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REVIEW ARTICLE

SERVICE PERFORMANCE OF CRACK REPAIR IN CONCRETE TRANSPORTATION AND CIVIL INFRASTRUCTURE UNDER SEVERE CONTINENTAL CLIMATES: A CRITICAL REVIEW

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Abstract. *Concrete crack repair in transport and civil infrastructure is governed by defect cause, moisture, movement, installation conditions and retained interface function, not by product strength alone. Severe continental service adds cold application, saturation, freeze–thaw, deicing salts, thermal movement, abrasion and traffic loading. This targeted critical evidence review considered 60 sources published in 2000-2026: 51 peer-reviewed papers and nine standards, agency reports or official sources. The corpus comprised a 45-source core and 15 DOI-verified records added through a focused regional, coupled-exposure and 2026 update. Evidence was coded by repair function, application variables, outcome, validation scale and direct or supporting role; incompatible tests were not pooled. Stable structural cracks may justify low-viscosity rigid injection, whereas water-bearing or moving cracks require leakage- or movement-oriented systems. Within individual studies, gravity-filled epoxy reduced the compressive-strength deficit to 8.23%; low-viscosity epoxy produced a 25% greater slant-shear response than a high-viscosity comparator; and low-temperature epoxy pre-curing increased wet bond by up to 34.3% while reducing cured-resin shrinkage by 12.0%. Direct coupled abrasion-freeze-thaw and bond-deterioration studies confirm that initial strength cannot represent retained interface performance. A threshold-based selection framework is proposed, but it remains an author-developed framework requiring prospective validation. Regional field comparisons, long-duration conditioned interfaces and monitored pilot repairs remain priority gaps.*

Keywords: *crack diagnosis; injection viscosity; repair-substrate interface; freeze-thaw; deicing salts; bridge-deck preservation; performance-based selection.*

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ШОЛУ МАҚАЛА

КҮРТ КОНТИНЕНТТІК КЛИМАТ ЖАҒДАЙЫНДА КӨЛІК ЖӘНЕ АЗАМАТТЫҚ ИНФРАҚҰРЫЛЫМ НЫСАНДАРЫНЫҢ БЕТОН КОНСТРУКЦИЯЛАРЫНДАҒЫ ЖАРЫҚТАРДЫ ЖӨНДЕУДІҢ ПАЙДАЛАНУ ТИІМДІЛІГІ: СЫНИ ШОЛУ

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Аңдатпа. *Көлік және азаматтық инфрақұрылымдағы бетон жарықтарын жөндеу өнімнің беріктігімен ғана емес, ақаудың себебі, ылғал, қозғалыс, орындау жағдайлары және түйісу функциясының сақталуымен анықталады. Қатаң континенттік орта суықта орындау, қанығу, мұздату–еріту, тұздар, температуралық қозғалыс, қажалу және көлік жүктемесін біріктіреді. 2000-2026 жылдардағы 60 дереккөзге (51 рецензияланған жұмыс және 9 стандарт, ресми немесе ведомстволық құжат) мақсатты сыни талдау жүргізілді. 45 дереккөзден тұратын бастапқы корпус өңірлік, кешенді әсер және 2026 жылғы 15 DOI-тексерілген жазбамен толықтырылды. Тұрақты құрылымдық жарықтар үшін тұтқырлығы төмен қатты инъекция негізді болуы мүмкін, ал суланған немесе қозғалатын жарықтар су ағынын және қозғалысты бақылауға бағытталған жүйелерді қажет етеді. Жекелеген зерттеулерде эпоксид беріктік тапшылығын 8,23%-ға дейін азайтты; тұтқырлығы төмен эпоксид көлбеу ығысу нәтижесін 25%-ға арттырды; төмен температурада алдын ала қатайту ылғалды адгезияны 34,3%-ға дейін арттырып, шайыр шөгуін 12,0%-ға төмендетті. Шекті көрсеткіштерге негізделген таңдау жүйесі ұсынылды, бірақ ол болашақта тексерілуі тиіс авторлық тұжырымдама болып табылады. Өңірлік далалық салыстырулар мен ұзақ мерзімді түйісу сынақтары негізгі олқылық болып қалады.*

Түйінді сөздер: *жарық диагностикасы; инъекциялық тұтқырлық; жөндеу-негіз түйісуі; мұздату–еріту; көктайғаққа қарсы тұздар; көпір төсемдері; пайдалану көрсеткіштері бойынша таңдау.*

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ОБЗОРНАЯ СТАТЬЯ

ЭКСПЛУАТАЦИОННАЯ ЭФФЕКТИВНОСТЬ РЕМОНТА ТРЕЩИН В БЕТОННЫХ КОНСТРУКЦИЯХ ТРАНСПОРТНОЙ И ГРАЖДАНСКОЙ ИНФРАСТРУКТУРЫ В УСЛОВИЯХ РЕЗКО КОНТИНЕНТАЛЬНОГО КЛИМАТА: КРИТИЧЕСКИЙ ОБЗОР

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Аннотация. *Ремонт трещин в бетонной транспортной и гражданской инфраструктуре определяется не только прочностью продукта, но и причиной дефекта, влажностью, перемещениями, условиями нанесения и сохранением функции контактной зоны. Резко континентальная эксплуатация сочетает холодное нанесение, насыщение, замораживание-оттаивание, противогололёдные соли, температурные перемещения, истирание и транспортные нагрузки. Выполнен целевой критический анализ 60 источников 2000-2026 гг.: 51 рецензируемой работы и девяти стандартов, ведомственных или официальных документов. Исходный корпус из 45 источников дополнен 15 DOI-проверенными записями регионального, комплексно-экспозиционного и временного поиска. Для стабильных конструктивных трещин может быть обоснована низковязкая жёсткая инъекция, тогда как водонесущие или подвижные трещины требуют систем, ориентированных на герметичность или восприятие перемещений. В отдельных исследованиях эпоксидное заполнение уменьшило дефицит прочности до 8,23%; низковязкий эпоксид дал на 25% большую прочность при косом срезе; низкотемпературное предварительное отверждение повысило влажную адгезию до 34,3% и снизило усадку смолы на 12,0%. Предложена пороговая система выбора, однако она является авторской концепцией и требует перспективной валидации. Приоритетными пробелами остаются региональные полевые сравнения, длительные испытания кондиционированной контактной зоны и мониторинг пилотных ремонтов.*

Ключевые слова: *диагностика трещин; инъекционная вязкость; контактная зона ремонта; замораживание-оттаивание; противогололёдные соли; мостовые плиты; выбор по эксплуатационным показателям.*

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1 INTRODUCTION

Crack repair is a decision problem before it is a materials problem. A visible discontinuity may be the stabilized residue of plastic or drying shrinkage, a leakage path driven by hydrostatic pressure, a flexural crack that opens under traffic, a thermal joint behaving as an unintended hinge, or a symptom of corrosion, settlement or alkali-aggregate reaction. Treating these conditions with the same product merely because their surface widths appear similar risks sealing a symptom while leaving the damage mechanism active. Repair guidance therefore requires the cause, activity, structural significance and exposure of a crack to be established before an intervention is selected [1, 2, 3]. For concrete transport infrastructure, diagnosis must also account for reopening time, traffic vibration, skid and abrasion demands, access constraints and the consequences of failure at the repair-substrate interface.

The problem is intensified in severe continental climates. Repaired bridge decks, pavements, tunnel portals, culverts and hydraulic structures may pass from sub-zero saturation to warm, dry conditions within short periods. Water in incompletely filled cracks freezes; deicing solutions enter the same pathways and sustain corrosion; daily and seasonal thermal strains repeatedly load a repair whose coefficient of thermal expansion and stiffness differ from those of the substrate. Kazakhstan's climatic data and durability provisions treat cold-period parameters, repeated freezing and thawing, water impermeability and aggressive exposure as location- and asset-specific design variables [4, 5, 6]. Consequently, acceptance limits must be derived for the project location and structure rather than transferred from a dry room-temperature test.

Existing reviews address adjacent but incomplete questions. Bridge-deck sealer syntheses emphasize products and agency practice [7]; broader crack-repair reviews catalogue techniques [8]; interface reviews focus on substrate-overlay bond [9]; coating reviews concentrate on protective layers [10]; and freeze-thaw reviews synthesize deterioration of hydraulic concrete rather than repaired cracks [11]. None integrates defect diagnosis, installation limits, method-specific verification and retained repair–substrate function under severe continental exposure. The present review therefore narrows its claim to a targeted, performance-based synthesis for crack-repair selection; it does not attempt an exhaustive inventory of all repair materials or climates.

Three gaps follow. First, catalogues often conflate stopping water with restoring force transfer. Second, single-property rankings overlook constructability: nominal strength is irrelevant if viscosity, pressure loss, moisture or cold cure prevents filling. Third, bulk freeze-thaw or regional concrete performance is sometimes transferred directly to a repaired interface, although only an interface- or component-level test can verify retained repair function. The additional 2026 literature strengthens regional and coupled-exposure context but does not remove this boundary [10, 12, 13, 14, 15, 16]. Table 1 distinguishes the present contribution from adjacent reviews.

Table 1 – Comparison with adjacent review literature and specific contribution of the present review [developed by the author]

Review	Primary focus	Repair interface	Severe continental exposure	Selection framework	Unresolved boundary
Ni et al. [7]	Bridge-deck crack sealers and agency practice	Partial	Partial	Product/practice synthesis	No integrated diagnostic-to-retained-function framework
Zhao et al. [8]	Crack-repair technologies	Broad, mostly descriptive	Limited	Technology catalogue	Climate transfer and test incompatibility not central
Manawadu et al. [9]	Substrate–overlay bond	Central	Limited	Bond-characterization focus	Not centered on crack injection or leakage control
Ariyadasa et al. [10]	Protective coatings	Coating/substrate	Durability context	Coating selection context	Not a crack-repair synthesis

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Zhu et al. [11]	Freeze–thaw degradation of hydraulic concrete	No repair-interface focus	Central	Damage-model review	Bulk deterioration cannot validate repaired cracks
Present review	Diagnosis, installation and retained crack-repair function	Central and method-specific	Operationally classified	Threshold-based, author-proposed	Targeted rather than exhaustive; framework requires validation

The review addresses four questions: (i) which crack and exposure variables govern the defensible selection of injection, gravity filling, routing-and-sealing, grouting and surface-treatment methods; (ii) which quantitative evidence supports mechanical restoration, water control and retained interface performance; (iii) how severe continental exposure changes the admissibility of candidate methods; and (iv) what minimum experimental and field evidence is required before a technology can be recommended for a transport or civil-infrastructure asset. The central proposition is conditional: no technology is intrinsically superior; the preferred option is the one that retains the required function for a defined crack state, substrate condition, installation window and exposure.

2 MATERIALS AND METHODS

2.1 Review scope and operational definition

This study used a targeted critical evidence-review design and does not claim exhaustive or systematic-review coverage. ‘Severe continental climate’ was operationalized for evidence coding rather than treated as a universal climatic class. Evidence was direct climate-repair evidence when a repaired interface or repaired component was exposed to freeze-thaw and at least one relevant co-stressor (salt or saturation, abrasion, mechanical cycling, or a defined thermal range). Bulk concrete tested under comparable cold or plateau conditions was coded as supporting evidence; climate descriptions, standards and reviews were contextual evidence. This rule limits transfer from bulk material performance to repaired-interface performance.

2.2 Identification and focused update

The 45-source core was identified through publisher platforms, Crossref metadata, open repositories, FHWA, ACI, J-STAGE, ASCE Library, ScienceDirect and backward/forward citation chaining. Scopus and Web of Science were considered as indexing contexts but were not independently queried through a reproducible database export; the manuscript therefore does not state that those databases were systematically searched. Searches used title, abstract and keyword fields where available. Representative strings were: (‘concrete crack repair’ OR ‘crack injection’) AND (epoxy OR polyurethane OR methacrylate OR ‘cementitious grout’) AND (bond OR interface OR leakage OR freeze-thaw OR chloride OR fatigue); ‘concrete repair interface’ AND (freeze-thaw OR abrasion OR chloride); and (Kazakhstan OR ‘Central Asia’ OR ‘continental climate’) AND (‘concrete repair’ OR freeze-thaw OR ‘transport infrastructure’). The main search was completed on 5 September 2026; a focused update on 28 September 2026 added 15 DOI-verified records addressing Kazakhstan/comparable regions, coupled exposure and 2026 publications [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

2.3 Eligibility, extraction and synthesis

Inclusion required a direct connection to post-cracking intervention in concrete or a verification method needed to select that intervention. Direct repair evidence, supporting bulk-material evidence, numerical or mechanistic studies, focused reviews, standards and agency guidance were kept analytically separate. The retained set contains 60 sources: 51 peer-reviewed papers and nine standards, agency reports or official sources. The earlier working log did not preserve reliable counts for initially identified, duplicate or title/abstract-excluded records; these quantities were not reconstructed. Online Supplementary Information reports the 60 retained sources, their evidence role,

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climate/asset relevance and confidence class. Outcomes from incompatible bond, permeability, fatigue or freeze–thaw methods were not pooled.

2.4 Evidence-confidence rule

High confidence required a direct repair-interface or repaired-component test, a relevant comparator, sufficiently described conditioning, a method-specific quantitative outcome and interpretable failure or replication information. Moderate confidence was assigned when repair evidence was direct but one or more of those elements were incomplete. Supporting evidence included bulk materials, numerical models, reviews, standards, agency reports and regional studies without a repaired interface. Coding was performed by one author; ambiguous cases were conservatively downgraded. No independent duplicate screening or inter-rater agreement assessment was available, and the confidence labels should therefore be interpreted as transparent analytical judgments rather than validated risk-of-bias scores.

2.5 Methodological limitations

The evidence base is heterogeneous in crack geometry, product chemistry, moisture, cure, exposure sequence and test configuration. It supports method-specific comparison and within-study quantitative signals, but not a pooled population estimate or universal product ranking. The targeted update improves regional and temporal coverage without converting the review into a systematic search. Author-developed decision diagrams are identified as conceptual proposals and are not presented as experimentally validated standards. Figure 1 summarizes the workflow, and Table 2 states the coding safeguards.

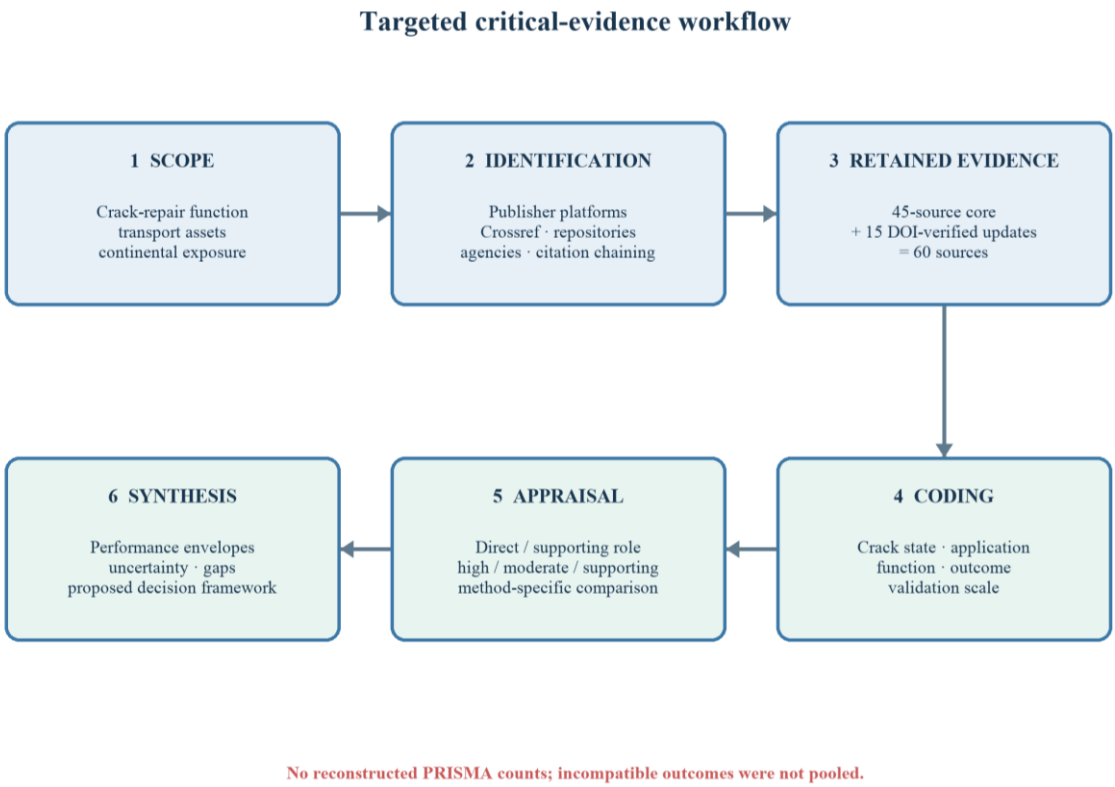

Figure 1 – Targeted evidence-identification, coding and synthesis workflow. The corpus contains a 45-source core and 15 DOI-verified focused additions (60 sources total). Earlier identification and exclusion counts were not reconstructed because they were not preserved. Author-developed workflow; not a PRISMA flow diagram.

Table 2 – Evidence coding framework and analytical safeguards [developed by the author]

Domain	Extraction question	Primary evidence	Safeguard
Crack state	Cause, width/depth, activity, moisture, structural role	Inspection record; controlled crack specimen	Width alone is not treated as a sufficient selector.

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Domain	Extraction question	Primary evidence	Safeguard
Application	Viscosity, pressure, access, temperature, surface preparation, reopening	Injection/filling observation; field QA	Nominal product data are separated from achieved filling.
Function	Continuity, leakage control, ingress reduction, movement accommodation	Load, bond, permeability or movement test	Different functions are not ranked on one strength scale.
Exposure	Freeze–thaw, salt, thermal cycling, wet–dry, fatigue, abrasion	Conditioned repair/interface test	Bulk-material durability is not substituted for retained interface function.
Scale	Coupon, member, pilot, field	Laboratory and field evidence	Laboratory suitability is not described as field validation.
Confidence	Comparator, replication, method clarity, duration	Full method and traceable result	No pooling across incompatible methods or proprietary products.

3 RESULTS AND DISCUSSION

3.1 Failure-oriented diagnosis: selecting the repair function

A repair decision should begin by assigning two independent labels: the cause of cracking and the required intervention function. Cause determines whether treatment is admissible; function determines the technology family. Cracks driven by ongoing corrosion, reactive aggregate, settlement or continuing overload cannot be made durable by filling alone. The source mechanism must be mitigated or accommodated. Stable cracks created by a completed shrinkage event may be structurally rebonded. Active thermal or traffic-induced cracks require a deformable, replaceable sealing detail unless movement can be arrested. Leaking cracks require water-pressure and wet-adhesion verification even when no structural reconnection is intended [1, 2, 3, 25, 26].

This distinction resolves a common semantic error. Epoxy injection is a structural bonding technique when it reconnects crack faces and restores stiffness; a gravity-fed methacrylate is principally a penetrant and ingress barrier; hydrophilic polyurethane is primarily a water-control material; and a routed elastomeric seal deliberately sacrifices rigid continuity to accommodate movement. A surface coating may reduce liquid uptake without filling a through-depth crack. Each can be successful against its own performance target and unsuccessful against another. Figure 2 converts these relationships into a diagnosis-to-intervention sequence, while Table 2 links each diagnostic variable to the required verification.

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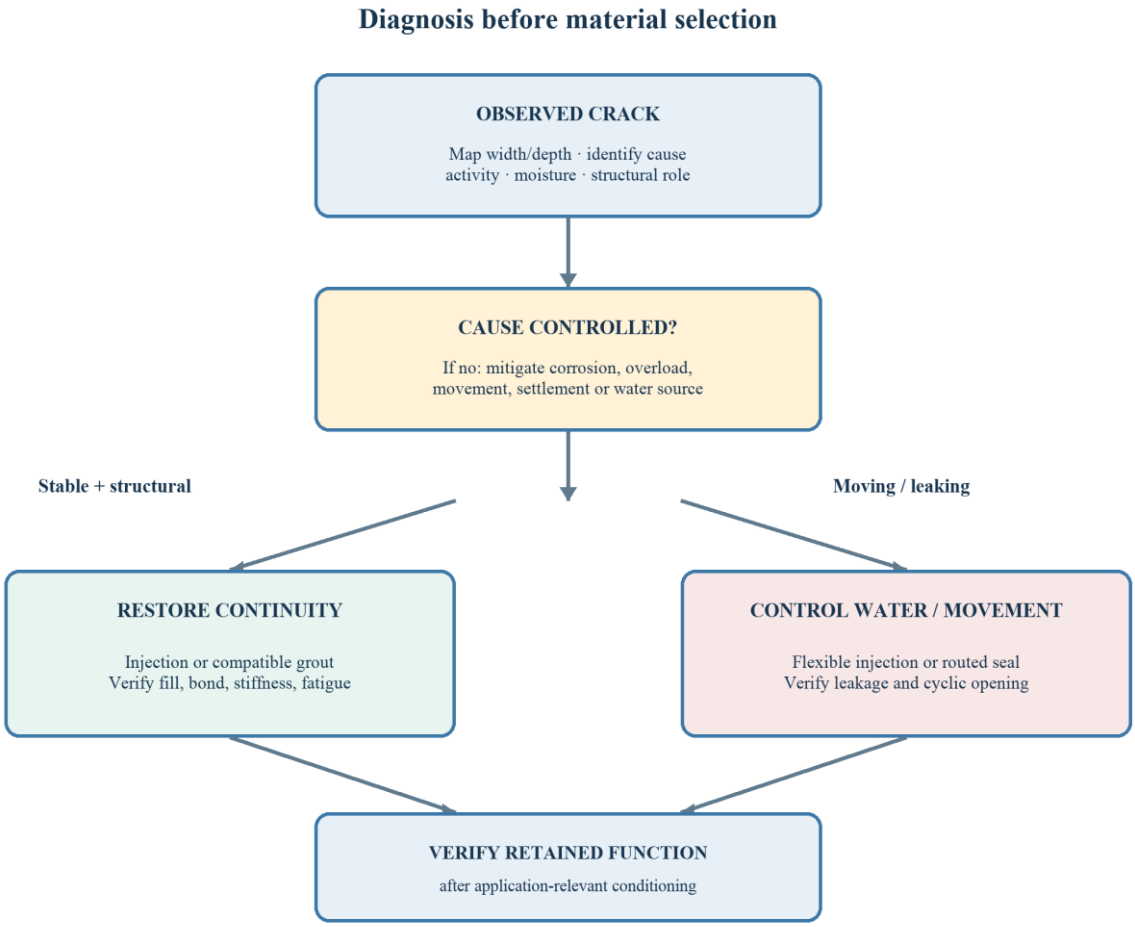

Figure 2 – Diagnosis-to-intervention decision tree.

3.2 Technology classes and functional envelopes

Pressure injection is the most direct route to structural reconnection when a stable crack is accessible and can be sealed for controlled delivery. Epoxy chemistry offers high adhesive and cohesive strength, but the outcome depends on viscosity, pot life, cure temperature and moisture tolerance. Injection pressure must overcome line losses and capillary resistance without extending the crack or rupturing the surface seal. Controlled experiments show that areal injection velocity varies with the square of crack width, pressure and inverse viscosity, while surface roughness and equipment pressure loss introduce additional effects [27]. Visualized specimens confirm that apparent surface closure does not demonstrate complete internal filling [28]. Comparative material tests and EN 1504-5 provide complementary evidence on product behavior and injection requirements [29, 30].

Gravity filling with low-viscosity epoxy, HMWM or MMA avoids pressure equipment and is attractive for horizontal deck cracks. HMWM and MMA are considered separately at product-qualification level because their formulation, reactivity, volatility, modulus and curing controls are not interchangeable. Their shared application advantage is low-viscosity penetration into stable, open surface networks where sealing or partial rebonding is required. Neither low viscosity nor chemical family alone establishes structural restoration: achieved penetration, cure and retained bond must be verified under the field moisture and temperature window [7, 31, 32, 33].

Polyurethane and acrylic injection systems occupy a different functional region. Water-reactive polyurethane can expand and block active leakage, while flexible gels tolerate some movement. Two tank models exposed to water pressures up to 3 bar over three days showed that polyurethane injection substantially stopped leakage where waterproofing alone was insufficient [26]. This demonstrates water-control capability, not structural load recovery. Artificial-crack movement testing across fifteen commercial materials also found large differences within nominal cement, acrylic, epoxy, urethane

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and synthetic-rubber groups; several flexible products retained movement response, but leakage resistance could be lost after local debonding or material displacement [25]. Generic chemical family is therefore an inadequate specification.

Cementitious and microfine grouts are potentially compatible with mineral substrates, noncombustible and economical for accessible voids or wider cracks. Their limitations are particle filtration, bleeding, washout, shrinkage and reduced ability to follow movement. Cement grout and epoxy injection restored comparable cracking-load gains in one full-scale slab comparison, yet the same result does not establish equal penetration, fatigue resistance or water tightness [34]. Polyurethane grouting developed for ballastless railway mud pumping demonstrates how wet/dry bond, expansion and application geometry must be optimized together [35], but subgrade-bed performance should be treated as supporting evidence for concrete crack repair rather than direct equivalence.

Surface impregnation and coatings are preservation treatments, not universal crack repairs. They can reduce absorption and chloride ingress around fine surface cracking, while through-cracks may remain hydraulically connected. Laboratory comparison of acrylic, polyurethane, epoxy, epoxy–polyurethane and polymer–cement systems showed that adhesion, water barrier, vapor transmission and crack-bridging behavior differ in ways not captured by compressive strength [36]. For bridge decks, crack chasing or gravity-fed resin and surface treatment may be combined, but entrapped chloride, skid resistance and future overlay bond must be considered [7, 31, 37]. Figure 3 summarizes the functional taxonomy; Table 3 compares the corresponding performance envelopes and limitations.

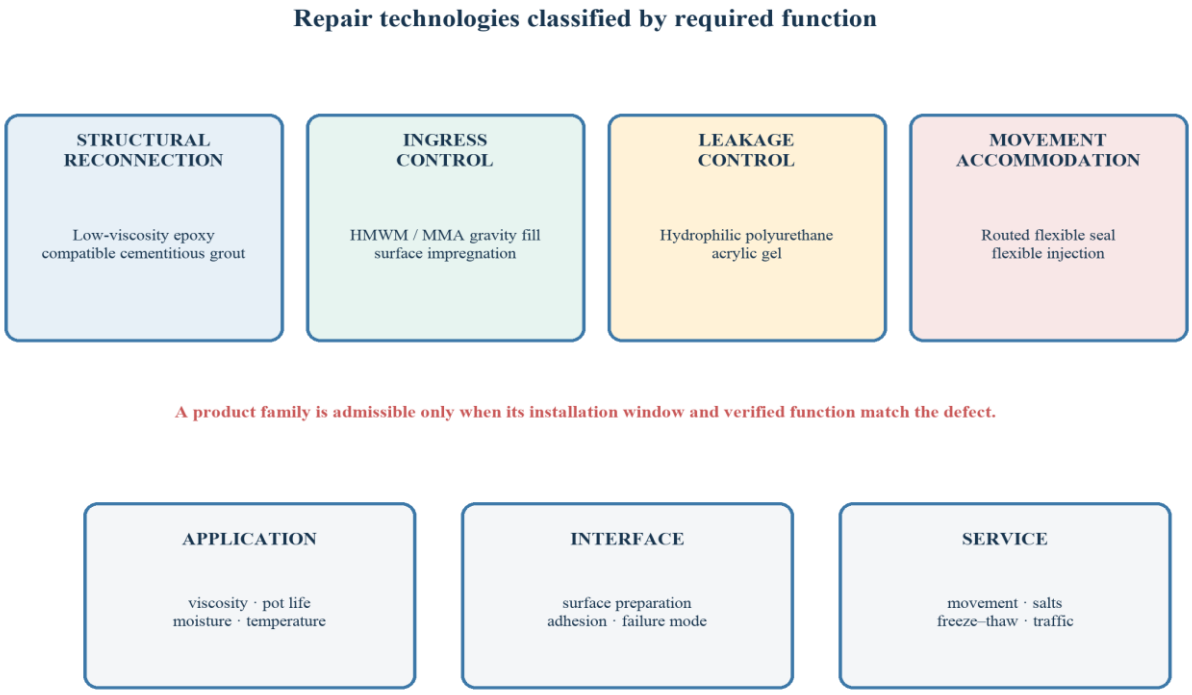

Figure 3 – Crack-repair technologies classified by required function rather than product name.

Table 3 – Functional comparison of principal post-cracking technologies [developed by the author]

Technology	Primary function	Best-supported condition	Principal advantages	Critical limitations
Low-viscosity epoxy pressure injection	Structural reconnection and sealing	Stable, clean, dry or product-qualified damp crack	High bond; stiffness/load recovery possible	Cold cure, moisture sensitivity, rigidity, incomplete penetration.

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Technology	Primary function	Best-supported condition	Principal advantages	Critical limitations
HMWM or MMA gravity filling	Penetration and ingress reduction	Fine stable horizontal deck cracks	Low viscosity; rapid deck treatment	Volatility/cure control; limited movement; later overlay-bond issue.
Hydrophilic/foaming polyurethane	Stop active leakage; flexible filling	Wet or water-bearing nonstructural cracks	Fast water reaction; deformation capacity	Expansion control; variable wet bond; limited structural evidence.
Acrylic gel / flexible polymer	Leakage control and movement accommodation	Fine wet cracks with recurrent movement	Low viscosity; flexible gel behavior	Washout, durability and product variability.
Cementitious/microfine grout	Mineral filling and partial continuity	Wider cracks/voids where particles can enter	Fire resistance; mineral compatibility; cost	Filtration, bleeding, washout, shrinkage and low movement tolerance.
Routing and elastomeric sealing	Accommodate active surface movement	Accessible active cracks/joints	Replaceable; geometry can be designed	No structural continuity; workmanship-sensitive.
Surface impregnation/coating	Reduce surface absorption/ingress	Shallow cracking and porous deck surface	Rapid coverage; chloride/water protection potential	Does not prove through-crack filling; wear and reapplication.
Exogenous bio/mineral treatment	Precipitate crack-filling solids	Research-scale, water-accessible cracks	Transport recovery demonstrated in selected studies	Slow kinetics, environmental control, limited field maturity.

3.3 Injectability, moisture and cold-weather constructability

Injection success is governed by a coupled transport–reaction window. Lower viscosity improves access to fine cracks, but dilution or heating used to reduce viscosity may alter cure, shrinkage and final properties. Higher pressure increases flow until equipment losses, crack tortuosity and surface-seal capacity become controlling. Pot life must exceed the time needed to fill the network, yet rapid reopening favors short cure. Cold weather lengthens cure and increases viscosity; preheating material or substrate can improve flow but may shorten working time. A defensible specification therefore states viscosity at application temperature, gel-time evolution, minimum substrate temperature, crack moisture class and equipment pressure at the port rather than relying on a room-temperature datasheet [27, 28, 38].

Moisture is not a binary variable. Moodi et al. separated dry, damp, wet and water-filled simulated cracks and found the dry state most reliable; the presence and location of water altered bond, and repaired panels outside the dry condition failed the applied 24-cycle freeze–thaw sequence [38]. Low-viscosity epoxy produced 25% greater slant-shear response than the high-viscosity resin within that study, but this is a formulation-specific comparison rather than a universal viscosity law. In hydraulic repair, controlled low-temperature pre-curing of an epoxy reduced the subsequent exothermic temperature rise, lowered cured-material shrinkage by 12.0%, increased wet bond by up to 34.3%, and shifted failure from the crack plane toward the substrate [39]. The mechanism was attributed to improved cure development; transferability requires the same resin chemistry and pre-reaction control.

Surface preparation, specified in accordance with the intended repair system, remains the most controllable source of reliability [40]. Dust, laitance, oil, standing water and existing salts prevent intimate contact. Compressed air can redistribute oil or moisture if not filtered; pressure washing requires a verified drying interval unless the material is qualified for damp concrete. For gravity-fed

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deck sealers, sanding or broadcasting aggregate may be needed to restore skid resistance and preserve bond to a future overlay. HMWM treatment reduced subsequent overlay bond, whereas light sandblasting or broadcast sand restored approximately 80% and 85%, respectively, of the unsealed-surface bond in one study [37]. A successful first intervention can thus create a compatibility problem for the next maintenance action.

3.4 Mechanical restoration, stiffness and fatigue

Mechanical repair should be assessed against three baselines: intact capacity, damaged capacity before repair and post-repair capacity. Comparing only repaired and damaged specimens can exaggerate recovery, while comparison only with intact specimens hides the benefit obtained. In gravity-filled cracked cubes, cracking reduced compressive strength by as much as 40.93%; proper epoxy filling reduced the remaining deficit to 8.23% relative to intact concrete [41]. This is substantial restoration under a simplified compression test, but it does not demonstrate member-level fatigue, bond retention or behavior of an active crack.

Member tests provide a more relevant load path. Epoxy injection, cement grout and section enlargement increased the first-cracking load of previously cracked one-way slabs by about 35% relative to the reported control condition, while repaired strength and ductility approached those of the control slabs [34]. Ultra-low-viscosity epoxy beam studies and polymer-modified mortar tests on full-scale cracked reinforced-concrete beams support structural plausibility, while a 2026 arch-bridge study evaluated injection-based strengthening numerically; none alone constitutes field durability validation [14, 23, 42, 43]. Metakaolin-polymer concrete and recycled-polyethylene mortars provide additional repair-material evidence, but their distinct formulations and test programs preclude direct ranking against injection resins [22, 24].

Stiffness compatibility complicates a strength-only interpretation. HMWM-repaired concrete modeling and experiments show that capacity recovery depends on crack filling and cohesive transfer, yet a very stiff repair can redirect cracking into adjacent concrete [32]. A 2024 epoxy-concrete study for rapid bridge-deck pavement repair added rubber powder and carbon black; at two hours the modified system showed 20% higher compressive strength and 25% lower elastic modulus than the unmodified epoxy concrete [44]. Those changes are favorable for early reopening and compliance within that formulation, although its asphalt-deck context prevents direct transfer to exposed portland-cement concrete.

Fatigue is where apparently strong repairs become vulnerable. Temperature and movement-amplitude experiments on epoxy-injected mortar and concrete showed declining fatigue resistance as both variables increased, with failure shifting from concrete to mixed resin/interface modes at higher temperature [45]. After freeze-thaw conditioning and fatigue loading, epoxies and HMWM products generally outperformed cementitious alternatives in a six-product bridge-oriented study, but performance varied significantly between products and the cementitious system resisted very little fatigue loading [46]. These studies are important precisely because they contradict the assumption that a static bond or compressive test is sufficient. Figure 4 visualizes selected within-study quantitative signals without pooling unlike outcomes, and Table 4 preserves their test conditions and interpretive boundaries.

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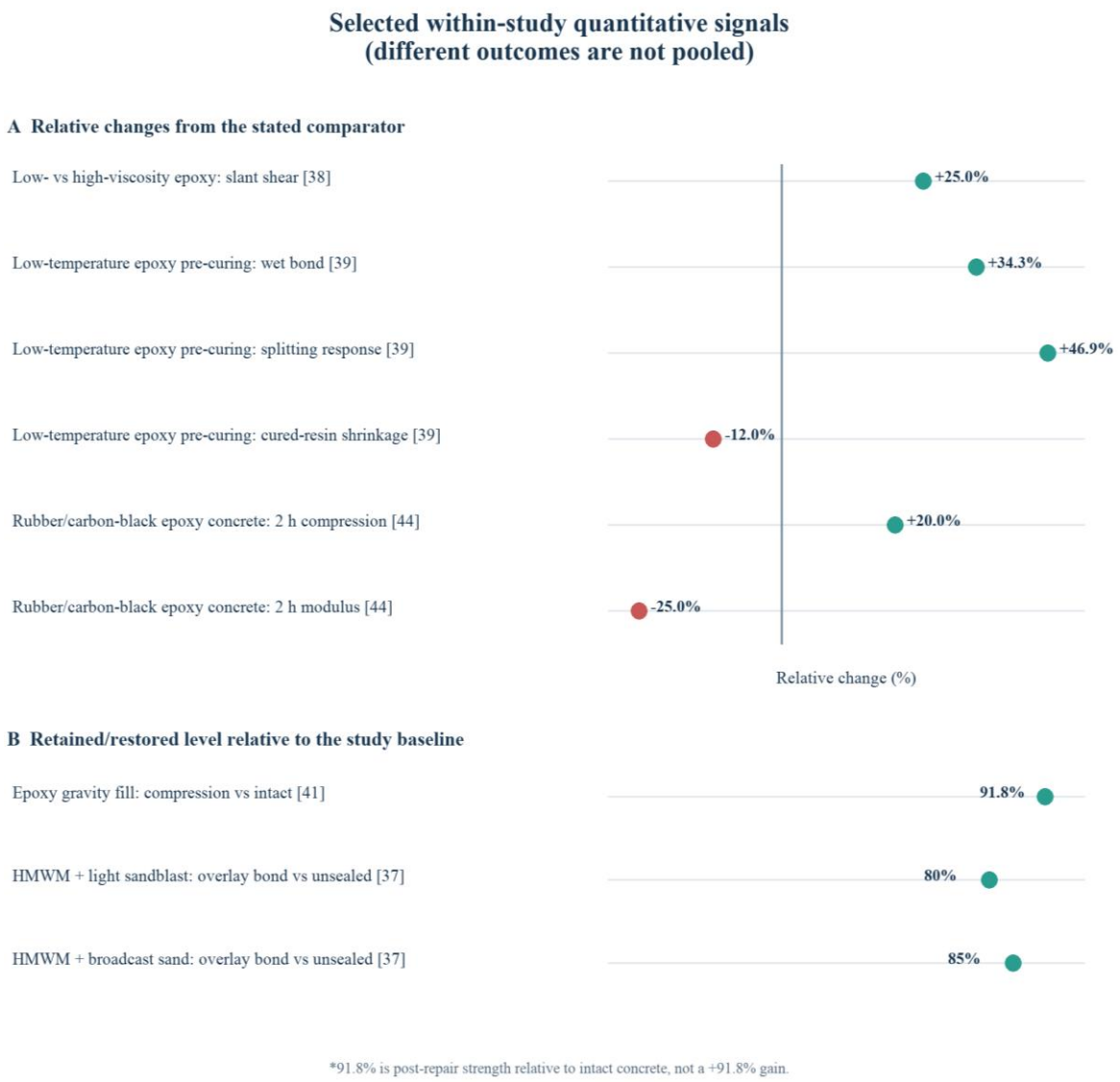

Figure 4 – Selected within-study quantitative signals shown using separate baselines: (a) relative changes from a stated comparator and (b) retained or restored performance as a percentage of the study baseline. Prepared by the author using data reported in sources [38], [37], [39], [41], [44].

Table 4 – Traceable quantitative signals used in the synthesis [developed by the author]

Source	System and comparator	Condition/test	Reported response	Interpretive boundary
Issa & Debs [41]	Cracked cubes; gravity-filled epoxy; intact cubes	Compression	Strength loss relative to intact concrete: up to 40.93% before repair and 8.23% after repair.	Simplified artificial cracks; not a bond-retention test.
Moodi et al. [38]	Low- vs high-viscosity epoxy	Slant shear; dry/damp/wet/water-filled; 24 freeze–thaw cycles	Low-viscosity resin gave 25% greater shear response; only dry repairs remained stable through the reported cycles.	Product-specific and short conditioning sequence.

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Source	System and comparator	Condition/test	Reported response	Interpretive boundary
Chang et al. [39]	Low-temperature pre-cured vs reference epoxy	Wet-crack repair	Wet bond +34.3%; splitting response +46.9%; resin shrinkage −12.0%; compressive recovery reached 100%.	Chinese hydraulic-repair study; pre-curing protocol is chemistry-specific.
Sun et al. [44]	Rubber/carbon-black modified vs ordinary epoxy concrete	Early-age bridge-deck pavement material	At 2 h: compression +20%; elastic modulus −25%.	Material rather than injected interface; asphalt-deck context.
Thanoon et al. [34]	Previously cracked one-way RC slabs; grout, epoxy injection or enlargement	Member first-cracking load	Each repair route increased the reported first-cracking load by about 35%.	Control definition and repair mechanisms differ; not a product-ranking test.
Tsiatas & Robinson [46]	Six commercial crack-repair systems	Cracks of 0.51, 6.35 and 12.70 mm; freeze–thaw followed by fatigue	Epoxy and HMWM systems generally retained the strongest response; the cementitious system showed very little fatigue resistance.	No pooled percentage is defensible across products, widths and failure modes.
Safan et al. [26]	Polyurethane injection vs waterproofing-only tank models	Water pressure up to 3 bar for 3 days	Injected polyurethane substantially stopped leakage in both tank models.	Hydraulic cut-off evidence; no structural-load recovery claim.
Wang et al. [47]	Asphalt-modified epoxy repair material	Freeze–thaw and chemical conditioning	Compression 56.6 MPa; tensile shear 5.9 MPa; reported mass change <1%.	Bulk repair material, not a repaired portland-cement crack interface.
Shahrooz et al. [37]	Overlay on HMWM-sealed vs unsealed deck surface	Overlay bond	Light sandblasting and broadcast sand restored about 80% and 85% of unsealed-surface bond.	Addresses compatibility with later overlay, not crack-face bond.
Xiao et al. [48]	Silane-treated concrete pavement joints	Field cores after service	Penetration 1.46–11.75 mm, mean 5.14 mm; more than half still showed improved contact angle/absorption after 8.2 years.	Surface/joint treatment; field variability limits causality.
Perrin et al. [49]	Injected exogenous biorepair in a large cracked slab	Two cracks, 430 ± 60 µm	Water flow reduced 99% after 11 weeks.	Water-control outcome; slow research-scale process.
Briggs et al. [50]	Delaminated bridge deck repaired with anchors and/or epoxy injection	Service-level interface shear evaluation	Allowable-stress ratios: delaminated 0.71; epoxy 1.40; anchors + epoxy 1.67.	Delamination interface, not isolated narrow crack.

3.5 Water tightness, transport protection and movement response

Water control must be verified under pressure and movement. A material may initially fill a crack yet lose hydraulic function when the crack opens, when adhesion peels from a wet wall, or when thermal cycling creates a bypass path. The artificial-crack apparatus used by Kim et al. applied repeated crack movement and water pressure to five material families. Results varied within every family, and several acrylic and urethane products failed the specified movement sequence or subsequently leaked [25]. This demonstrates why elongation of the cured bulk polymer cannot

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substitute for a repaired-crack test: adhesion, confinement and local defects govern the actual response.

For bridge decks, ingress reduction and structural rebonding should be treated as separate outcomes. HMWM and MMA generally offer deep penetration and surface sealing, whereas epoxies often produce higher bond; neither characteristic alone predicts chloride protection after traffic and winter exposure [7, 31, 33]. Sealing an old chloride-contaminated crack may also trap contaminants near reinforcement. Surface impregnation can reduce absorption around the crack but does not prove that the crack is filled. A combined epoxy-injection and impregnation treatment performed strongly in short-term carbonation, chloride and freeze-thaw indicators in one laboratory comparison [51], but the study does not provide long-term field evidence or isolate the life-cycle contribution of each step.

Emerging mineral and biological treatments demonstrate a different trade-off. Microbial mineralization reduced chloride migration and improved splitting response in load-induced cracks in one controlled study [52]. A field-oriented bio-cementitious grout improved flexural response and water tightness across different crack orientations [53], and a large-slab exogenous biorepair reduced water flow by 99% after eleven weeks [49]. Air-coupled ultrasonic mapping found manual polyurethane injection more uniform across a cracked section than stimulated autogenous healing [54]. These results establish measurement possibilities and selected transport recovery, but long treatment times, biological sensitivity and sparse cold-climate data preclude parity with mature injection systems.

3.6 Severe continental exposure: interacting damage chains

Cold-climate qualification should reproduce the sequence through which failure develops. Moisture first enters or remains in the crack; freezing generates hydraulic and crystallization stresses; deicing solution modifies saturation and chemical exposure; temperature changes impose differential strain; traffic cycles open the crack or abrade surface treatment. A repair can survive a bulk freeze-thaw test while the interface debonds, or retain adhesion while the surrounding concrete scales. Figure 5 makes this causal chain explicit. Jointed-concrete testing under freeze–thaw and compressive load provides supporting-not repair-interface-evidence for the role of discontinuities [55].

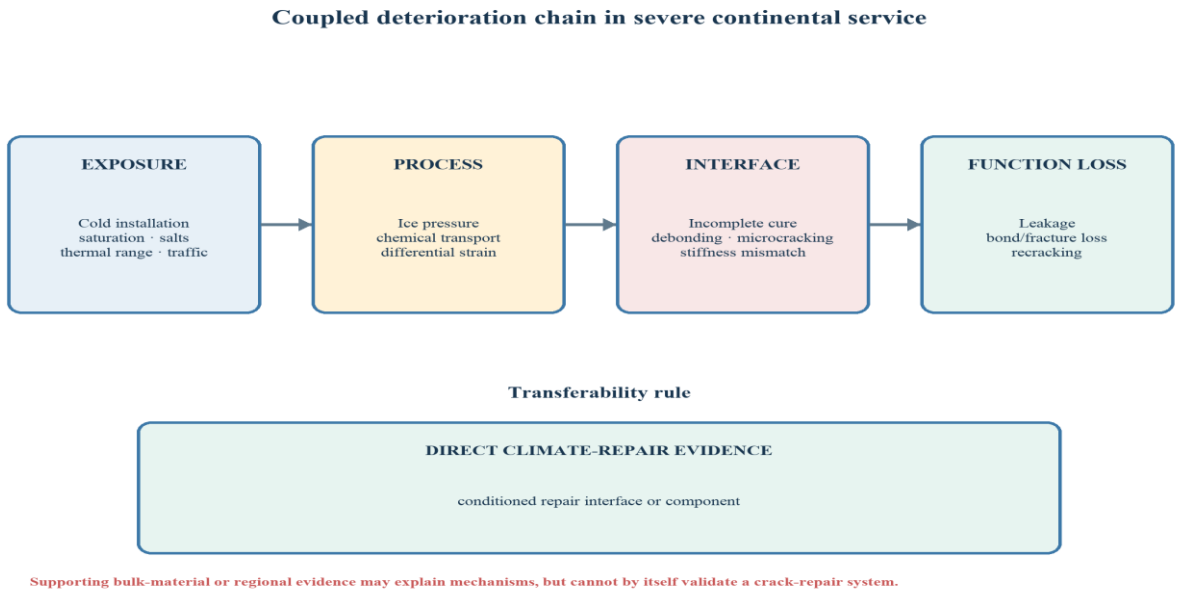

Figure 5 – Coupled exposure–process–interface–failure chain and evidence-transfer boundary for severe continental service. Author-developed mechanistic synthesis.

Direct interface studies support this concern. Wedge-splitting tests on an epoxy/concrete interface showed exponential losses in bond strength and fracture energy with freeze–thaw cycling in water and sulfate solution, accompanied by a shift from concrete failure toward adhesive interface failure [56]. Cement-based repairs assessed through flexural bond, interface cracking, mass loss and non-destructive indicators likewise showed progressive bond deterioration under freeze–thaw

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exposure [15]. A separate repair-interface study reported severe adhesion loss when abrasion and freeze-thaw were coupled, demonstrating that sequential damage cannot be inferred from either bulk freeze-thaw or abrasion alone [13]. These tests are more transferable to repair decisions than bulk-material conditioning, although their products, substrates and exposure histories remain study-specific.

Polymer modification can improve cold resistance but may introduce thermal or stiffness mismatch. Asphalt-modified epoxy with 10 parts per hundred resin achieved 56.6 MPa compressive strength and 5.9 MPa tensile-shear strength in one material study, with mass change below 1% after the reported freeze–thaw and chloride exposures [47]. Salty freeze-thaw research on polyester-resin-modified bridge-deck pavement concrete adds microstructural context [18], while alternating freeze–thaw–abrasion, freeze–thaw–load and plateau-concrete studies clarify coupled damage in bulk concrete [19, 20, 21]. Because these studies did not test a repaired crack interface, they are supporting mechanism evidence rather than direct proof of repair durability.

Pavement and bridge practice adds abrasion and future-maintenance constraints. Joint sealant failure under excessive opening and freezing is controlled by permissible elongation, installation geometry and adhesion [57]. Concrete pavement guidance treats crack sealing, joint resealing, partial-depth repair and load-transfer restoration as distinct preservation actions selected from distress mechanism and structural condition [4]. Field validation must use an outcome aligned with the repair objective.

3.7 Regional evidence and transferability to Kazakhstan

Kazakhstan-specific evidence is emerging but remains mostly supporting rather than direct crack-repair validation. Fine-grained concrete with complex modifiers was developed for repair and restoration with reduced cement content [17]. Silica-fume self-compacting concrete reinforced with polypropylene fibres reached the reported F350 frost-resistance class and lower absorption than its control, and ferroalloy-waste concrete was examined for railway sleepers [12, 16]. These studies are regionally relevant to material availability, railway infrastructure and cold exposure, but neither verifies a repaired crack or long-term repair–substrate retention. A Kazakhstan hydraulic-restoration study compared candidate materials using adhesion, chloride and freeze–thaw indicators [58]; it addresses repair selection more directly, yet still lacks a monitored repaired-interface field comparator. Consequently, regional material performance should be used to design local qualification tests, not to certify a technology by analogy.

Transfer from other cold or plateau regions was accepted only when the exposure chain and measured function matched the decision question. Direct repaired-interface studies under freeze–thaw or coupled abrasion [13, 15] inform retained adhesion. Bulk hydraulic, plateau and bridge-deck materials [11, 18, 19, 20, 21] inform damage mechanisms and conditioning design. This tiered transfer rule prevents climatic similarity from being treated as equivalent to field validation in Kazakhstan.

3.8 Transportation asset-requirement matrix

Application changes the priority order. A bridge-deck crack exposed to deicing salts prioritizes penetration, chloride exclusion, skid resistance and rapid reopening; structural cracks additionally require load transfer and fatigue. Concrete pavements demand movement capacity, routing geometry and abrasion resistance. Tunnel and culvert repairs are often governed by wet adhesion and water pressure. Hydraulic structures require resistance to washout, erosion and recurrent saturation. Thin overlays introduce another interface whose bond may be compromised by a previous sealer [37]. Table 5 connects these asset-specific demands to verified quantitative signals and unresolved validation needs.

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Table 5 – Asset–exposure-function matrix for severe continental climates [developed by the author]

Asset	Dominant exposure	Required repair function	Preferred verification	Evidence signal / unresolved risk
Bridge deck–stable fine crack	Deicing salts, freeze–thaw, traffic wear	Penetrate and exclude water/chloride; preserve skid resistance	Penetration/fill mapping; absorption/chloride indicator; abrasion; seasonal inspection	Silane field cores: 1.46–11.75 mm penetration (mean 5.14 mm) after 8.2 y [48]; this is surface/joint evidence, not crack-fill proof.
Bridge deck–structural crack/delamination	Traffic fatigue, thermal strain, salt	Restore shear/tension transfer and seal	Member load test; interface fracture; fatigue; conditioned leakage	Allowable-stress ratios 0.71 delaminated, 1.40 epoxy and 1.67 anchors + epoxy [50]; geometry is a deck interface, not an isolated crack.
Concrete pavement crack/joint	Large opening range, wheel abrasion, freeze–thaw	Accommodate movement and keep incompressibles/water out	Low-temperature extension; cyclic movement; adhesion; abrasion	Long-term movement and water-control performance remains poorly linked to network-level pavement-condition indices.
Tunnel/underground structure	Active seepage, wet substrate, hydrostatic pressure	Stop water while tolerating recurrent movement	Wet adhesion; pressure leakage; movement cycling	PU injection substantially stopped leakage at up to 3 bar over 3 days [26]; structural and long-term retention were not established.
Culvert/retaining structure	Wet–dry, salts, limited access	Seal leakage and resist debonding	Pressure/permeability; pull-off after conditioning	Surface preparation under constrained access.

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Asset	Dominant exposure	Required repair function	Preferred verification	Evidence signal / unresolved risk
Hydraulic concrete	Saturation, low-temperature work, erosion	Water cut-off, mineral/chemical compatibility	Washout; wet bond; erosion; thermal cycling	One low-temperature pre-cure protocol gave wet bond +34.3% and cured-resin shrinkage −12.0% [39]; formulation-specific.
Thin overlay after crack treatment	Differential shrinkage/temperature, traffic	Maintain overlay bond across treated surface	Method-specific overlay bond; restrained cycling	After HMWM, light sandblasting and broadcast sand restored about 80% and 85% of unsealed-surface overlay bond [37].

3.9 Evidence density and the danger of product-family rankings

The reviewed literature is asymmetric. Epoxy injection has direct evidence for strength restoration, member flexure, moisture sensitivity, temperature-dependent fatigue and freeze–thaw response. HMWM and MMA systems have stronger field and deck-penetration evidence but less structural continuity data. Polyurethane has direct leakage-control evidence and some railway-grouting application evidence, yet limited structural and long-term freeze–thaw interface data. Cementitious grout has member-scale and compatibility evidence but inconsistent injectability and movement resistance. Emerging mineral/biological systems show impressive water-flow or transport recovery in selected studies, but field maturity is low. Figure 6 maps evidence density rather than intrinsic quality.

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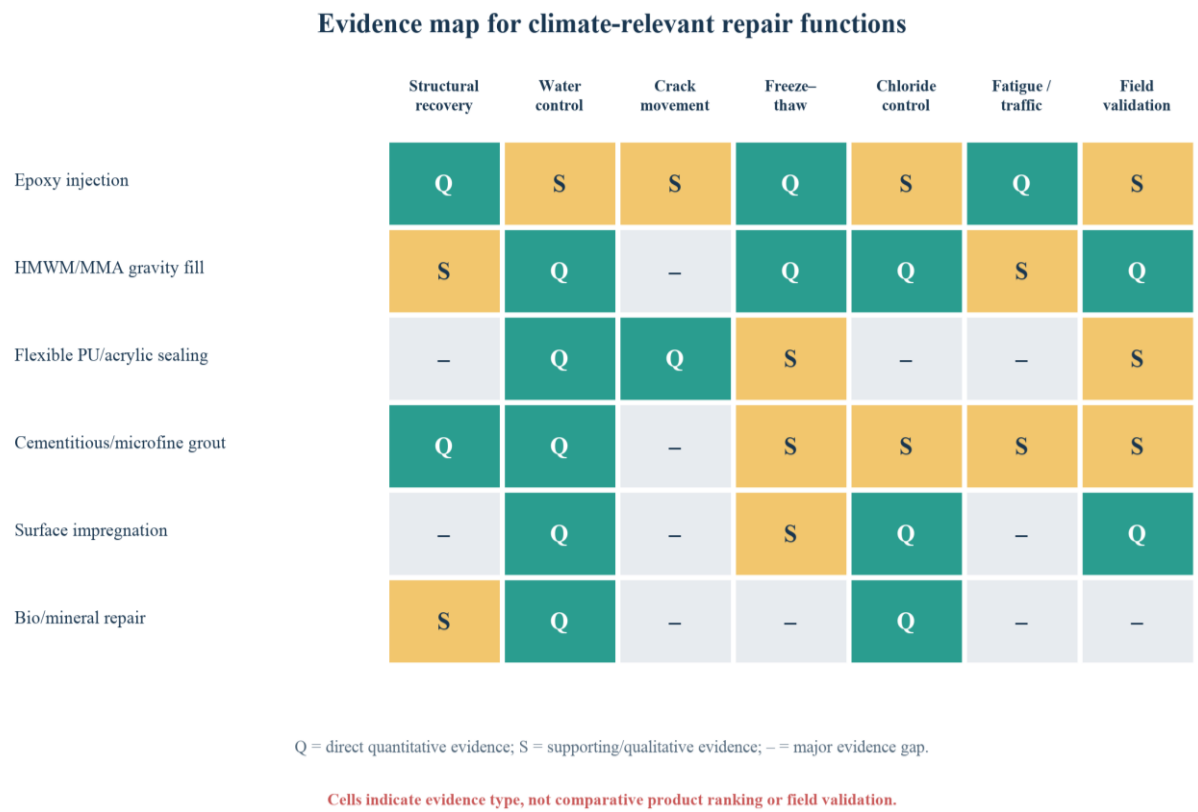

Figure 6 – Evidence map by repair function and exposure. Q denotes direct quantitative evidence, S supporting or qualitative evidence, and – a major gap. Cells indicate evidence type, not prevalence, product superiority or field validation.

Within-family variability is itself a principal result. Ten crack sealers in a bridge-oriented laboratory program showed substantially different bond retention after freeze-thaw despite shared generic labels [31, 46]. Fifteen leakage-repair products displayed divergent movement and permeability responses [25]. Eight commercial rapid-repair materials tested across more than 450 specimens differed in early strength, modulus, shrinkage, restrained cracking, resistivity and slant-shear bond; one-year patch inspection further showed that laboratory ranking must be checked against field cracking [59]. Specifications should therefore define measurable performance thresholds for the intended condition rather than approve a chemical family by name. Table 6 calibrates confidence for the principal technology–performance questions.

Table 6 – Evidence confidence by technology–performance question [developed by the author]

Question	Evidence status	Confidence	Reason for rating
Can stable cracks regain structural continuity after epoxy injection?	Compression deficit reduced from up to 40.93% to 8.23% [41]; slab first-cracking load rose about 35% [34].	Moderate	Multiple direct studies, but proprietary formulations and crack geometries differ.
Does lower viscosity improve injection?	One low-viscosity epoxy produced 25% greater slant shear than the high-viscosity comparator [38].	Moderate	Viscosity covaries with chemistry, temperature and cure.
Can polyurethane stop active leakage?	Two tank models retained water cut-off at up to 3 bar for 3 days [26].	Moderate	Sparse long-term structural and cold-climate data.

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Question	Evidence status	Confidence	Reason for rating
Can HMWM treatment impair the bond of a later overlay?	After HMWM treatment, surface preparation recovered about 80–85% of unsealed-surface overlay bond [37].	Moderate	This quantifies a future-overlay trade-off, not crack-face structural restoration or retained fatigue.
Which material family is best under freeze–thaw?	No universal ranking is defensible.	Supporting	Protocols, moisture states and products vary; interface and bulk outcomes differ.
Do bio/mineral methods provide durable transport recovery?	One large-slab study reduced water flow 99% after 11 weeks in 430 ± 60 µm cracks [49].	Supporting	Slow kinetics, limited climate conditioning and almost no field monitoring.
Can laboratory results predict field life?	A program exceeding 450 specimens was followed by one-year patch inspection [59], but only partial correlations emerged.	Supporting	Few controlled field comparators and inconsistent inspection outcomes.

3.10 Performance-based selection framework

A performance-based decision process defines project-specific acceptance thresholds before ranking products. Step 1 establishes the defect and its cause. Step 2 states the required function in measurable terms: load-transfer recovery, maximum permissible leakage, ingress reduction or movement capacity. Step 3 rejects technologies outside the actual temperature, moisture, access and closure window. Step 4 verifies mechanical and thermal compatibility at the repaired interface. Step 5 conditions the repair under the relevant coupled exposure and measures retained function. Step 6 records evidence confidence and a monitoring and reintervention plan. The numerical threshold must come from the applicable standard, asset-owner specification or project risk assessment; this review does not propose one universal value for unlike assets. Figure 7 formalizes these gates.

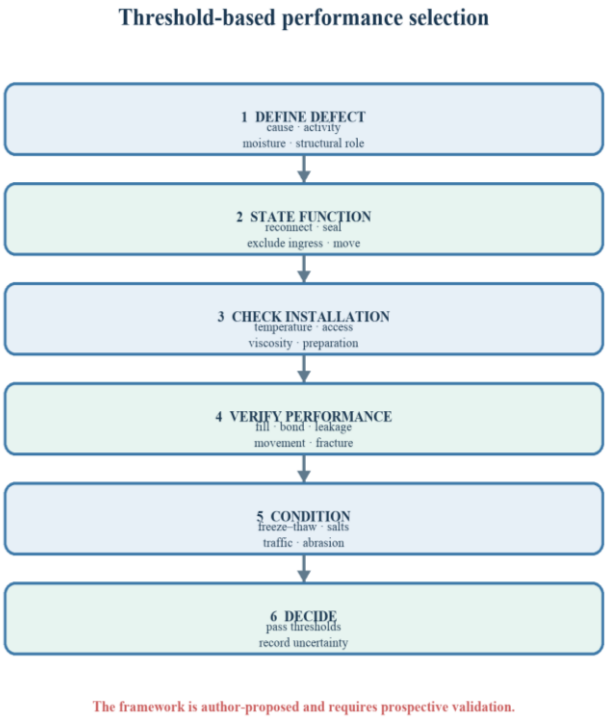

Figure 7 – Threshold-based performance-selection framework for crack repair. Author-proposed framework requiring prospective validation.

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The framework deliberately avoids universal weights and acceptance values. For a leaking tunnel crack, pressure tightness and movement response can outweigh structural stiffness. For a bridge-deck flexural crack, fatigue load transfer and chloride exclusion are both essential. For an interior stable crack, compatible load transfer may dominate. These pathways are hypotheses organized from the reviewed evidence, not field-validated prescriptions. Project-specific thresholds should be defined by the owner and verified with the same method before and after relevant conditioning.

3.11 Research gaps and validation roadmap

The first gap is factorial evidence. Moisture, crack width, viscosity, temperature and pressure are often varied in separate studies, so interactions cannot be identified. Future experiments should combine representative crack widths, moisture states, application temperatures and delivery conditions, report fill continuity and cure, and include untreated and method-matched controls. The specific levels should follow the intended asset and applicable standard rather than a universal schedule.

The second gap is retained interface function under coupled exposure. Direct studies show bond deterioration under freeze-thaw and large losses under combined abrasion-freeze-thaw [13, 15], whereas bulk concrete studies indicate additional interactions with salt, load and altitude [18, 19, 20, 21]. Repair qualification should therefore use application-specific, standard-compliant sequences and report retained bond or fracture response, leakage, mass/transport indicators and failure mode. Bulk strength alone is insufficient.

The third gap is scale transition. Laboratory cracks are planar, clean and deliberately opened; field cracks are tortuous, contaminated and partly closed. Component-scale slabs and beams should incorporate realistic precracking, reinforcement, chloride contamination and repair access. Non-destructive methods-including air-coupled ultrasonics, impact echo, thermography and electrical response-should be calibrated against destructive sectioning so that injection quality can be verified without extensive coring [28, 54].

The fourth gap is field monitoring. The 8.2-year silane joint study [48], the ten-year joint-resealing evaluation [60], and transportation-agency reports [4, 31] show the value of longitudinal evidence, but comparable treated and untreated controls are rare. Pilot repairs should record crack activity, preparation, batch and environmental conditions, then monitor leakage, bond proxies, reopening and visible failure. The staged research roadmap is provided as Figure S1 in the Supplementary Information; it is an author-proposed translation sequence, not a validated standard. Table 7 converts these gaps into minimum, decision-oriented experiments.

Table 7 – Evidence gap and minimum recommended experiment [developed by the author]

Gap	Why it matters	Minimum experiment	Decision contribution
Multi-factor application window	Field variables interact and change fill/cure simultaneously.	Factorial crack width × moisture × temperature × viscosity; quantify fill and cure.	Defines a verified injectability envelope.
Coupled cold-climate durability	Separate tests miss sequential interface damage.	Repaired-interface cycling with saturation, deicing solution, thermal range and mechanical movement.	Measures retained rather than initial function.
Structural fatigue after repair	Static recovery may conceal brittle interface failure.	Precracked RC members; repair; variable-amplitude fatigue; residual capacity and failure mode.	Distinguishes structural rebonding from temporary stiffness recovery.
Movement–leakage coupling	Flexible bulk material may debond in a confined crack.	Cyclic opening under hydraulic pressure with wet-substrate controls.	Qualifies water-cutoff systems for active cracks.
Verification of internal filling	Surface closure is an unreliable proxy.	NDT mapping calibrated with sectioning/micro-CT or dye tracing.	Enables installation quality assurance.

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Gap	Why it matters	Minimum experiment	Decision contribution
Field life and reintervention	Laboratory indicators do not define maintenance interval.	Controlled pilot sections with untreated comparator and seasonal monitoring.	Supports service-life and life-cycle cost models.
Future-treatment compatibility	Sealers may impair later overlay bond.	Sequential maintenance specimens: sealer ageing, surface preparation, overlay and fatigue.	Avoids locking the asset into an incompatible repair path.

4 CONCLUSIONS

1. Selection must begin with crack cause, activity, moisture and structural role. Surface width alone cannot distinguish structural injection from movement-tolerant sealing or cause mitigation.

2. Technology families serve different functions: epoxy injection can restore continuity in stable cracks; HMWM/MMA can penetrate fine horizontal cracks; flexible polyurethane/acrylic systems can control leakage or movement; and cementitious grout can fill compatible mineral voids. No family is universally superior.

3. Injectability depends jointly on crack geometry, viscosity at application temperature, pressure loss, pot life, moisture and surface preparation. Within-study results show large but formulation-specific gains in compression, member response and bond, including improved wet-interface response after controlled low-temperature pre-curing.

4. Initial strength is not a durability surrogate. Direct repaired-interface evidence shows deterioration under freeze–thaw and coupled abrasion–freeze–thaw [13, 15]; bulk cold-climate studies are mechanistically useful but cannot validate interface retention.

5. Severe continental exposure should be represented as an application-relevant sequence of cold installation, saturation, freeze–thaw, deicing salts, thermal strain, traffic movement and abrasion. Kazakhstan studies support regional material screening [12, 16, 17, 58], but direct repaired-crack field comparisons and long-term monitoring remain scarce.

6. The threshold-based framework and research roadmap are author-proposed syntheses, not validated standards. They should be tested prospectively through method-specific laboratory qualification, component-scale trials and monitored field repairs.

REFERENCES

1. **ACI Committee 562.** (2016). Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary (ACI 562-16). American Concrete Institute.
2. **ACI Committee 224.** (2007). Causes, Evaluation, and Repair of Cracks in Concrete Structures (ACI 224.1R-07, reapproved 2013). American Concrete Institute.
3. **ACI Committee 546.** (2014). Guide to Concrete Repair (ACI 546R-14). American Concrete Institute.
4. **Smith, K. D., Harrington, D. S., Pierce, L., Ram, P., & Smith, K. L.** (2014). Concrete Pavement Preservation Guide (2nd ed., FHWA-HIF-14-014). Federal Highway Administration.
5. **RSE Kazhydromet.** (2025). Updated climatic characteristics of Kazakhstan: Climate inventory for 1966–2020. https://www.kazhydromet.kz/en/post/3161
6. **Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan.** (2019). Requirements for reliability and durability of concrete and reinforced-concrete hydraulic structures. Adilet Legal Information System. https://www.adilet.zan.kz/rus/docs/V1900019745
7. **Ni, X., Leon-Miquel, M., Greiner, Q. R., Paul, A., & Jin, Q.** (2023). Crack sealers for the preservation of concrete bridge decks: A synthesis of a national survey and literature review. Journal of Infrastructure Preservation and Resilience, 4, 23. https://doi.org/10.1186/s43065-023-00091-8

https://doi.org/10.51488/1680-080X/2026.3-13

8. **Zhao, H., Zhao, Y., & Tong, Y.** (2025). Crack repair in existing concrete structures: Progress in research and applications. Journal of Asian Concrete Federation, 11(1), 15–30. https://doi.org/10.18702/acf.2024.11.1.15
9. **Manawadu, A., Qiao, P., & Wen, H.** (2023). Characterization of substrate-to-overlay interface bond in concrete repairs: A review. Construction and Building Materials, 373, 130828. https://doi.org/10.1016/j.conbuildmat.2023.130828
10. **Ariyadasa, L. M., Bassuoni, M. T., & Ghazy, A.** (2026). Coatings for improving the durability of concrete: State of knowledge, code provisions, and research advances in nanocomposite systems. Construction and Building Materials, 515, 145646. https://doi.org/10.1016/j.conbuildmat.2026.145646
11. **Zhu, X., Zhou, X., Xia, Y., & Chen, X.** (2025). Performance degradation law and model construction of hydraulic concrete under freeze-thaw cycles: A comprehensive review. Buildings, 15(10), 1596. https://doi.org/10.3390/buildings15101596
12. **Ospanova, A., Tkach, E., & Myrzaliyev, T.** (2026). Effect of polypropylene fiber length on the mechanical properties, frost resistance, and microstructure of silica fume-modified self-compacting concrete. Technobius, 6(3), 0106. https://doi.org/10.54355/tbus/27897338.6.3.2026.0106
13. **Su, F., He, T., Yu, Q., Ma, X., Ke, Y., & Chen, G.** (2025). The adhesion performance of concrete repair interface under the coupling abrasion and freeze-thaw. Construction and Building Materials, 487, 142146. https://doi.org/10.1016/j.conbuildmat.2025.142146
14. **Rudavskyi, D., Sylovanyuk, V., & Marukha, V.** (2026). Evaluation of injection-based strengthening of a cracked concrete arch bridge. Procedia Structural Integrity, 81, 151–155. https://doi.org/10.1016/j.prostr.2026.03.027
15. **Wang, B., & Gupta, R.** (2021). Analyzing bond-deterioration during freeze-thaw exposure in cement-based repairs using non-destructive methods. Cement and Concrete Composites, 115, 103830. https://doi.org/10.1016/j.cemconcomp.2020.103830
16. **Imankulova, A., Alimkulov, M., Apshikur, B., Kambarov, M., Myrzaliyev, T., Akhmetov, D., & Utepov, Y.** (2026). A study of the effect of activated waste from ferroalloy production on the performance properties of concrete for reinforced concrete sleepers. Journal of Composites Science, 10(5), 240. https://doi.org/10.3390/jcs10050240
17. **Kozhasov, S., & Kozhas, A.** (2023). Fine-grained concrete for repair and restoration based on complex modifiers. Technobius, 3(2), 0038. https://doi.org/10.54355/tbus/3.2.2023.0038
18. **Zhang, Z., Zhang, H., Zhu, K., Tang, Z., & Zhang, H.** (2023). Deterioration mechanism on micro-structure of unsaturated polyester resin modified concrete for bridge deck pavement under salty freeze-thaw cycles. Construction and Building Materials, 368, 130366. https://doi.org/10.1016/j.conbuildmat.2023.130366
19. **Li, S., Wu, B., Jiang, C., & Wu, L.** (2024). Study on the damage mechanism of hydraulic concrete under the alternating action of freeze-thaw and abrasion. Construction and Building Materials, 447, 137976. https://doi.org/10.1016/j.conbuildmat.2024.137976
20. **Liu, Z., Ge, X., Lu, C., Zhang, Z., Duan, Y., & Jiang, Y.** (2024). Performance evolution and damage constitutive model of high air content hydraulic concrete coupled freeze-thaw and loads. Construction and Building Materials, 453, 139015. https://doi.org/10.1016/j.conbuildmat.2024.139015
21. **Mi, L., Mao, J., Li, L., Shi, Q., Fang, K., Li, S., Deng, X., & Li, G.** (2024). Microstructural damage and durability of plateau concrete: Insights into freeze-thaw resistance and improvement strategies. Structures, 60, 105888. https://doi.org/10.1016/j.istruc.2024.105888
22. **Dakwale, V. A., Pachpor, P. D., Mahesh, S., & Namdeo, D.** (2023). Use of metakaolin with polymer modified concrete in repairing of structures. Materials Today: Proceedings, 72, 9–18. https://doi.org/10.1016/j.matpr.2022.05.061
23. **Ahmad, S., Elahi, A., Barbhuiya, S. A., & Farid, Y.** (2012). Use of polymer modified mortar in controlling cracks in reinforced concrete beams. Construction and Building Materials, 27(1), 91–96. https://doi.org/10.1016/j.conbuildmat.2011.08.023

https://doi.org/10.51488/1680-080X/2026.3-13

24. **Aattache, A., Soltani, R., & Mahi, A.** (2017). Investigations for properties improvement of recycled PE polymer particles-reinforced mortars for repair practice. Construction and Building Materials, 146, 603–614. https://doi.org/10.1016/j.conbuildmat.2017.04.110
25. **Kim, S.-Y., Oh, S.-K., & Kim, B.** (2016). Artificial-crack-behavior test evaluation of the water-leakage repair materials used for the repair of water-leakage cracks in concrete structures. Applied Sciences, 6(9), 253. https://doi.org/10.3390/app6090253
26. **Safan, M. A., Etman, Z. A., & Konswa, A**. (2019). Evaluation of polyurethane resin injection for concrete leak repair. Case Studies in Construction Materials, 11, e00307. https://doi.org/10.1016/j.cscm.2019.e00307
27. **Seno, Y., & Uomoto, T**. (2008). An experimental study on the factors affecting injection properties during concrete crack repair. Concrete Research and Technology, 19(1), 11–20. https://doi.org/10.3151/crt1990.19.1_11
28. **Mohri, S., & Ohkubo, T.** (2015). Evaluation technology on injection behavior for concrete crack repair with visualized specimens. AIJ Journal of Technology and Design, 21(47), 29–34. https://doi.org/10.3130/aijt.21.29
29. **Goushis, R., & Mini, K. M.** (2022). Effectiveness of polymeric and cementitious materials to secure cracks in concrete under diverse circumstances. International Journal of Adhesion and Adhesives, 114, 103099. https://doi.org/10.1016/j.ijadhadh.2022.103099
30. **British Standards Institution.** (2013). BS EN 1504-5:2013. Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 5: Concrete injection. British Standards Institution.
31. **Issa, M. A., Alawieh, A. F., & Daoud, H. A.** (2024). Concrete Bridge Deck Crack Sealing (FHWA-ICT-24-007). Illinois Center for Transportation. https://doi.org/10.36501/0197-9191/24-007
32. **Ji, K., Gao, N., Wang, P., Stewart, L., & Arson, C.** (2021). Finite element model of concrete repaired by high molecular weight methacrylate (HMWM). Engineering Structures, 233, 111860. https://doi.org/10.1016/j.engstruct.2021.111860
33. **Rahim, A., Jansen, D., Abo-Shadi, N., & Simek, J.** (2010). Overview of high-molecular-weight methacrylate for sealing cracks in concrete bridge decks. Transportation Research Record, 2202(1), 77–81. https://doi.org/10.3141/2202-10
34. **Thanoon, W. A., Jaafar, M. S., Abdul Kadir, M. R., & Noorzaei, J.** (2005). Repair and structural performance of initially cracked reinforced concrete slabs. Construction and Building Materials, 19(8), 595–603. https://doi.org/10.1016/j.conbuildmat.2005.01.011
35. **Huang, Z., Su, Q., Huang, J., Dong, M., Li, D., & Liu, T.** (2022). Polyurethane grouting materials with different compositions for the treatment of mud pumping in ballastless track subgrade beds: Properties and application effect. Railway Engineering Science, 30(2), 204–220. https://doi.org/10.1007/s40534-021-00270-x
36. **Coffetti, D., Crotti, E., Gazzaniga, G., Gottardo, R., Pastore, T., & Coppola, L.** (2021). Protection of concrete structures: Performance analysis of different commercial products and systems. Materials, 14(13), 3719. https://doi.org/10.3390/ma14133719
37. **Shahrooz, B. M., Gillum, A. J., Cole, J., & Turer, A.** (2000). Bond characteristics of overlays placed over bridge decks sealed with high-molecular-weight methacrylate. Transportation Research Record, 1697(1), 24–30. https://doi.org/10.3141/1697-05
38. **Moodi, F., Bagheri, M., Dashti, P., & Ramezanianpour, A. A.** (2023). Mechanical properties and durability of injected SCC panels by epoxy against freezing and thawing. International Journal of Adhesion and Adhesives, 124, 103380. https://doi.org/10.1016/j.ijadhadh.2023.103380
39. **Chang, H., Yang, L., Zhao, Q., Zhang, Y., Wei, H., & Zhu, Y.** (2025). Effects of epoxy resin pre-curing in low-temperature environments on the repair performance of wet cracks in concrete. Hydro-Science and Engineering, no. 2, 112–120 (in Chinese). https://doi.org/10.12170/20240319001

https://doi.org/10.51488/1680-080X/2026.3-13

40. **International Concrete Repair Institute.** (2013). Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair (ICRI Guideline No. 310.2R-2013). International Concrete Repair Institute.
41. **Issa, C. A., & Debs, P.** (2007). Experimental study of epoxy repairing of cracks in concrete. Construction and Building Materials, 21(1), 157–163. https://doi.org/10.1016/j.conbuildmat.2005.06.030
42. **Yamaguchi, M., Wang, Y., Komiya, R., & Dozono, A.** (2024). Recovery effect of flexural performance of reinforced concrete beams by crack injection repair using ultra-low viscosity epoxy resin and tensile behavior of rebars embedded in repaired concrete. Cement Science and Concrete Technology, 77(1), 441–449. https://doi.org/10.14250/cement.77.441
43. **Shibuya, S., Yamaguchi, M., Morishima, S., & Shigeishi, M.** (2020). Effect of crack injection repair with ultra-low viscosity epoxy resin on flexural performance of reinforced concrete beams and its durability. Cement Science and Concrete Technology, 73(1), 325–332. https://doi.org/10.14250/cement.73.325
44. **Sun, L., Hao, X., He, J., Cai, Y., Guo, P., & Ma, Q.** (2024). Preparation and performance study of rapid repair epoxy concrete for bridge deck pavement. Materials, 17(11), 2674. https://doi.org/10.3390/ma17112674
45. **Shin, H.-C., Miyauchi, H., & Tanaka, K.** (2011). An experimental study of fatigue resistance in epoxy injection for cracked mortar and concrete considering the temperature effect. Construction and Building Materials, 25(3), 1316–1324. https://doi.org/10.1016/j.conbuildmat.2010.09.013
46. **Tsiatas, G., & Robinson, J.** (2002). Durability evaluation of concrete crack repair systems. Transportation Research Record, 1795(1), 82–87. https://doi.org/10.3141/1795-11
47. **Wang, Y., Ye, J., Liu, Y., Qiang, X., & Feng, L.** (2013). Influence of freeze–thaw cycles on properties of asphalt-modified epoxy repair materials. Construction and Building Materials, 41, 580–585. https://doi.org/10.1016/j.conbuildmat.2012.12.056
48. **Xiao, D. X., Adil, G., Kevern, J., & Owusu-Ababio, S.** (2021). Field performance of concrete pavement joints protected by silane sealer: Case study. Journal of Performance of Constructed Facilities, 35(6), 04021089. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001662
49. **Perrin, A., Gagné, R., Tran, N. C., Petit, L., & Lors, C.** (2024). Large-scale apparatus for the quantitative evaluation of biorepair in a cracked concrete slab. Construction and Building Materials, 448, 138174. https://doi.org/10.1016/j.conbuildmat.2024.138174
50. **Briggs, D., Neupane, S., & Pantelides, C. P.** (2025). Repair of bridge decks constructed with partial-depth precast concrete panels. Construction and Building Materials, 490, 142601. https://doi.org/10.1016/j.conbuildmat.2025.142601
51. **Kim, T.-K., & Park, J.-S.** (2021). Performance evaluation of concrete structures using crack repair methods. Sustainability, 13(6), 3217. https://doi.org/10.3390/su13063217
52. **Lu, C., Ge, H., Li, Z., & Zheng, Y.** (2022). Effect evaluation of microbial mineralization for repairing load-induced crack in concrete with a cyclic injection-immersion process. Case Studies in Construction Materials, 17, e01702. https://doi.org/10.1016/j.cscm.2022.e01702
53. **Anand, K., Goyal, S., & Reddy, M. S.** (2023). Development of field applicable remediation procedure using bio-cementitious grout for concrete cracks in variable orientations. Journal of Building Engineering, 67, 106024. https://doi.org/10.1016/j.jobe.2023.106024
54. **Lefever, G., Abdullah, A., Van Hemelrijck, D., Snoeck, D., & Aggelis, D. G.** (2024). Air-coupled ultrasonic mapping of stimulated autogenous self-healing and repair effectiveness within concrete mixtures. Construction and Building Materials, 419, 135547. https://doi.org/10.1016/j.conbuildmat.2024.135547
55. **Shen, Y., Liu, J., Zhou, S., & Li, G.** (2019). Experimental investigation on the freeze–thaw durability of concrete under compressive load and with joints. Construction and Building Materials, 229, 116893. https://doi.org/10.1016/j.conbuildmat.2019.116893

https://doi.org/10.51488/1680-080X/2026.3-13

56. **Wang, X., & Petrů, M.** (2019). Freeze–thaw resistance of epoxy/concrete interface evaluated by a novel wedge splitting test. Construction and Building Materials, 210, 434–441. https://doi.org/10.1016/j.conbuildmat.2019.03.139
57. **Lee, S. W., & Stoffels, S. M.** (2003). Effects of excessive pavement joint opening and freezing on sealants. Journal of Transportation Engineering, 129(4), 444–450. https://doi.org/10.1061/(ASCE)0733-947X(2003)129:4(444)
58. **Ilyassova, K. I., Moldamuratov, Zh. N., Seitkazinov, O. D., Abiyeva, G. S., Tukhtamisheva, A. Z., & Paktin, M.** (2025). Experimental studies of concrete materials for the restoration of hydraulic structures. Nanotechnologies in Construction, 17(6), 697–714. https://doi.org/10.15828/2075-8545-2025-17-6-697-714
59. **Banaeipour, A., Al Sarfin, M. A., Thomas, R. J., Maguire, M., & Sorensen, A. D.** (2022). Laboratory and field evaluation of commercially available rapid-repair materials for concrete bridge deck repair. Journal of Performance of Constructed Facilities, 36(4), 04022031. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001736
60. **Lynch, L. N., Chehovits, J. G., & Luders, D. G.** (2002). Ten-year field performance evaluation of joint reseating project. Transportation Research Record, 1795(1), 40–48. https://doi.org/10.3141/1795-05

https://doi.org/10.51488/1680-080X/2026.3-13

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CONFLICT OF INTEREST

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