectively construct a multi-level ion barrier system, significantly reducing chloride migration and enhancing concrete's long-term durability in chloride erosion environments. The results of this study are highly consistent with Zheng et al. [39], who applied *Sporosarcina pasteurii* bacterial solution to the surface of cement mortar and confirmed that MICP mineralization treatment could significantly reduce the chloride migration coefficient of the specimens. Yang et al. [36] and He et al. [40] also found that brushing microbial self-healing slurry onto concrete specimens reduced chloride ion permeability. Figure 9 illustrates how various strain coating solutions improve the resistance of concrete to chloride ion penetration.

To quantitatively and clearly assess the modification performance, this study introduces two indicators of relative reduction rates: the relative reduction rate of the migration coefficient (gD) and the relative reduction rate of the penetration depth (gx). In these indicators, D represents the chloride ion migration coefficient, and x signifies the chloride ion penetration depth. The formulas for calculating these two indicators are as follows:

$$\eta_x = [(x_{\text{control}} - x_{\text{experiment}}) / x_{\text{control}}] \times 100\% \quad (7)$$

$$\eta_D = [(D_{\text{control}} - D_{\text{experiment}}) / D_{\text{control}}] \times 100\% \quad (8)$$

Among them: x_{control} denotes the chloride ion penetration depth of the control group (mm), $x_{\text{experiment}}$ denotes the chloride ion penetration depth after coating with different microorganisms (mm), D_{control} denotes the chloride ion migration coefficient of the control group (m^2/s), $D_{\text{experiment}}$ denotes the chloride ion migration coefficient after coating with different microorganisms (m^2/s). Figure 9 further confirms that the K + B binary composite group achieved the most significant enhancement in concrete chloride penetration resistance, with relative reduction rates of migration coefficient (gD) and penetration depth (gx) reaching 58.4% and 54.2%, respectively. Among single-strain systems, Group K showed better anticorrosion improvement than Groups B and J, but still significantly inferior to the K + B composite. Other composite systems (K + J, B + J, and the ternary K + B + J group) exhibited markedly lower gD and gx values than the K + B group, fully verifying the overwhelming advantages of the K + B

compounding strategy. The excellent performance of the K + B group essentially originates from efficient temporal coordination of mineralization behavior and multilevel pore sealing.

Bacillus pasteurii (B) has high urease activity and rapid mineralization initiation, catalyzing urea hydrolysis at the initial coating stage to induce in-situ calcium carbonate formation. This early mineralization preferentially seals surface open pores and interconnected channels, rapidly constructing a dense initial ion barrier to inhibit initial chloride ingress. Meanwhile, *Bacillus cohnii* (K) secretes EPS with excellent adhesion and long-term permeability, which extends deep into pore channels. EPS acts as a stable nucleation carrier to firmly anchor CaCO_3 crystals on pore walls and accurately fill fine pores and microcracks uncovered by B's mineralization products, realizing long-term dynamic sealing of chloride transport channels. This 'early rapid film formation-late continuous filling' mechanism precisely matches the two-stage chloride transport behavior (initial capillary adsorption and subsequent diffusion).

In contrast, single strains only achieve limited single-time-scale sealing, while other composites suffer from poor temporal coordination with strain J, triggering pore space competition and mineralization interference, resulting in lower performance improvement. To quantitatively evaluate the improvement effect of the microbial mineralized coatings on the chloride penetration resistance of concrete, specimens in each group were classified into the corresponding impermeability grades based on the results of the DRCM test. The relevant detailed data are summarized in Table 4. Table 4 presents the classification results of chloride penetration resistance grade based on DRCM. Significant differences exist in the protective efficacy against chloride attack for concrete with different microbial mineralized coatings.

The blank control group and the single strain J modification group only achieved a P-III grade of chloride penetration resistance. This result indicates that concrete has limited barrier capacity against chloride ingress without effective microbial mineralization modification or when treated with strain J alone. Such concrete can hardly meet the service requirements in medium-to-high chloride attack risk environments. The single strain B and K modification groups reached an upgraded P-IV grade. This demonstrates that both single strains can optimize the concrete pore structure via mineralization and improve the anti-penetration performance.

However, their enhancement effects still have obvious limitations, failing to achieve a leapfrog improvement in chloride penetration resistance. Notably, the K + B binary composite modification group was the only one that achieved the highest P-V grade among all test groups. This result not only verifies the engineering applicability of this modification scheme, but also further confirms the synergistic comineralization and pore sealing effect of *Bacillus cohnii* (K) and *Bacillus pasteurii* (B) at the microscopic level. The two strains realize sequential coordination and scale complementarity in pore sealing, and jointly construct a multi-level and dense ion barrier system. This system significantly reduces the transport efficiency of chloride ions and ultimately achieves a leapfrog upgrade in the chloride penetration resistance grade of concrete.

This finding completes the investigation on the anti-penetration mechanism of microbial mineralization-based coatings and clarifies the engineering practical value of the K + B composite strain modification scheme. It also provides critical grade evaluation support and a theoretical basis for the subsequent application of microbial mineralized coatings in the long-term protection engineering of concrete structures.

3.6. Microstructural characterization

Figure 10 presents the X-ray diffraction (XRD) patterns of all concrete specimens collected with Cu K α radiation. Characteristic diffraction peaks at $2\theta \approx 26.6^\circ$, 27.3° , 34.0° and 29.4° correspond to quartz (SiO₂), Friedel's salt (F), calcium hydroxide (Ca(OH)₂), and vaterite-type calcium carbonate (CaCO₃), respectively [38,41,42]. Friedel's salt content, calculated via peak area integration to quantitatively evaluate chloride intrusion degree, is summarized in Figure 11.

Figure 11. Phase analysis shows all specimens have identical core phase compositions of the cement matrix, indicating that microbial mineralization induced by K, B, and J coatings only regulates the crystal morphology, crystallinity, and spatial distribution of mineralization products without altering the intrinsic matrix phase composition. This confirms that microbial mineralized coating modification is a safe physicochemical synergistic treatment, providing theoretical support for its feasibility at the phase level.

Friedel's salt is the characteristic binding product of chloride ions with aluminate phases in cement hydrates, and its content directly reflects the degree of chloride ingress and reaction, serving as a key microscopic indicator for evaluating concrete chloride penetration resistance. Figure 11 shows that the K + B binary composite group had the lowest relative peak area ratio of Friedel's salt among all groups, significantly lower than the uncoated control group (Group C), which had the highest ratio corresponding to the most severe chloride invasion. This microscopic observation directly confirms the superior chloride penetration resistance of the K + B group, as reduced Friedel's salt formation indicates effectively inhibited chloride ingress rate and total amount, slowing down the erosion of cement matrix aluminate phases. This result is in excellent agreement with macroscopic test results of chloride penetration resistance grade, migration coefficient, and penetration depth, realizing mutual verification between macroscopic performance and microscopic phase composition. The excellent inhibition effect of the K + B composite coating originates from the complementary functions and synergistic effect of the two strains. Strain B has a significant advantage in mineralization rate, inducing rapid in-situ calcium carbonate formation to achieve fast pore sealing and physically block chloride transport channels. Although strain K has a relatively slower mineralization rate, it strongly secretes extracellular polymeric substances (EPS), especially polysaccharide-protein complexes, which act as stable nucleation sites and binding agents to enhance the interfacial bonding stability between mineralization products and concrete pore walls. Their combined action forms a dual protective mechanism of rapid mineralization filling and enhanced interfacial bonding, ensuring both timely pore sealing and long-term stability of the mineralized barrier layer, which continuously retards chloride ingress and Friedel's salt formation during long-term chloride exposure, maintaining concrete matrix phase stability. This finding further consolidates the theoretical basis for the K + B binary composite system as the optimal modification scheme.

Figure 12 displays the Fourier transform infrared (FTIR) spectra of all test groups. The absorption peak at 3640 cm^{-1} is assigned to the -OH stretching vibration, which originates from calcium hydroxide and represents the typical alkaline hydration phase of cement. The band at 3520 cm^{-1} corresponds to Al-OH functional groups, derived from aluminate hydration gels that contribute to matrix reinforcement and chloride binding capacity. The broad absorption band ranging from 3400 to 3500 cm^{-1} is attributed to the H-O-H vibration of adsorbed water, which facilitates the penetration and transport of chloride ions. Characteristic peaks within $950\text{--}1000\text{ cm}^{-1}$ are ascribed to C-H-S gel [43], the primary strength-bearing hydration product of concrete. In addition, the bending vibration peak near 850 cm^{-1} corresponds to chloride ions from external erosion media [44]. Figure 12 presents the Fourier transform infrared (FTIR)

spectra of concrete specimens from all test groups, revealing the effects of different microbial modification systems on concrete chloride penetration resistance at the functional group level. The K + B binary composite group showed significantly higher absorption intensity of the calcium silicate hydrate (C-S-H) characteristic peak at 950–1000 cm^{-1} , with a sharp, narrow, and well-defined shape. This directly confirms enhanced concrete hydration degree, with the formation of abundant dense, highly crystalline C-S-H gel. As the core strength-bearing hydration product, C-S-H gel has excellent filling and bonding properties, effectively sealing micropores and interconnected pore channels to form a dense physical barrier against aggressive chloride ions, which is the fundamental mechanism for the superior chloride penetration resistance of the K + B group. Furthermore, the K + B group exhibited significantly reduced intensity of the Cl^- bending vibration peak at 850 cm^{-1} , indicating lower free chloride ion content and effectively inhibited chloride infiltration and accumulation. The -OH stretching vibration peak and H-O-H vibration band remained stable and well-defined, suggesting intact hydration product structures without obvious erosion or damage, further verifying the effective protection of the K + B composite coating. In contrast, the blank control group (Group C) showed clear structural deterioration signs. Its C-S-H characteristic peak had significantly weakened intensity with a broad, diffuse shape, indicating insufficient hydration and limited C-S-H gel formation, resulting in a porous internal structure with high pore connectivity that creates continuous chloride transport pathways. Meanwhile, Group C exhibited extremely high Cl^- peak intensity, corresponding to severe matrix invasion. A distinct carbonate ion (CO_3^{2-}) peak was also detected, indicating strong carbonation that damages hydration product structures and exacerbates chloride corrosion. Ultimately, the untreated control group showed the lowest chloride penetration resistance.

Figure 13 presents the thermogravimetric (TG) curves of concrete specimens from all test groups. The mass loss in the temperature range of 250–400 $^{\circ}\text{C}$ is assigned to the thermal decomposition of Friedel's salt. The mass loss between 400–500 $^{\circ}\text{C}$ is attributed to the dehydroxylation of calcium hydroxide ($\text{Ca}(\text{OH})_2$). The mass loss in the range of 600–780 $^{\circ}\text{C}$ is ascribed to the thermal decomposition of calcium carbonate (CaCO_3) [44,45].

The TG curves of all the test groups were analyzed. The mass fractions of Friedel's salt, calcium hydroxide ($\text{Ca}(\text{OH})_2$), and calcium carbonate (CaCO_3) in each group were calculated using the standard thermogravimetric formula. The modification and protective effects of microbial mineralized coatings were comprehensively characterized from the perspectives of the chemical composition and thermal stability of the hydration products.

$$x_{\text{Friedel-salt}} = (\Delta m_{250-400^{\circ}\text{C}} / m_0) \times (M_{3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}} / M_{10\text{H}_2\text{O}}) \quad (9)$$

$$x_{\text{Ca}(\text{OH})_2} = (\Delta m_{400-500^{\circ}\text{C}} / m_0) \times (M_{\text{Ca}(\text{OH})_2} / M_{\text{H}_2\text{O}}) \quad (10)$$

$$x_{\text{CaCO}_3} = (\Delta m_{600-780^{\circ}\text{C}} / m_0) \times (M_{\text{CaCO}_3} / M_{\text{CO}_2}) \quad (11)$$

Figure 14 illustrates the synergistic regulatory mechanism of microbial mineralized coatings on three key concrete products: Friedel's salt, calcium hydroxide ($\text{Ca}(\text{OH})_2$), and calcium carbonate (CaCO_3). The blank control group, without microbial modification, had the highest Friedel's salt content due to massive chloride ingress reacting with cement hydration phases, reflecting the weakest chloride penetration resistance. In contrast, all microbial-modified groups showed reduced Friedel's salt content, with the K + B binary composite group exhibiting the lowest, indicating the strongest inhibition of chloride invasion and accumulation, confirming its excellent anti-penetration performance from the chemical phase perspective. High $\text{Ca}(\text{OH})_2$ content was maintained in all groups, demonstrating that microbial

mineralization did not compromise the concrete matrix's highly alkaline environment ($\text{pH} \approx 12.5$), which is critical for steel reinforcement passivation and corrosion protection. Microbial activity only regulated $\text{Ca}(\text{OH})_2$ consumption and distribution, showing excellent matrix compatibility. Notably, CaCO_3 content varied most significantly among groups, with the K + B group having a markedly higher content, confirming its superior mineralization efficiency. Abundant microbially induced CaCO_3 effectively filled pore channels, optimized pore structure, reduced connectivity, and formed a dense physical barrier, significantly enhancing concrete impermeability and chloride erosion resistance. Microbial coatings achieved dual optimization of chemical composition and microstructure via three synergistic effects: inhibiting Friedel's salt formation, stabilizing $\text{Ca}(\text{OH})_2$ content, and promoting CaCO_3 deposition. The K + B binary composite group exhibited the optimal synergistic regulation effect.

Figure 15 presents the scanning electron microscope (SEM) micromorphology analysis results of concrete specimens, revealing the effects of different microbial modification systems on concrete chloride penetration resistance at the microstructural level. The blank control group exhibited severe microstructural deterioration. Abundant needle-shaped ettringite (AFT) crystals caused volume expansion and loose interfacial structure, forming interconnected transport channels for aggressive ions. Lamellar calcium hydroxide ($\text{Ca}(\text{OH})_2$) crystals were not effectively encapsulated and prone to dissolution, further damaging microstructure integrity. Fluffy calcium silicate hydrate (C-S-H) gel was dispersed without forming a dense three-dimensional network, failing to fill internal pores and microcracks, resulting in low matrix density and poor chloride resistance. In contrast, the K single-strain and K + B binary composite groups showed significantly optimized microstructures and excellent matrix compactness. C-S-H gels in both groups aggregated to form a dense three-dimensional network, effectively filling micropores and microcracks, and enhancing matrix density and interfacial bonding strength. A small amount of AFT crystals was uniformly distributed, avoiding interfacial loosening caused by volume expansion and improving microstructure stability. Notably, the K + B group exhibited higher matrix compactness than the K single-strain group, with a more regular three-dimensional network, more sufficient pore filling, and tighter interfacial bonding. This optimized microstructure effectively blocks external chloride ion ingress and transport, providing the critical microstructural basis for its superior chloride penetration resistance.

3.7. Elucidation of the synergistic protection mechanism

This study is the first to develop a ternary composite microbial system consisting of *Bacillus cohnii*, *Bacillus pasteurii*, and *Clavispora lusitanae* and apply it to anti-permeability microbial mineralized coatings for concrete. The experimental results confirmed that the composite microbial coating achieved outstanding chloride and water penetration resistance, and its protective performance was markedly superior to that of single strain coatings and conventional coating materials, which verified the prominent synergistic effect of this composite system. Figure 16 summarizes the multi-scale protection mechanism of the K + B + J composite coating. The synergistic function is realized through three pathways. K strain secretes EPS to promote biofilm formation.

B strain induces calcium carbonate mineralization for pore filling. The J strain produces low-hydrophilic metabolites and forms cross-linked structures to construct a dense surface layer. Collectively, these effects reduce concrete porosity and water absorption. Figure 17 further reveals the sequential mineralization and multi-stage chloride blocking mechanism. In the early stage, the high urease activity of the B strain accelerated CaCO_3 precipitation and capillary sealing.

In the later stages, EPS secreted by the K strain tightly bound mineralized CaCO_3 . This stable organic-inorganic complex sustains long-term microcrack self-healing and effectively blocks continuous chloride ingress into the concrete matrix.

4. Conclusion

This study, through a systematic investigation encompassing strain screening, coating preparation, multi-scale characterization, and molecular simulation, derives the following principal conclusions:

1. Three microbial strains were subjected to alkali domestication and co-culture. The results showed that under single-culture conditions, *Bacillus pasteurii* and *Bacillus cohnii* exhibited stronger alkali resistance than *Clavispora lusitaniae*. In binary co-culture systems, the optimal proportion ratios were determined to be 8:2 for *Bacillus pasteurii* and *Clavispora lusitaniae*, 3:7 for *Clavispora lusitaniae* and *Bacillus cohnii*, and 3:7 for *Bacillus pasteurii* and *Bacillus cohnii*. Meanwhile, the optimum mixing ratio of the ternary composite system of *Bacillus cohnii*, *Bacillus pasteurii* and *Clavispora lusitaniae* was 3:2:1.
2. The ternary microbial coating solution with an optimal ratio of 3:2:1 (K:B:J) was coated onto the concrete specimens. Consequently, a stable synergistic protection system was constructed. This system integrates three functional effects: EPS adhesion of the K strain, calcium carbonate mineralization and pore filling of the B strain, and low-hydrophilicity modification induced by the J strain. Multidimensional pore structure regulation was achieved through biological activation, mineral filling, and organic crosslinking. After the coating treatment, the surface open porosity decreased from 7.60% (control group) to 4.40%, with a reduction rate of 42%. The surface contact angle increased from 11.3 to 55.9°. Meanwhile, the capillary water absorption coefficient decreased to $1.004 \times 10^{-4} \text{ kg}/(\text{m}^2 \cdot \text{s}^{0.5})$.
3. The binary composite microbial coating was prepared using a bacterial suspension of *Bacillus pasteurii* (B) and *Bacillus cohnii* (K) at an optimal proportion ratio of 3:7. The chloride ion penetration depth of the coated concrete was as low as 2.243 mm, and its chloride migration coefficient reached $2.72 \times 10^{-10} \text{ m}^2/\text{s}$, which meets the concrete anti-permeation grade P-V. The binary composite coating exhibited excellent resistance to chloride ion erosion.
4. Microscopic characterization tests, including X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TG), and scanning electron microscopy (SEM), were performed. The results confirmed that the K + B binary composite microbial system formed a dense and stable mineralized structure, which effectively inhibited chloride ingress into the concrete matrix. This study only completed short-term performance verification under laboratory-standard conditions and did not conduct systematic long-term durability tests. There is a lack of support from performance attenuation laws in complex service environments, the long-term stability of microbial agents and mineralized structures, and on-site measurement data from engineering projects. Subsequent research will focus on in-depth studies of long-term durability system tests, full-cycle dynamic monitoring, engineering pilot tests and service life prediction.

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Author contributions

CRediT: Jinpeng Dai: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Validation, Writing – original draft; Yuhu Qi: Conceptualization, Investigation, Software, Supervision; Yan Wang: Writing – review & editing; Song Mu: Data curation, Formal analysis; Kai Yang: Investigation; Tong Liu: Investigation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Tables

Table 1. Microbial mineralized coating composition.

Composition	Microbial suspension	Distilled water	SA	PVA	Nano-Al ₂ O ₃	Glucose	Silane coupling agent
Dosage	100 mL	100 mL	4.0 g	4.0 g	4.0 g	1.0 g	4.0 g

Table 2. Cement composition (%).

Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	K ₂ O	Na ₂ O	TiO ₂
Content	63.50	21.10	4.64	4.68	2.67	1.12	1.09	0.58	0.41

Table 3. Comparison of capillary water absorption coefficients of concrete with different microbial mineralized coatings.

Group	C	K	B	J	K + B	K + J	B + J	K + B + J
Capillary water absorption coefficient ($\times 10^{-4}$ kg/(m ² ·s ^{0.5}))	1.839	1.638	1.464	1.163	1.418	1.061	1.500	1.004
Reduction rate relative to group C	—	10.9%	20.4%	36.8%	22.9%	42.3%	18.4%	45.4%

Table 4. Chloride penetration resistance grade of concrete with different microbial mineralized coatings classified by D_{RCM}.

Impermeability grade	P-I	P-II	P-III	P-IV	P-V
D _{RCM} ($\times 10^{-12}$ m ² /s)	>2000	1000–2000	500–1000	100–500	<100
Test group	—	—	C, J, K + J	B, K, B + J, K + B + J	K + B

Figures

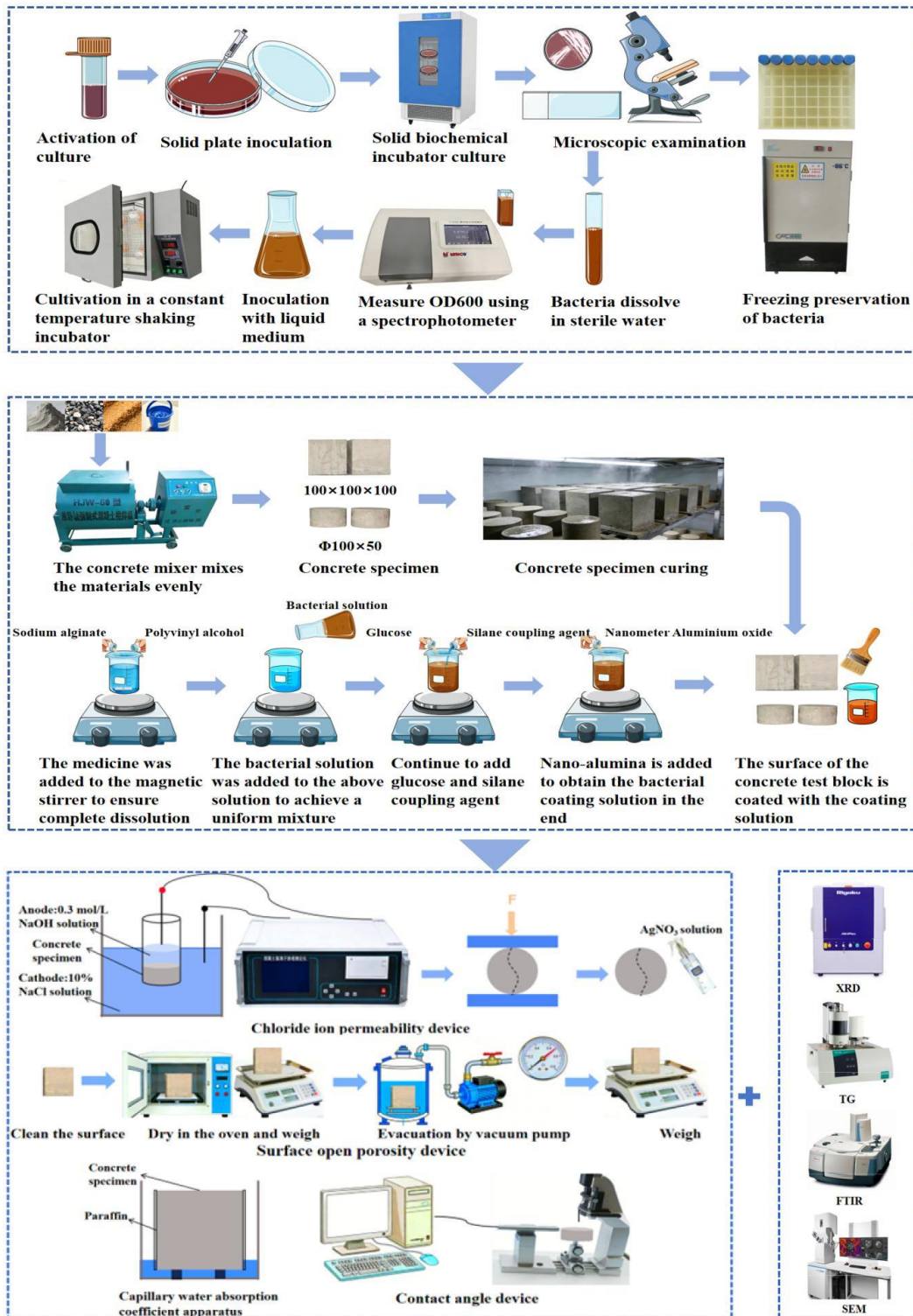
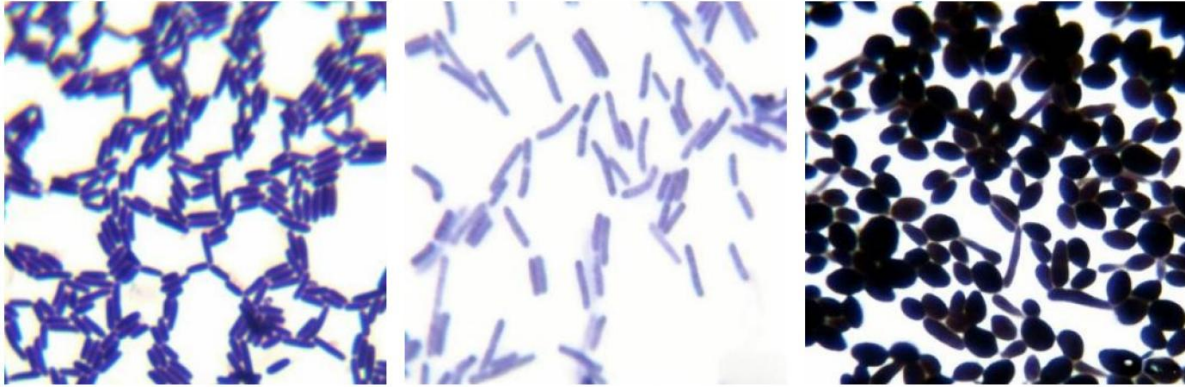


Figure 1. Schematic diagram of the experimental workflow.

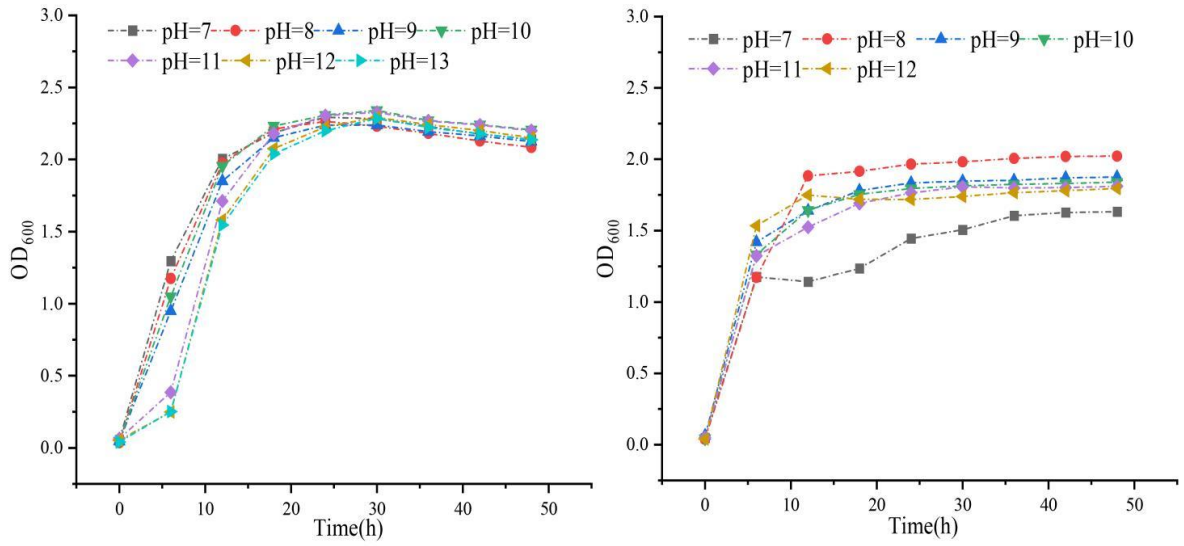


(a) *Bacillus pasteurii*

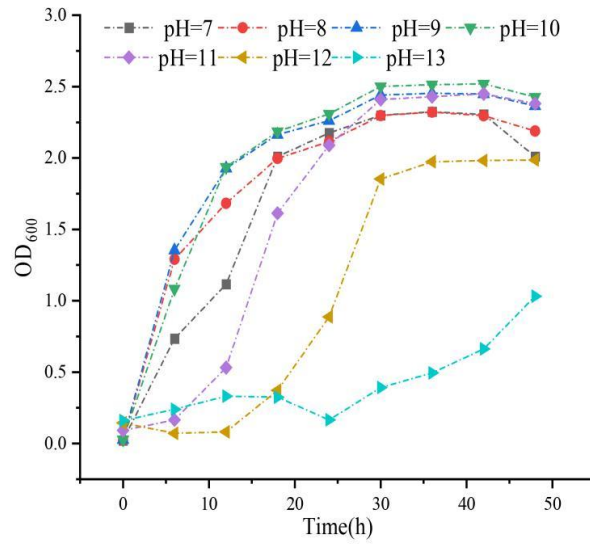
(b) *Bacillus cohnii*

(c) *Clavispora lusitaniae*

Figure 2. The morphology of the strain under the microscope.



(a) Alkaline tolerance domestication of K (b) Alkaline tolerance domestication of J



(c) Alkaline tolerance domestication of B

Figure 3. Alkaline tolerance growth curves of single microbial strains.

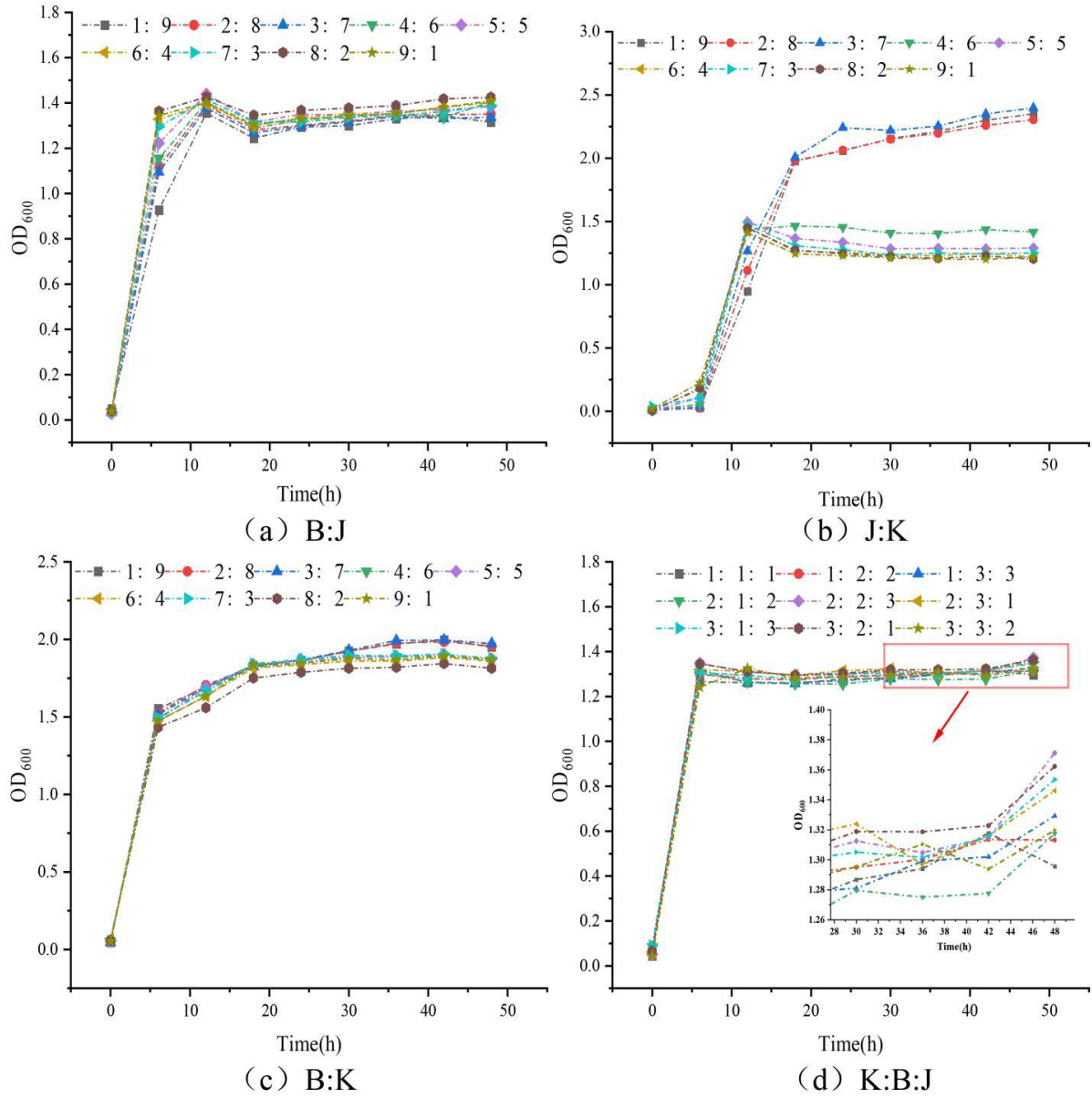


Figure 4. Growth curves of different strain combinations.

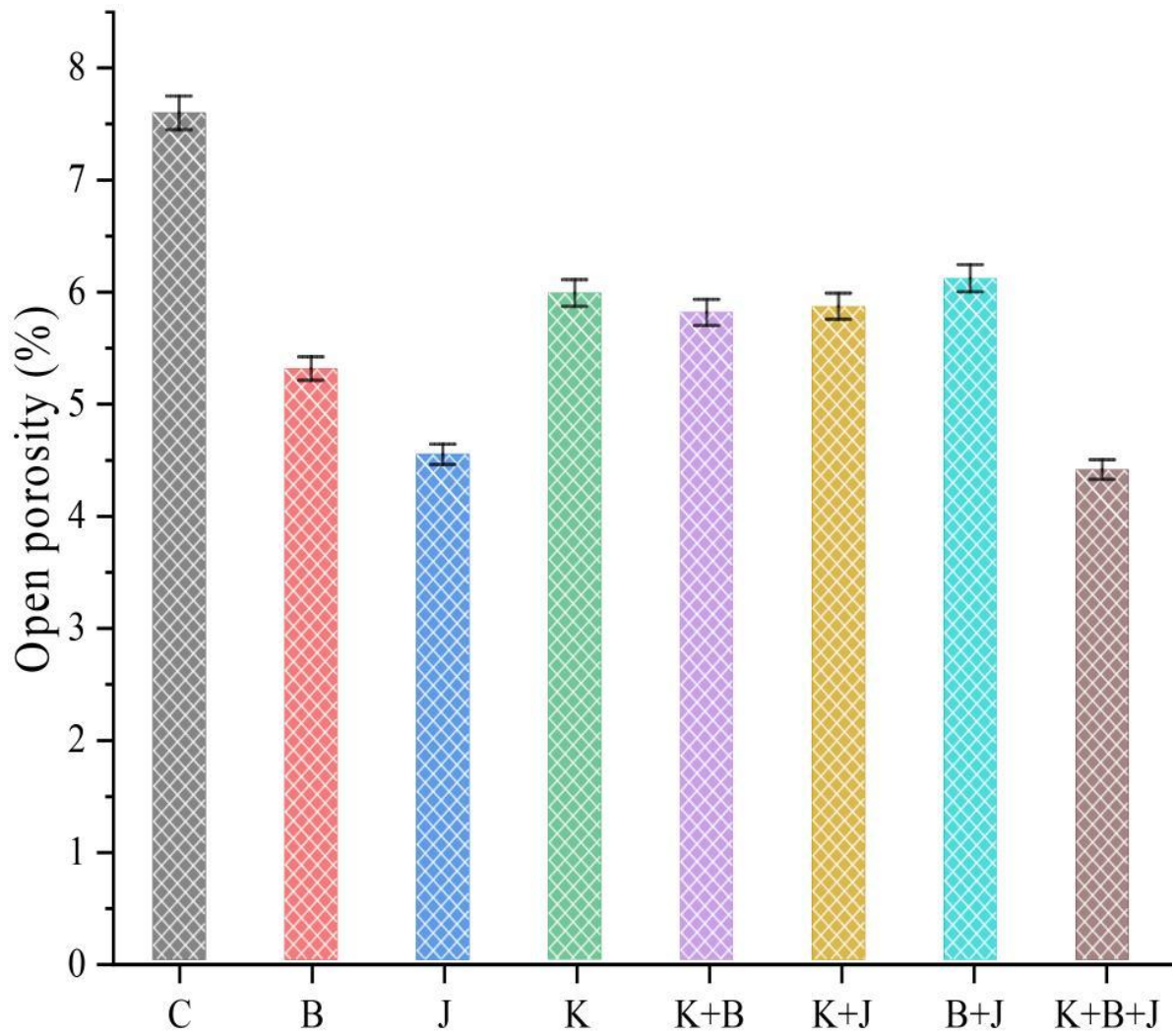


Figure 5. Surface open porosity of concrete with different microbial mineralized coatings.

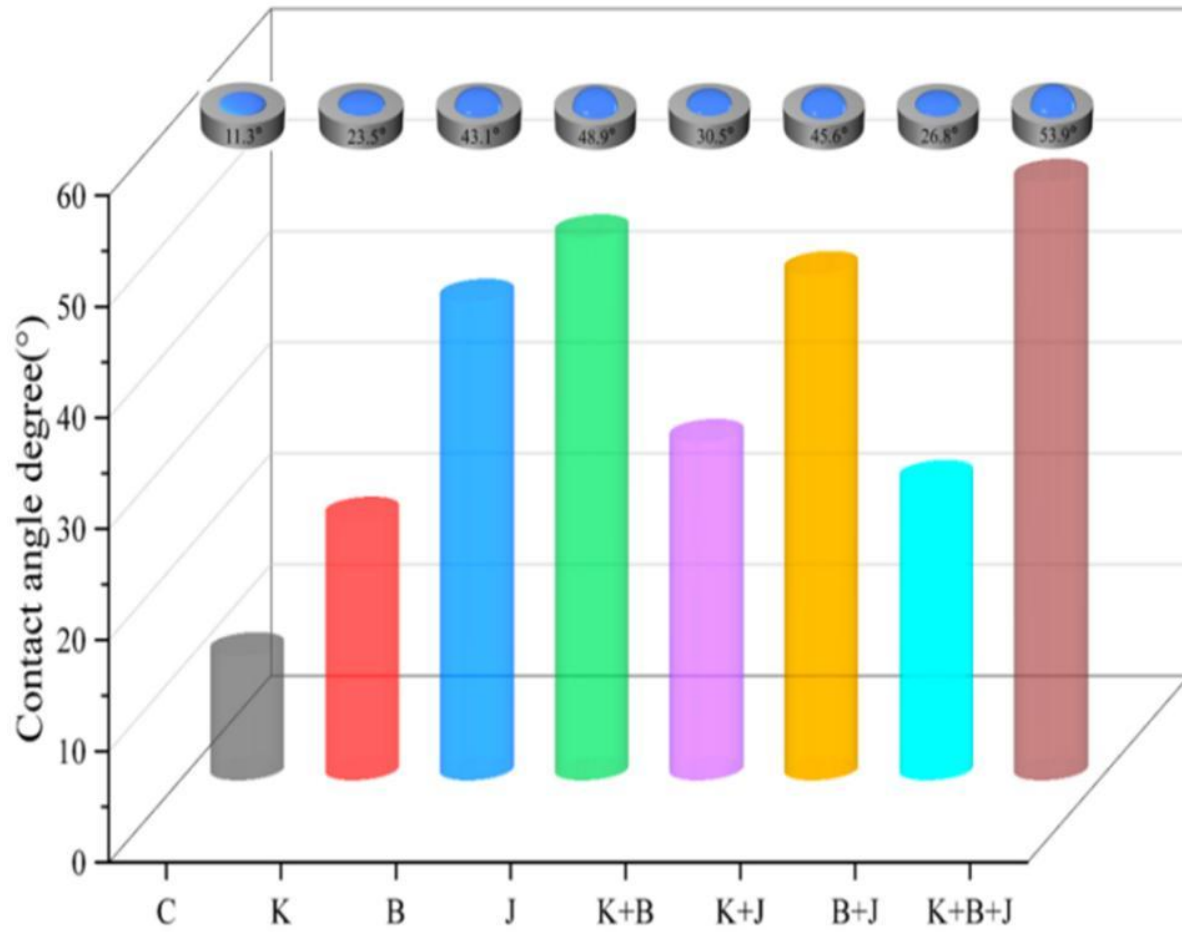


Figure 6. Surface contact angle of concrete with different microbial mineralized coatings.

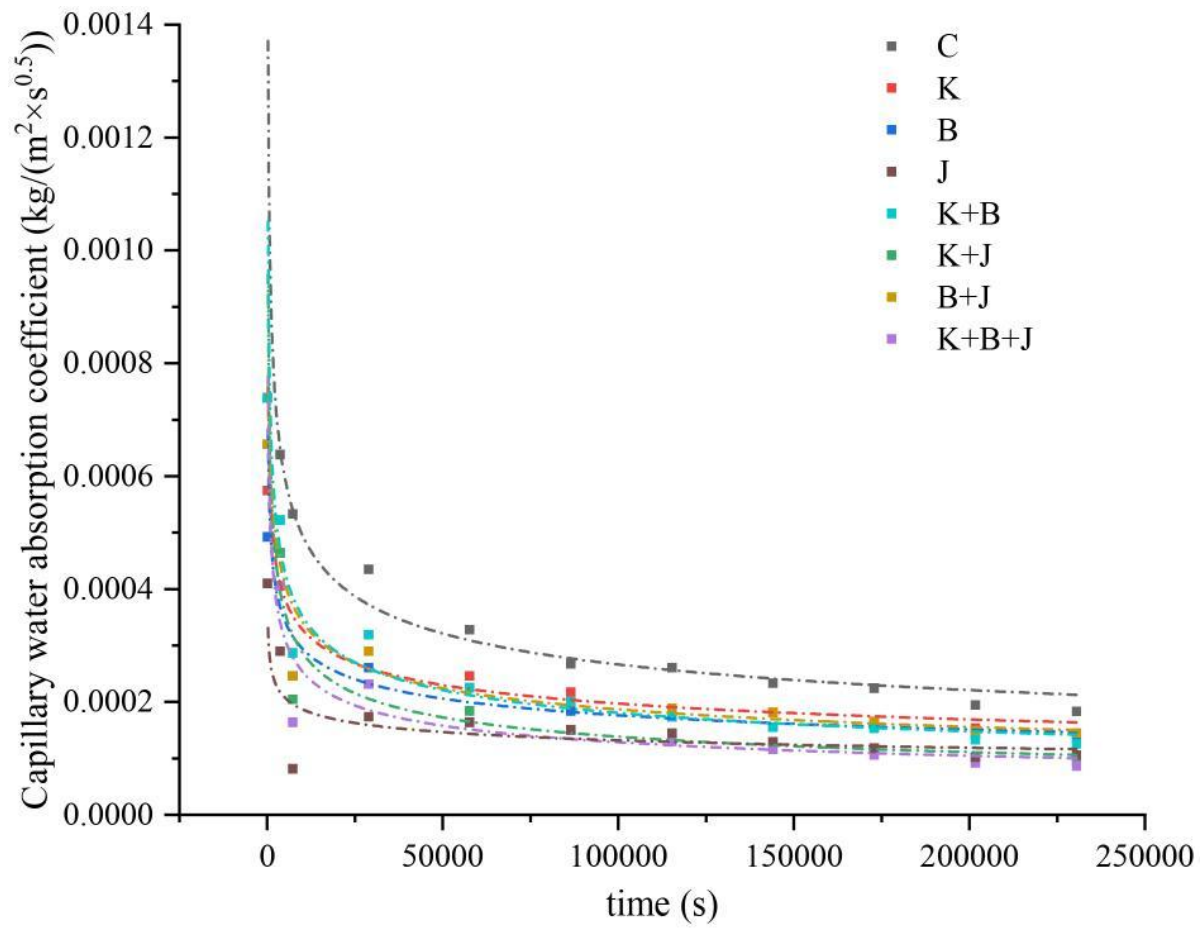


Figure 7. Capillary water absorption coefficient of concrete with different microbial mineralized coatings.

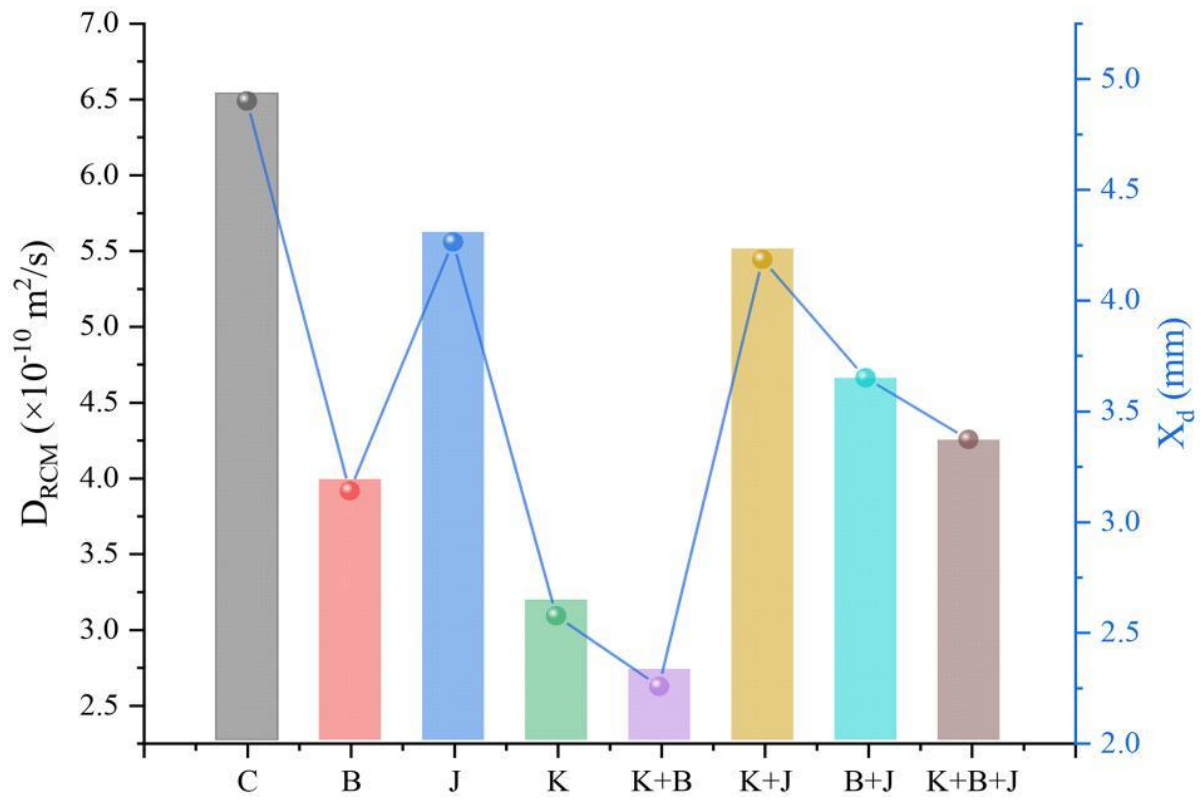


Figure 8. Chloride ion migration and penetration performance of concrete with different microbial mineralized coatings.

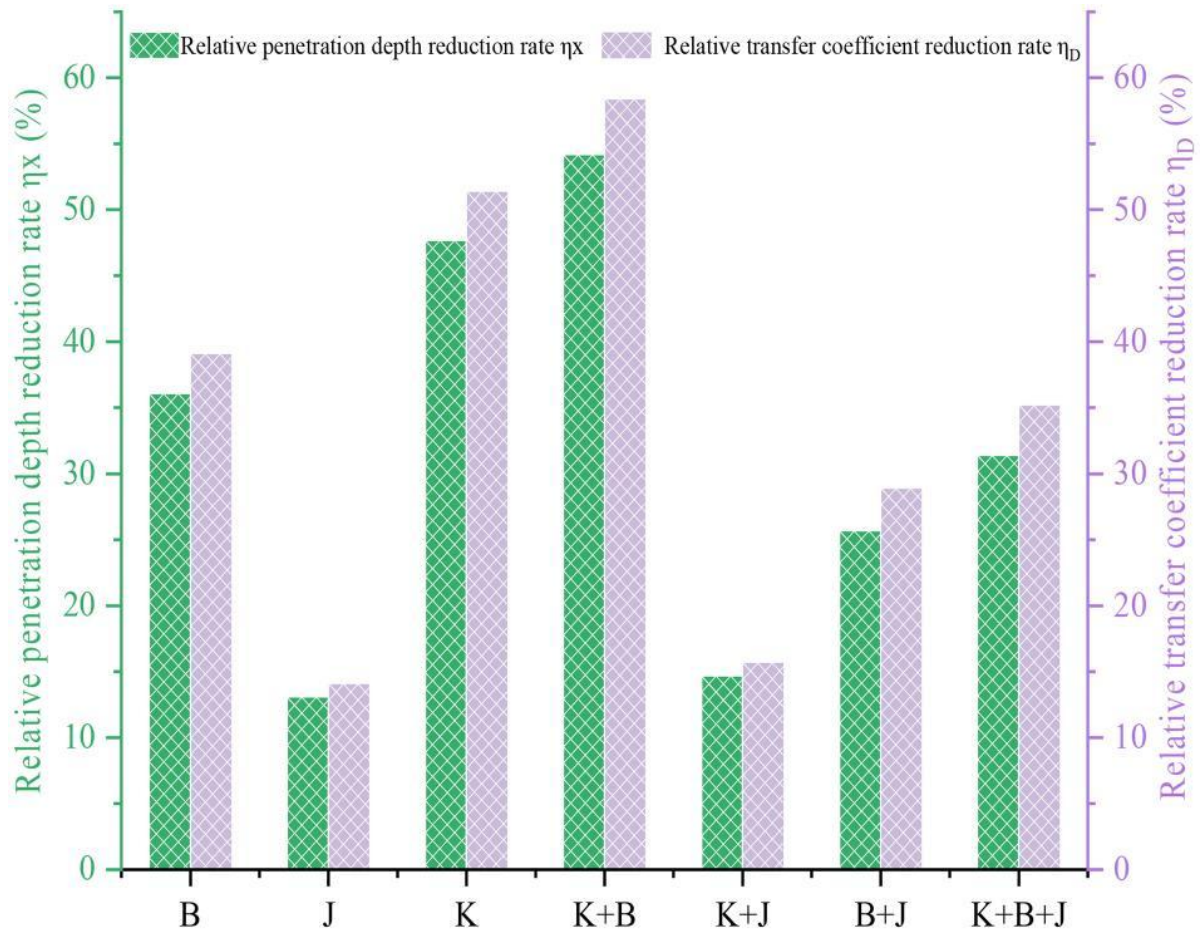


Figure 9. Relative reduction rates of chloride migration coefficient and penetration depth of concrete with different microbial mineralized coatings.

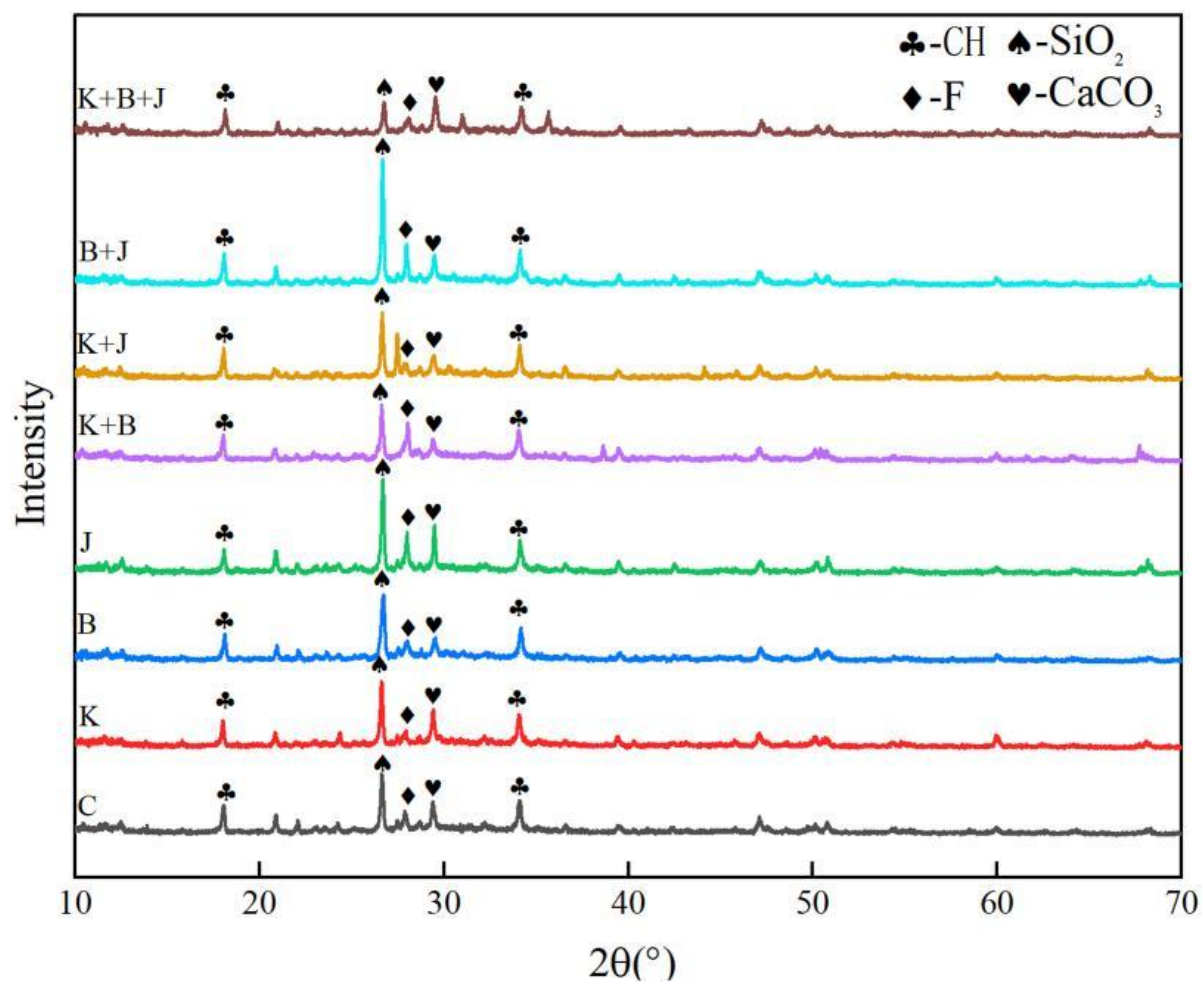


Figure 10. X-Ray diffraction (XRD) patterns of concrete with different microbial mineralized coatings.

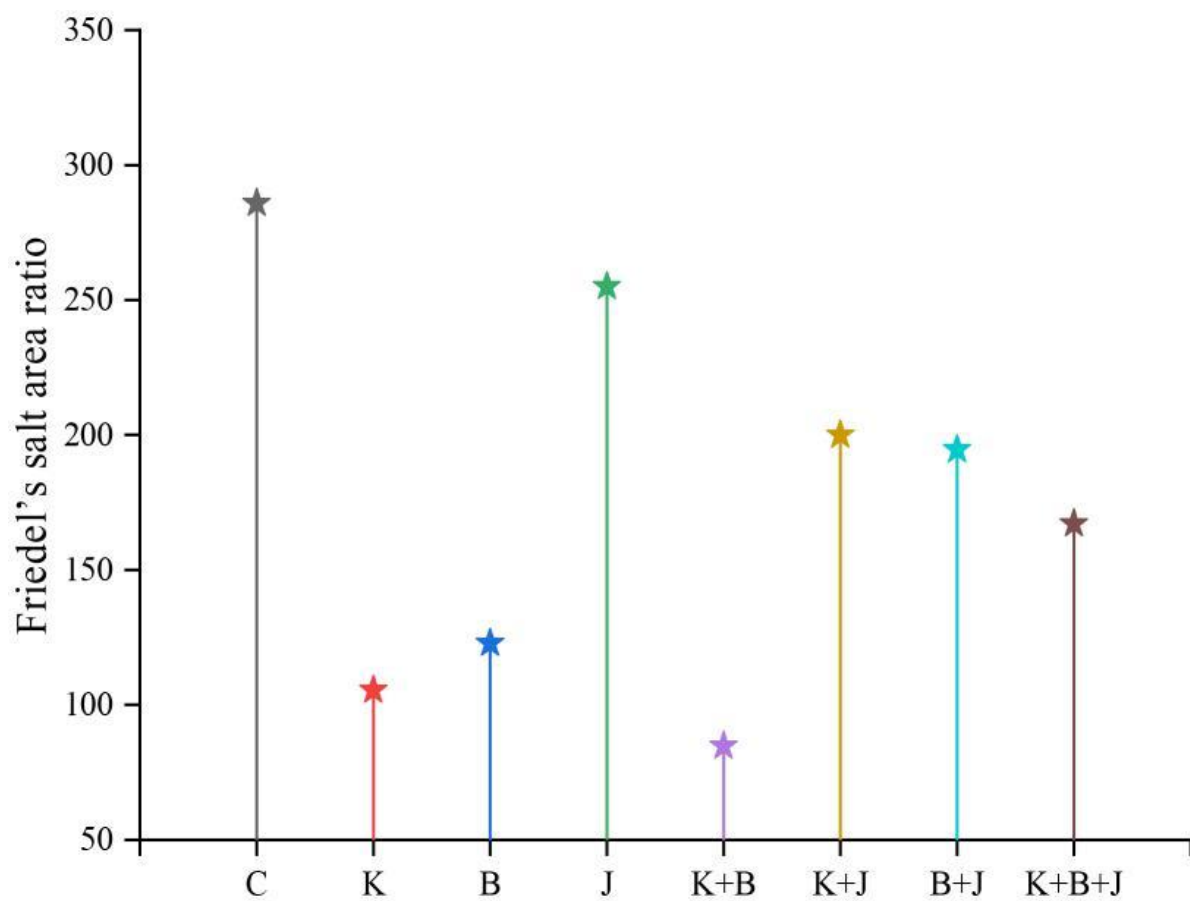


Figure 11. Peak area ratio of Friedel's salt (F) from XRD patterns of concrete with different microbial mineralized coatings.

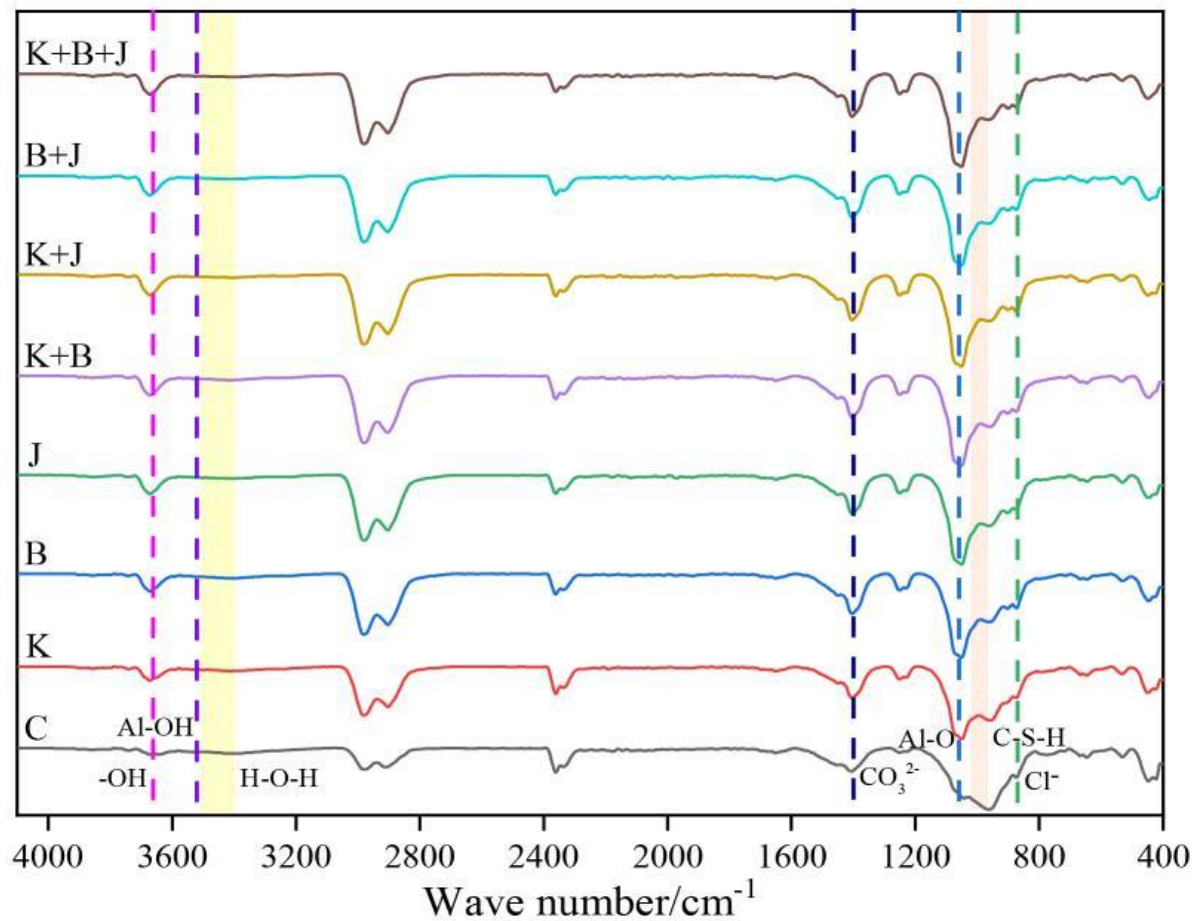


Figure 12. FTIR spectra of concrete with different microbial mineralized coatings.

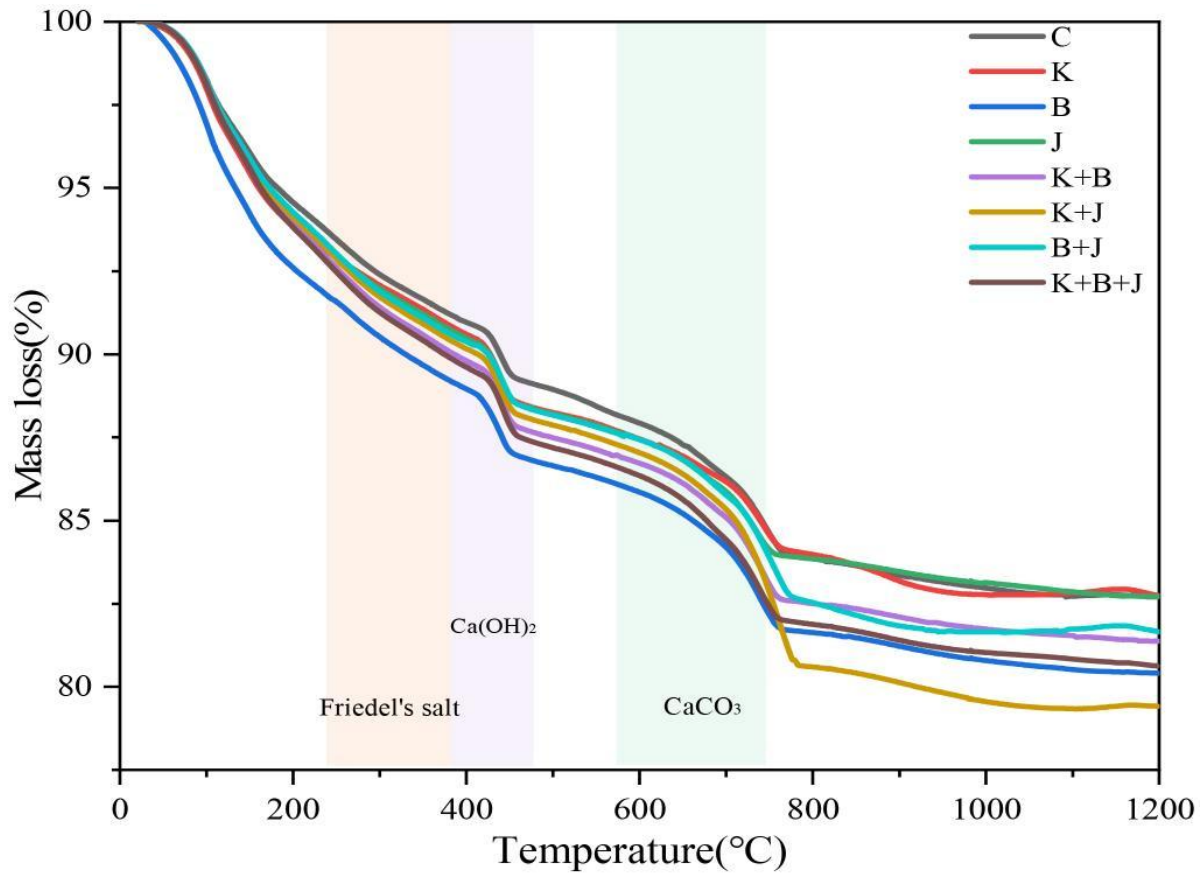


Figure 13. Thermogravimetric (TG) curves of concrete with different microbial mineralized coatings.

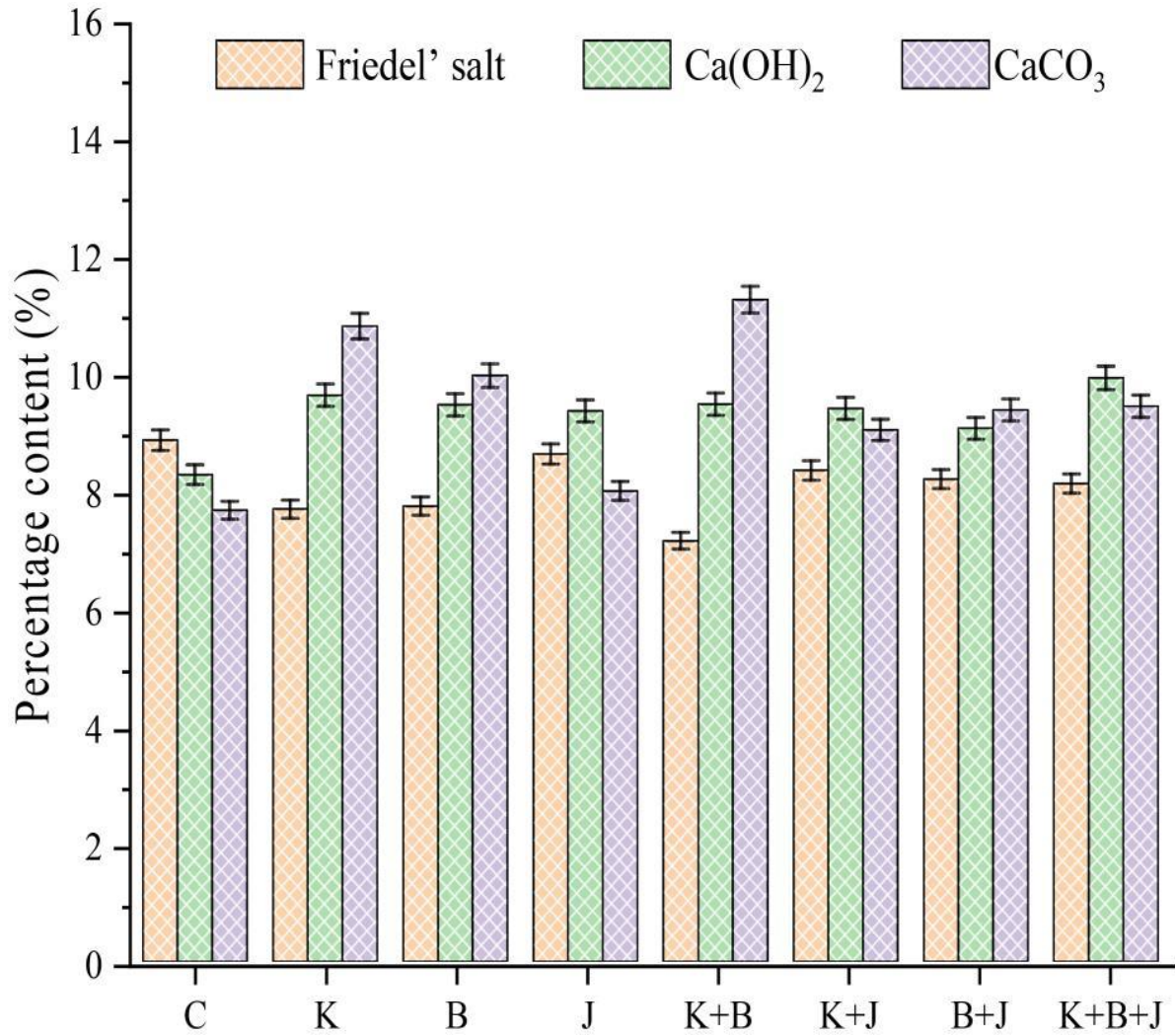


Figure 14. Contents of Friedel's salt, calcium hydroxide and calcium carbonate in concrete with different microbial mineralized coatings.

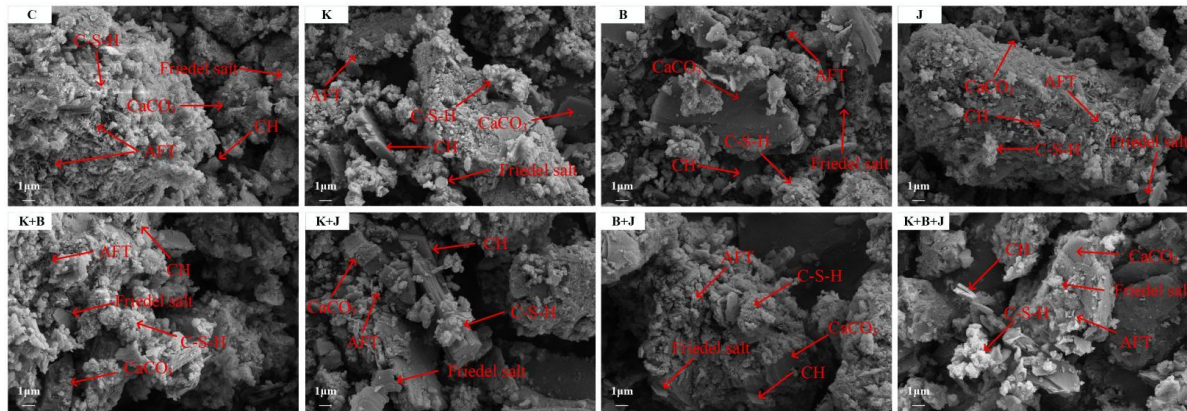


Figure 15. Scanning electron microscope (SEM) micromorphology of concrete with different microbial mineralized coatings.

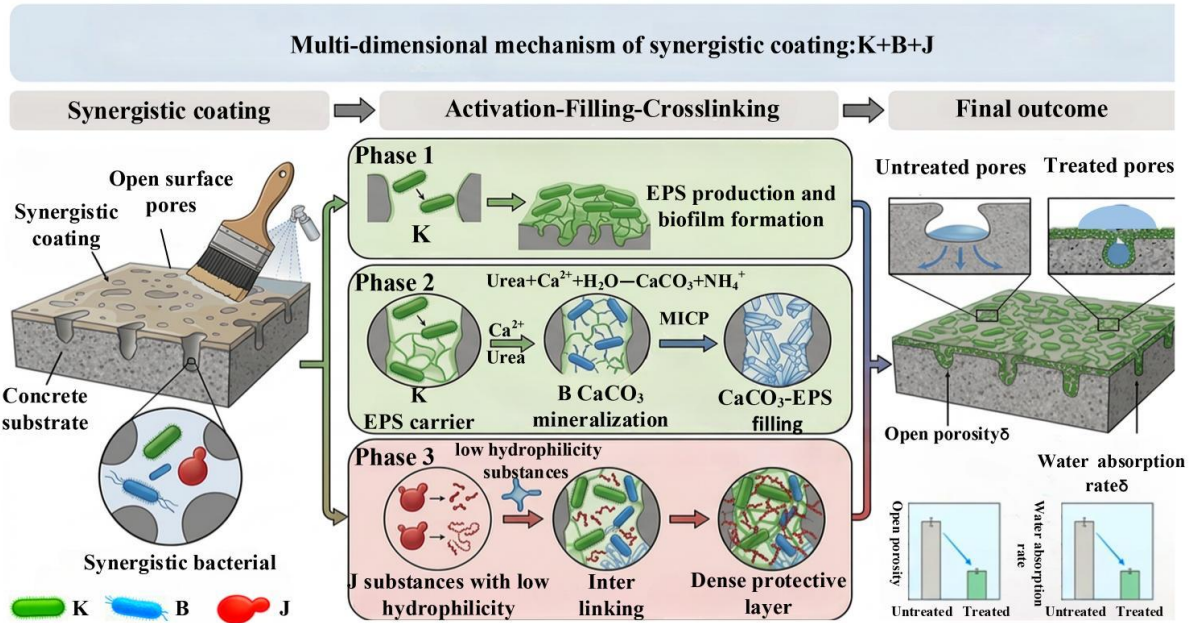


Figure 16. Mechanism diagram of water impermeability for K + B + J composite microbial mineralized coating.

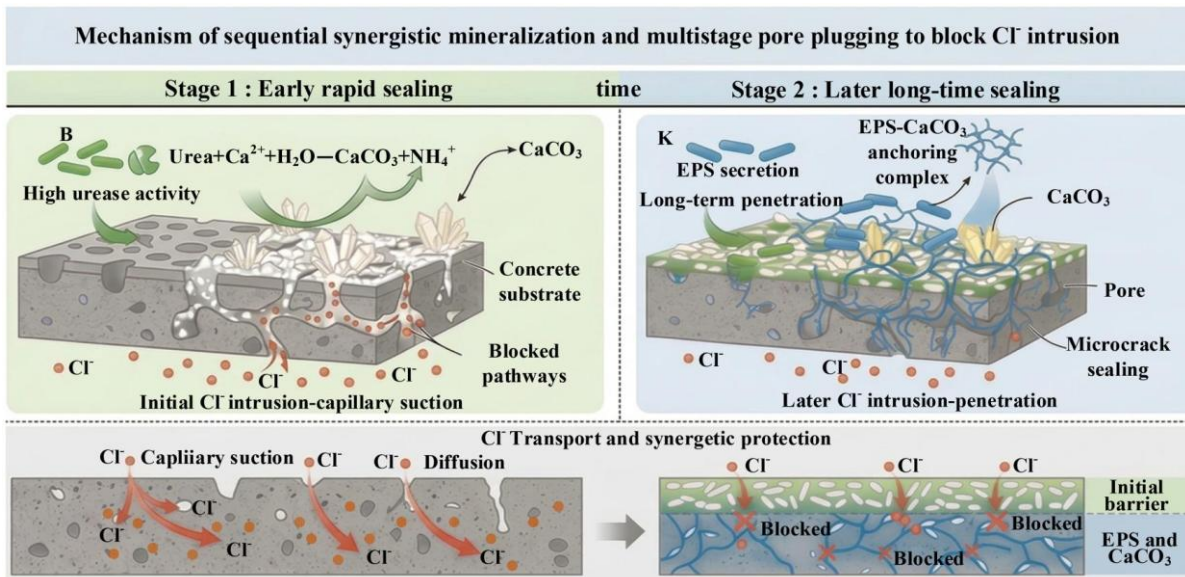


Figure 17. Mechanism diagram of chloride ion resistance of K + B composite microbial mineralized coating.