

Research Progress on Sodium Alginate-Assisted Microbially Induced Carbonate Precipitation for Concrete Crack Repair

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Abstract

Microbially induced carbonate precipitation (MICP) can seal concrete cracks through the formation of calcium carbonate by ureolytic microorganisms. Conventional immersion and low-viscosity grouting, however, are limited by bacterial washout, inefficient calcium utilization and erosion of mineral deposits under hydraulic flow. Sodium alginate (SA) improves MICP repair through viscosity enhancement, cell immobilization, Ca^{2+} adsorption and in situ formation of calcium alginate gels. This review summarizes the reaction mechanism, material systems, construction routes, concentration effects, crack-scale effects, hydraulic-head effects and durability of SA-assisted MICP for concrete crack repair. Surface coating, single-shot grouting, composite biogROUT and externally crosslinked hydrogel layers are compared. Reported evidence indicates that approximately 1.5% SA with an SA-solution/bacterial-suspension ratio near 7:3 is favorable for surface coating, whereas approximately 0.67% (w/v) SA balances sedimentation resistance and injectability for 0.2–0.5 mm cracks. Composite slurries containing bacteria, preformed CaCO_3 particles and SA provide enhanced permeability reduction and erosion resistance under hydraulic heads. The optimum SA content depends on crack aperture, solids content, injection equipment and hydraulic pressure. Future research should clarify the coupled SA-cell- CaCO_3 mechanism, long-term interfacial stability and field applicability in complex crack networks.

Keywords

Microbially Induced Carbonate Precipitation; Sodium Alginate; Calcium Alginate; Concrete Cracks; BiogROUTing

1. Introduction

Concrete has high compressive strength but limited tensile capacity and fracture resistance, making shrinkage, thermal and load-induced cracking unavoidable during service. Cracks provide preferential pathways for water, chloride, carbon dioxide and sulfate ingress, accelerating reinforcement corrosion, freeze-thaw damage,

dissolution and interfacial spalling. For tunnel linings, bridge members and hydraulic concrete, crack sealing directly affects durability and service safety.

Epoxy, polyurethane and cementitious grouts can restore crack integrity, but epoxy and polyurethane are affected by wet-surface curing, aging and environmental compatibility, while cementitious grouts have limited penetration into cracks narrower than 0.3 mm. MICP uses microbial metabolism to generate carbonate ions that react with Ca^{2+} and form CaCO_3 . The mineral is compatible with cement-based materials and offers a low-carbon route for crack repair.

Conventional MICP is mainly implemented by bacterial immersion or repeated grouting. Because bacterial suspensions have low viscosity, cells and calcium sources can migrate out of cracks, while early mineral deposits are vulnerable to seepage. SA is a natural anionic polysaccharide that forms calcium alginate (CaAlg) after Ca^{2+} crosslinking and can immobilize cells, nutrients and mineral products. SA-assisted MICP therefore links biomineralization, polymer gels and concrete crack repair.

2. Reaction and structural mechanisms

2.1. MICP carbonate formation

Ureolytic bacteria hydrolyze urea to ammonia and carbon dioxide. Ammonia forms NH_4^+ and OH^- in water, increasing local pH, while carbon dioxide is converted to bicarbonate and carbonate. In the presence of Ca^{2+} , supersaturation is reached and CaCO_3 precipitates. Cell surfaces, charged groups and extracellular polymers adsorb Ca^{2+} , lower the nucleation barrier and influence crystal morphology. The reaction is governed by bacterial activity, substrate concentration, temperature, pH, ionic strength and mass transfer.

Repair performance cannot be judged only from the mass of CaCO_3 produced. Carbonate must form a continuous and stable filling body at crack walls and pore throats. Oversized crystals may block the crack entrance and limit deep penetration, whereas very fine particles may be displaced by water flow. Spatial coordination among cell retention, calcium supply and carbonate generation is therefore central to crack repair.

2.2. SA crosslinking and synergy

SA consists of mannuronic and guluronic acid units. Na^+ associated with neighboring guluronic units can be replaced by Ca^{2+} to form a three-dimensional CaAlg gel. The gel contains substantial water and retains a degree of flexibility, allowing a continuous network to form inside cracks. SA increases residence time of cells and particles, while carboxyl groups enrich Ca^{2+} and facilitate carbonate nucleation at gel, cell and crack-wall interfaces.

The synergy between SA and MICP is not a simple additive effect. Low SA contents may be unable to resist flow and sedimentation, whereas excessive SA can encapsulate cells and restrict mass transfer. Ca^{2+} is consumed both by CaAlg

crosslinking and CaCO_3 precipitation. If crosslinking is too rapid, a gel plug may form at the crack mouth and prevent deep penetration. SA content, calcium concentration and addition sequence should therefore be optimized together.

At the pore scale, SA changes both viscous resistance and the location of solid deposition inside a crack. Uncrosslinked SA chains can form an adsorbed layer near the crack wall and slow local flow. After Ca^{2+} crosslinking, the gel network further decreases the effective pore size and provides continuous nucleation interfaces for CaCO_3 . This favors a graded structure in which the gel occupies the space first and mineral crystals reinforce it later, but premature sealing at the entrance remains possible. Repair should therefore be evaluated separately for entrance sealing, deep filling and interfacial bonding.

The highly alkaline pore solution of concrete may also alter SA conformation and crosslinking kinetics. Na^+ , K^+ , sulfate and chloride ions from cement hydration change ionic strength and can cause chain contraction, charge screening or local dehydration. These effects influence bacterial activity and CaCO_3 morphology. Future work should combine rheology, ion analysis and microscopy to establish causal links among solution chemistry, SA conformation, cell distribution and precipitate structure.

3. Representative studies and construction routes

Table 1. Representative studies of SA-assisted MICP crack repair

Route	Representative Studies	SA/Calcium-Source Process	Crack and Curing Conditions	Key Findings
Surface coating	Rong et al. (2022); Hu et al. (2023), M30 mortar, <i>B. sphaericus</i>	SA solution+bacteria+urea as A; calcium acetate as B; A followed by B and repeated after ~3 h	~0.2 mm surface cracks; two coating cycles	1.5% SA and an SA/bacteria ratio near 7:3 gave good overall performance; surface water absorption decreased by ~67%; CaAlg and CaCO_3 formed a compact composite
Single-shot grouting	Liu (2023), C40 concrete; Ai (2022), cement mortar	Bacterial sludge+SA+urea injected after sealing the crack bottom; calcium source supplied subsequently	Liu: 1.5 mm wide and 100 mm deep; Ai: 1.5 mm wide and 20 mm deep	Single injection sealed the cracks; Liu reported 100% seven-day water penetration resistance and 63.64% compressive-strength recovery; Ai reported flexural strength recovery from 3.5 to 4.2 MPa
Composite biogROUT	Zhang et al. (2026), seepage cracks in tunnel concrete	Bacteria+urease-active CaCO_3 particles+SA; 0.33%, 0.67% and 1.33% SA; cementation solution circulated after grouting	0.2–0.5 mm cracks; 0–2.0 bar hydraulic head	0.67% balanced stability and passage through a 0.3 mm needle; BE reduced permeability 4–6 times more than single-component biogROUTs; damage ratio decreased to 0–0.4 for high-concentration BE
External crosslinked layer	Snoeck et al. (2024), existing horizontal concrete	3% SA+5% $\text{Ca}(\text{NO}_3)_2$ (CaAlg3) or 5% SA+10% $\text{Ca}(\text{NO}_3)_2$ (CaAlg5); SA applied before calcium salt spray	300 μm cracks; 0.024 bar low pressure and 1–7 bar high pressure; chloride and freeze–thaw exposure	Low-pressure impermeability was restored; CaAlg reduced chloride ingress along crack faces and improved freeze–thaw resistance, but local extrusion and weak bonding occurred at high pressure
Mineralization mechanism	Yu et al. (2024), <i>B. pumilus</i> Z6 liquid mineralization and CaAlg tablets	0.001–0.005% SA; CaCl_2 and carbonate buffer; separate CaAlg tablet tests	30-day liquid mineralization; 15-day tablet mineralization	Ca^{2+} precipitation reached 80.7%, 82.6% and 87.9%; carboxyl groups enriched Ca^{2+} and promoted surface nucleation while retaining more vaterite

Table 1 shows that SA-assisted MICP has developed from surface coating to seepage-resistant grouting. Rong et al. and Hu et al. used coating to retain SA, bacterial suspension and urea on mortar surfaces before calcium acetate was supplied. Liu and Ai used single-shot grouting and emphasized retention of bacterial sludge and sand. Zhang et al. premixed bacteria, urease-active CaCO_3 particles and SA for composite grouting under hydraulic heads.

The routes should not be ranked by a single metric. Coating requires simple equipment and is suitable for exposed surface cracks, but its applicability to vertical surfaces and continuous seepage is limited. Single-shot grouting reduces the number of operations but is sensitive to crack connectivity and slurry viscosity. Composite biogROUT combines early particle filling with subsequent microbial mineralization and is promising for seepage-controlled repair.

From a construction-management perspective, surface coating suits visible cracks on components that can remain moist and are not immediately exposed to heavy traffic. Single-shot grouting is appropriate when a deep crack can be sealed at the entrance and pressurized injection is available. Composite biogROUT is attractive where seepage is persistent or rapid impermeability recovery is required. Each route also has different quality-control priorities: coating requires uniform thickness, grouting requires control of pressure, return flow and depth distribution, and composite grout requires simultaneous monitoring of particle settling, cell activity and cementation-solution circulation.

4. Governing factors

4.1. SA concentration, viscosity and sedimentation

Increasing SA concentration generally improves viscosity, film formation and sedimentation resistance. In systems containing 1.0%, 1.5% and 2.0% SA, the 1.5% formulation provided a favorable balance among film formation, water absorption and crack coverage. In Liu's study, increasing SA solution concentration from 0 to 1.0 g/L increased initial viscosity from approximately 9 to 1434 mPa·s. Sand-column strength was highest at an intermediate concentration, whereas gel shrinkage at high concentration generated internal voids.

In composite biogROUT, 0.33% SA showed pronounced settling, with the solid volume fraction below 10% after 20 h. At 0.67%, the fraction exceeded 90% and the grout passed through a 0.3 mm needle. At 1.33%, stability approached 99%, but a larger injection aperture was required. SA content should therefore be matched to crack aperture and particle size rather than maximized.

4.2. SA-to-bacteria ratio and microbial activity

The SA-solution/bacterial-suspension ratio controls carrier continuity, cell concentration and substrate transport. Excessive SA can encapsulate cells and limit urea and Ca^{2+} transfer, while excessive bacterial suspension produces a thin film

with low viscosity and poor retention. A ratio near 7:3 is a useful starting point for surface coating, whereas high-solids grouts require recalculation based on final solids content.

Cell concentration alone does not describe mineralization capacity. Different strains can show different urea-hydrolysis rates at the same OD600, and cells entering alkaline concrete cracks are affected by Ca^{2+} , salts, temperature and wet-dry exposure. OD600, pH, urease activity, Ca^{2+} consumption rate and precipitate mass should be recorded together to separate microbial activity from SA immobilization.

4.3. Calcium source, crosslinking sequence and crack interface

Rapid SA- Ca^{2+} crosslinking can provide early sealing but may also block the crack entrance. External crosslinking experiments showed that applying SA first and spraying $\text{Ca}(\text{NO}_3)_2$ afterward produced a more uniform CaAlg layer, whereas the reverse sequence produced a loose layer. For internal crack repair, the SA-bacteria mixture should enter the crack before calcium is supplied in stages, allowing CaAlg and CaCO_3 to form throughout the target zone.

Calcium-source selection also affects bacterial activity and product composition. Calcium acetate supplies Ca^{2+} without excessive inorganic by-products, calcium nitrate is suitable for external spraying, and urea-calcium cementation solutions can be circulated after injection. Time-dependent Ca^{2+} measurements are needed to distinguish consumption by CaAlg crosslinking, CaCO_3 precipitation and residual pore solution.

4.4. Crack aperture, seepage and hydraulic erosion

Crack aperture determines available flow space and resistance. For 0.2–0.5 mm microcracks, low viscosity and small particles are required; cracks around 1.5 mm can tolerate higher SA contents or fine CaCO_3 particles to increase volume filling and compressive resistance. Crack length, depth, roughness and connectivity also influence cell retention and the distribution of mineral deposits.

Under static or low-head water, CaAlg swelling and CaCO_3 deposition can reduce permeability. Under high hydraulic heads, pressure gradients drive gels and loose particles downstream. Zhang et al. reported that BE containing bacteria, preformed CaCO_3 and SA showed greater permeability reduction and lower damage ratios than single-component biogrouts. Preformed particles provide early filling, newly formed CaCO_3 cements the particles, and the SA network improves structural integrity.

4.5. Mineral phase, nucleation and durability

Yu et al. found that SA did not change the basic carbonate phases induced by *B. pumilus* Z6, which mainly comprised vaterite and calcite. SA carboxyl groups adsorbed Ca^{2+} and provided nucleation sites; Ca^{2+} precipitation reached 80.7%, 82.6% and 87.9% as SA concentration increased. In SA-containing media, carboxyl

groups favored the persistence of vaterite, while nanoscale carbonate and amorphous calcium carbonate formed on CaAlg tablets.

Long-term CaAlg performance depends on water content, ionic environment and interfacial bonding. Snoeck et al. showed that external CaAlg layers restored low-pressure impermeability and reduced chloride ingress along crack faces. After salt and freeze–thaw exposure, the gel still improved crack-zone resistance, but local extrusion and interfacial failure occurred at high pressure. Durability programs should therefore include low- and high-pressure permeability, chloride ingress, freeze–thaw, wet–dry cycles and repeated loading.

Long-term service also involves possible biodegradation of SA and dissolution or transformation of carbonate. Microbial metabolism, temperature and humidity changes, and degradation of organic matter may cause gradual dehydration or void formation in the gel network. Acid rain, carbonation and sulfate exposure can additionally alter CaCO_3 stability. Mass loss, dynamic permeability, interfacial fracture energy and mineral-phase changes should be measured together, preferably with micro-CT or three-dimensional scanning to follow internal continuity rather than relying only on surface photographs.

5. Research parameters and evaluation framework

For better comparability, studies should report strain, culture conditions, SA stock concentration, final mixed concentration, SA-to-bacteria ratio, slurry viscosity, crack aperture and hydraulic conditions. Table 2 provides a parameter framework, Table 3 lists control and synergy groups, and Table 4 summarizes multiscale evaluation from constructability to product mechanism.

5.1. Constructability and injection control

Constructability should cover mixing, storage, transport and crack entry. In addition to apparent viscosity, shear thinning, thixotropic recovery, usable time and pumping pressure should be recorded. For slurries containing preformed CaCO_3 particles, particle-size distribution, solids content and long-term settling curves are required. Injection should use staged pressure: low pressure first to remove air, followed by gradual pressurization to reduce gel channeling and interfacial peeling.

5.2. Mineralization efficiency and interface structure

Mineralization should be evaluated by sampling the liquid, gel and solid phases separately. Mass balances of Ca^{2+} , urea and ammonium can estimate the fraction of calcium converted into CaCO_3 . Micro-CT, SEM and EDS can then determine whether precipitates continuously cover the crack wall. CaAlg enrichment with little CaCO_3 indicates excessively rapid crosslinking, whereas crystals concentrated near the crack mouth indicate insufficient transport or penetration depth.

5.3. Durability and statistical design

Durability tests should include distinct damage and recovery stages and compare property retention during cyclic exposure. At least three parallel specimens per formulation are recommended, with differences reported using analysis of variance or confidence intervals. For skewed permeability data, medians and interquartile ranges should accompany means. Statistical design prevents accidental local plugging in a single specimen from being interpreted as a general synergy effect.

Table 2. Parameter-recording framework for SA-assisted MICP tests

Item	Suggested Setting	Design Note
Bacterial strain	<i>B. sphaericus</i> , <i>S. pasteurii</i> or <i>B. pumilus</i>	Report strain source, culture time, OD600 and urease activity
SA concentration	Surface coating: 1.0%, 1.5%, 2.0%; grouting: 0.33%, 0.67%, 1.00% (w/v)	Report both stock and final mixed concentrations
SA/bacteria ratio	8:2, 7:3 and 6:4 by volume	Suitable for coating-type A; recalculate for high-solids slurries
Calcium source	0.6–2.0 mol/L calcium acetate; optional $\text{Ca}(\text{NO}_3)_2$ crosslinking control	Separate CaAlg crosslinking consumption from CaCO_3 precipitation
Crack parameters	0.2–0.5 mm microcracks; add 1.5 mm cracks if needed	Record aperture, length, depth, connectivity and volume
Environmental conditions	Static water, cyclic hydraulic head, chloride, freeze–thaw and wet–dry exposure	Record temperature, pH, ionic strength and hydraulic-head history

Table 3. Control and synergy groups for SA-assisted MICP

Code	Composition	Purpose
C0	Unrepaired crack	Establish permeability, strength and durability baseline
C1	No bacteria+SA+calcium source	Separate physical CaAlg sealing
C2	Bacteria+calcium source without SA	Evaluate conventional MICP mineralization and washout
C3	Bacteria+SA+calcium source	Core synergy group with multiple SA concentrations
C4	Bacteria+preformed CaCO_3 +SA+cementation solution	Composite slurry group for seepage and high-pressure conditions
C5	SA crosslinked with Ca^{2+} before bacterial addition	Evaluate reverse sequencing on deep injectability and interfacial bonding

Table 4. Multiscale evaluation framework for SA-assisted MICP

Level	Indicators/methods	Interpretation
Constructability	Viscosity, usable time, sedimentation, needle passage and injection pressure	Match SA-induced rheology with equipment and crack scale
Mineralization efficiency	Ca^{2+} consumption, CaCO_3 content, urea hydrolysis rate and pH evolution	Separate SA crosslinking, microbial mineralization and abiotic precipitation
Crack sealing	Crack closure, surface absorption, low- and high-pressure permeability	Report both absolute and normalized values
Mechanical recovery	Compressive/flexural recovery, splitting strength and bond strength	Avoid judging repair only from surface appearance
Durability	Wet–dry cycles, freeze–thaw, chloride ingress and cyclic hydraulic erosion	Include unrepaired and MICP-without-SA controls
Product mechanism	XRD, FTIR, TGA/DSC, SEM-EDS and, if needed, XPS or isotopes	Identify CaCO_3 phase, CaAlg thermal-decomposition range and interface structure

Permeability testing should include both low- and high-pressure modes. Low-pressure tests can quantify initial sealing through water flow or permeability coefficient, while high-pressure tests evaluate the stability of gels, particles and mineral products under pressure gradients. Crack width, length and effective flow area should be used for normalization. Surface absorption is useful for exposed surfaces but cannot replace internal crack-permeability testing.

Mechanical tests should be selected according to crack geometry and repair route. For through-cracks, compressive-strength recovery reflects global load capacity; for surface cracks, flexural and splitting tests better represent crack bridging. XRD identifies calcite and vaterite, FTIR and TGA characterize organic gel and carbonate coexistence, and SEM-EDS reveals connections among the CaAlg network, CaCO₃ particles and crack walls.

Uncertainty and repeatability should also be reported. Each formulation should include parallel specimens with mean values, standard deviations and failure modes. Permeability tests should state flow direction, pressure difference, steady-state criterion and normalization method. Strength-recovery ratios must identify whether the reference is an unrepaired specimen, an intact specimen of the same age or the initially cracked specimen. Consistent reporting is necessary to compare the contributions of strain, SA concentration and curing regime.

6. Conclusions and Research Needs

SA improves MICP crack repair through viscosity enhancement, cell immobilization, Ca²⁺ adsorption, nucleation control and CaAlg-network formation. Initial screening may use 1.5% SA and an SA-solution/bacterial-suspension ratio near 7:3 for surface coating, and approximately 0.67% (w/v) SA for 0.2–0.5 mm grouting cracks. These parameters must be recalibrated for the selected strain, calcium source, crack geometry and injection device.

The CaAlg–CaCO₃ gel–crystal composite is the main advantage of SA-assisted MICP, while hydrophilicity, drying shrinkage, ion screening and high-pressure interfacial failure remain limitations. Future studies should clarify the effects of SA on urease activity, extracellular polymer secretion, CaCO₃ phase transformation and calcium cycling; establish quantitative links among concentration, rheology, injectability, mineralization, interface and durability; and validate the method in complex crack networks, cyclic hydraulic heads, freeze–thaw, chloride exposure, repeated loading and field-scale repair.

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