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WHAT PHYSICS-BASED APPROACHES TO MATERIAL SCIENCE CAN IMPROVE THE DURABILITY OF ROAD SURFACES IN PAKISTAN'S SALT RANGE AREAS, REDUCING ENVIRONMENTAL IMPACTS OF FREQUENT RECONSTRUCTION AND MAINTENANCE?

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Abstract
The study was aimed to find out the physics-based approaches to material science that can improve the durability of road surfaces in Pakistan's salt range areas and how these can reduce the environmental impacts of frequent reconstruction and maintenance. Globally, literature explored that many physics-based approaches can improve the durability of road surfaces. Researcher extracted 17 physics-based approaches from literature that are directly relevant to improving the durability of road surfaces in the challenging environment of Pakistan's salt range based on the four categories of assessment: performance impact, implementation complexity, cost-effectiveness, and technology readiness and develop a Matrix Heatmap Data. On the base of this hypothetical data created a road durability assessment matrix for each of the selected 17 physics-based approaches with the help of R software. The matrix reveals a clear performance gradient from top to bottom, with practical engineering solutions.

INTRODUCTION

The Salt Range in Pakistan, named for its extensive rock salt deposits (Government of Pakistan's Directorate General of Archaeology, 2016), poses significant challenges to infrastructure durability, particularly road networks. The region's geology, dominated by Precambrian salt marls (Hussain et al., 2019), contributes to salt weathering, where sodium chloride (NaCl), sulfates, and nitrates infiltrate road materials, causing cracking, potholes, and structural weakening. The M-2 Motorway, which cuts through 33 km of the Salt Range (SMEC, 2022), faces severe deterioration due to salt-laden groundwater seepage and crystallization pressures (Hussain et al., 2020). Studies by Hussain et al. (2020, 2021) highlight that salt recrystallization cycles, particularly from NaCl and Na_2SO_4 expand within pavement pores, accelerating asphalt and concrete degradation. Poor drainage systems are another cause that exacerbate salt accumulation and corrosion of reinforcements in bridges and culverts (SMEC, 2022). Without salt-resistant materials and improved drainage, infrastructure in this region will continue to suffer reduced lifespans.

The unique geochemical composition, where saline-sodic soils and extensive evaporite deposits (including rock salt, gypsum, and limestone) create a perfect storm for rapid road deterioration in the Salt Range of Pakistan become a great challenge and the processes of swelling, shrinkage, and dissolution-precipitation in these areas lead to severe mechanical instability, causing surface deformation, cracking, and pothole formation that significantly reduce road

lifespan. National Highway Authority (2021) documented how salt laden groundwater exacerbates these issues, particularly along critical transport routes like the M-2 Motorway, where maintenance costs have skyrocketed due to repeated salt-induced damage. Doehne's (2020) research on salt weathering mitigation showed that solutions that are of physics based incorporating pore pressure dynamics, crystallization mechanics, and thermodynamic principles offer promising avenues for developing more resilient infrastructure. Engineers could develop specialized construction materials and drainage systems tailored to withstand the Salt Range's aggressive environment with the help of integrating advanced materials science with geochemical insights into the region's unique weathering processes. Such an approach would not only extend infrastructure longevity but also reduce the ecological footprint of constant repairs, aligning with Pakistan's growing need for sustainable development in its geologically sensitive regions. The situation calls for urgent interdisciplinary collaboration between geologists, materials scientists, and civil engineers to create cost-effective solutions that address both the immediate deterioration problems and long-term infrastructure planning in this strategically important area.

Study statement

The Salt Range (Punjab, Pakistan) is geologically unique: thick evaporite deposits and extensive rock-salt exposures create local environments where soluble salts are abundant in rock, soils and groundwater. Roads and other civil infrastructure crossing these terrains are often subject to accelerated failure modes such as surface blistering, delamination, loss of cohesion in base/subbase layers, and accelerated corrosion of metallic elements, driven largely by salt-related processes. Studies of saline environments and salt-affected soils emphasize that salts' presence alters both mechanical and hydraulic behavior of construction materials and promotes crystallization stresses that micro-damage and macro-failure exploit.

This article focuses on physics-based material science approaches such as interventions grounded in the physical mechanisms (fluid transport, crystallization pressure, hygroscopic swelling, thermal/humidity cycling) that cause salt damage to enhance road longevity in the Salt Range and thereby reduce the environmental impacts from repeated maintenance and reconstruction (resource consumption, emissions, waste). Where appropriate the chemistry is referenced to explain mechanism coupling (e.g., phase transitions of sodium sulfate), but the primary design rationale is physical (control of water and salt transport, mechanical resistance to internal pressures, and modulation of boundary conditions that produce damaging phase changes). The literature drawn upon includes pavement engineering, porous material crystallization studies, and materials development (geopolymers, fiber-reinforced binders, inhibitors, coatings).

Study objectives

The objectives of this study were to:

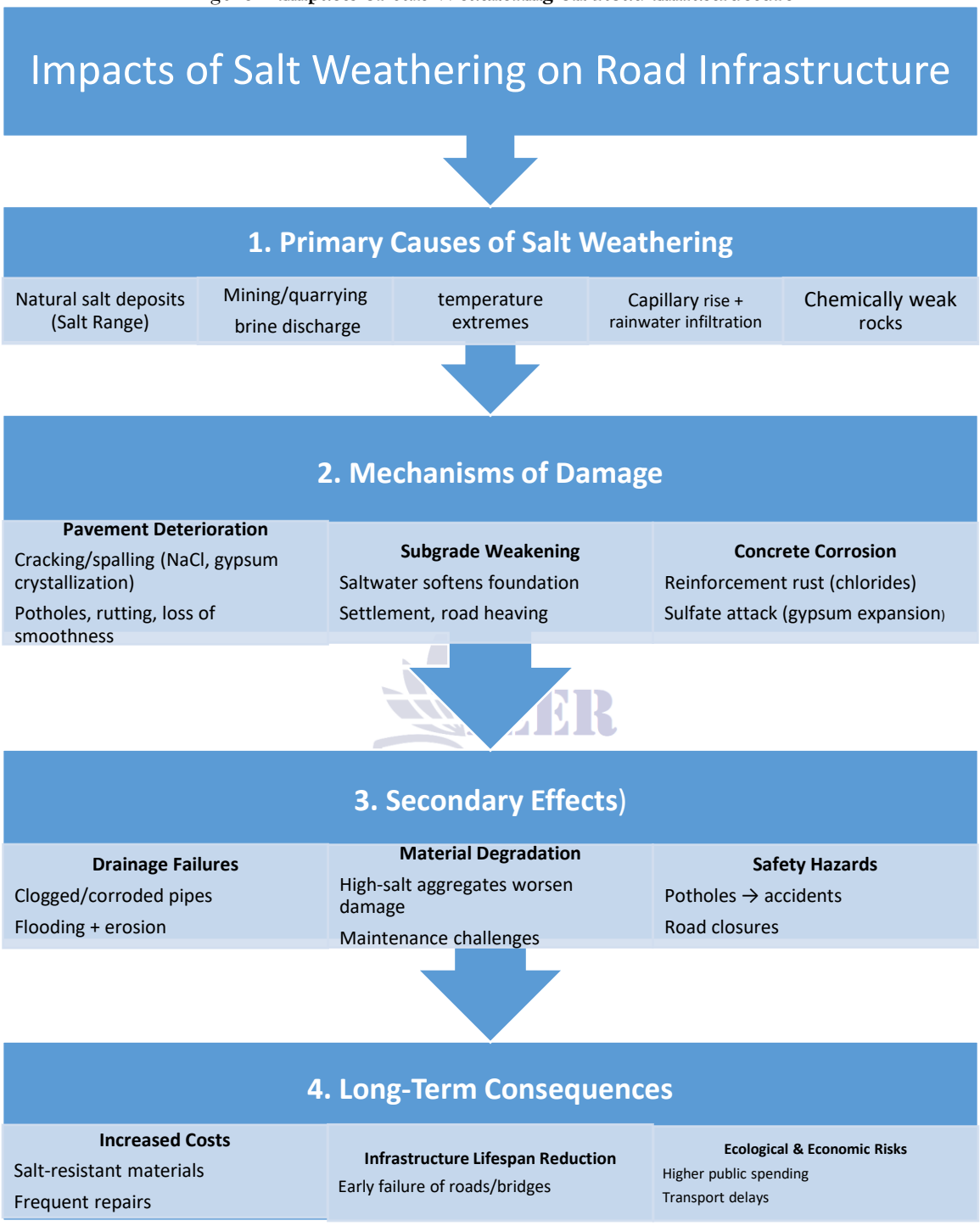
1. Find out the current road infrastructure issues specific to salt weathering in Salt Range of Pakistan.
2. Explore the impacts of salt weathering on road infrastructure.
3. Describe economic & environmental toll of road degradation in Pakistan's Salt Range.
4. Investigate Physics-based material science approaches used for the improvement of the durability of road surfaces at global and Pakistani level.
5. Explain some mitigation strategies and future considerations.

Road infrastructure issues specific to salt weathering

Road infrastructure issues specific to salt weathering There are many issues of salt weathering in the Salt Ranges that are driven by a combination of high natural salt content, moisture fluctuations (wet-dry cycles), temperature extremes, saline groundwater movement, chemically weak rocks, human disturbance, and minimal plant cover. The deterioration of roads in Pakistan's Salt Range is exacerbated by salt weathering, where salts like sodium sulfate (Na_2SO_4), sodium chloride (NaCl), and calcium sulfates ($CaSO_4$) infiltrate road materials, leading to structural weakening and surface decay. The National Highway Authority (NHA) Pakistan has documented severe road damage

in this region, attributing it to saline groundwater intrusion and evaporite dissolution (NHA, 2018). Local studies, such as those by the Pakistan Council of Research in Water Resources (PCRWR), confirm high salinity in the Salt Range's groundwater, which accelerates road degradation through crystallization pressure and hydration cycles (PCRWR, 2020). Furthermore, the Public Works Department (PWD) Punjab has reported frequent potholes, cracking, and asphalt stripping on highways like the M2 Motorway near the Salt Range, linking these issues to salt-laden runoff and poor drainage (PWD Punjab, 2019). Research by Shahidzadeh & Desarnaud (2012) supports these findings, demonstrating that sodium sulfate (abundant in the region) causes more damage than NaCl due to thenardite mirabilite phase transitions, which exert extreme stress on road materials. To mitigate these effects, the NHA recommends sulfate-resistant concrete, improved slope drainage, and polymer modified asphalt in vulnerable zones (NHA Technical Report, 2021). Without such interventions, salt weathering will continue to shorten the lifespan of critical infrastructure in this geologically sensitive area. The record-breaking heatwaves of 2022-2023, with temperatures peaking at 49.5°C, significantly exacerbated road deterioration in Pakistan's Salt Range through multiple mechanisms. These extreme weather events dramatically increased evaporation rates and salt crystallization processes (WMO, 2022; PMD, 2023), while simultaneously intensifying thermal expansion stresses on road surfaces. Scientific analyses (ECMWF, 2023) confirm that climate-change-induced temperature spikes and extended drought conditions have elevated groundwater salinity levels, progressively weakening road foundations. These compounding factors underscore the critical need for developing climate-adaptive infrastructure solutions tailored to the region's unique environmental challenges. During hot, dry periods, evaporation triggers salt crystallization causing porous aggregates to crumble and pavements to crack. ECMWF (European Centre for Medium-Range Weather Forecasts) weather forecasts help anticipate monsoonal rains and temperature swings, but rising heat worsens rutting in asphalt, while repeated wet-dry cycles accelerate salt-induced damage. Proactive measures like improved drainage, salt-resistant materials, and weather-responsive maintenance are critical to mitigating this degradation. Empirical data from Gul et al. (2024) showed that shallow groundwater (0.45 0.75 m depth) leads to high salt accumulation, with capillary rise depositing NaCl and sulfates (e.g., gypsum, epsomite) in roadbed materials. The Salt Range's roads, often built on sandstone and shale, likely face similar salt-induced deterioration as seen in Sato & Hattanji's (2018) experiments, where NaCl and $MgSO_4$ caused crumbling, flaking, and cracking in porous rocks. Groundwater-rich in sulfates (as noted by Wang, 2025) could further accelerate decay through capillary rise and evaporation. The region's high evaporation rates and saline groundwater would promote salt crystallization, leading to rapid road surface degradation—particularly in areas with fluctuating humidity. Mining and quarrying activities in Pakistan's Salt Range have caused severe environmental degradation, including landscape destabilization, soil and water contamination, and biodiversity loss due to unregulated blasting, excavation, and brine discharge. Bringedal et al. (2021) model how salt accumulates near the soil surface due to evaporation-driven density gradients, particularly under low vegetative cover.

Figure 1 **Impacts of Salt Weathering on Road Infrastructure**



Economic & environmental toll of road degradation in Pakistan's salt range

The road degradation caused by salt weathering in Pakistan's Salt Range imposes severe economic and environmental costs, disproportionately burdening local communities. Economically, frequent repairs drain budgets, provincial authorities spend 20-30% of annual road maintenance funds on salt-damaged highways, with costs soaring due to repeated pothole filling and premature reconstruction (World Bank

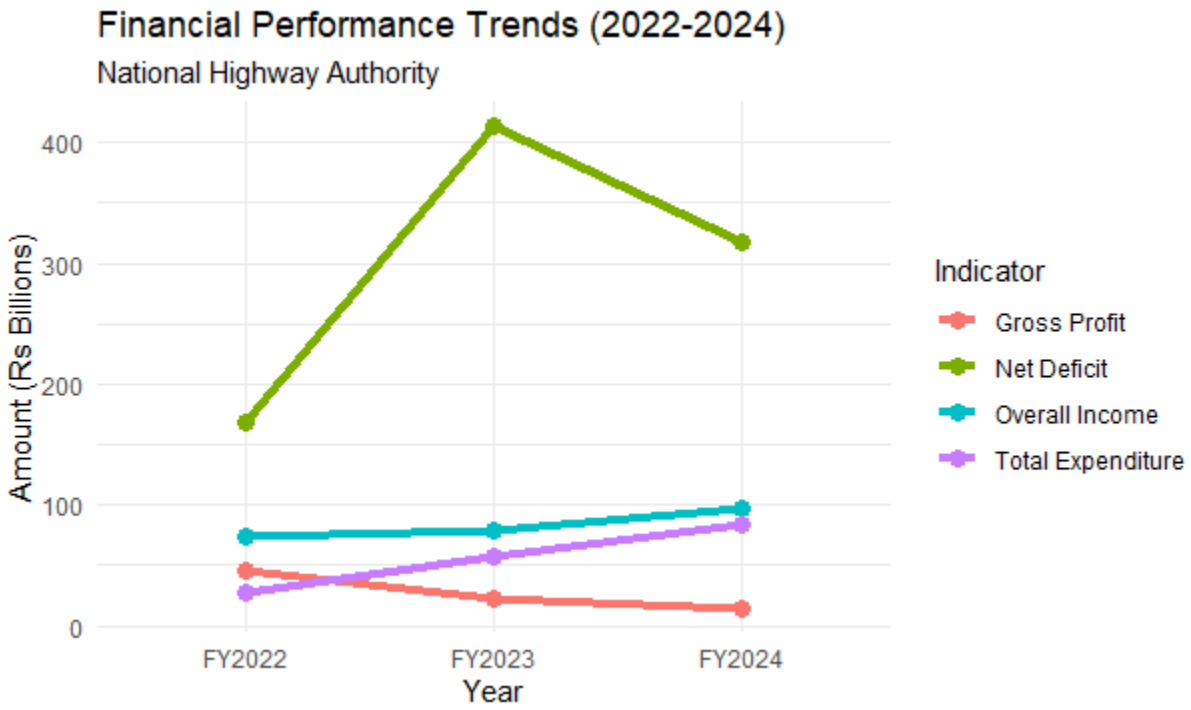
Group, 2024). Environmental damage is equally dire: dust and emissions from constant roadworks worsen air quality, while brine runoff contaminates groundwater, rendering it unfit for drinking or irrigation (PCRWR, 2020). The socioeconomic ripple effects include crop losses from salinized soils, heightened respiratory and kidney diseases among residents, and transport disruptions that isolate villages (Malik et al., 2021; SDPI, 2021). Salinity on paved roads has always a drastic effect (Dasgupta et Al., 2014). Most of the studies ignored the roads segments information. It is found that maintenance expenditure increased 15–20% more per kilometer in districts close to the Salt Range as compared to other regions in Pakistan. In Pakistan 90% of transport suffer chronic underfunding while public-private participation, sustainable financing and emerging management strategies can improve assets (Javed, 2005). Infrastructure is the basic yardstick for assessing human living standard. Traffic volume based on the heavy and light traffics is also responsible for roads kriging (Song et Al., 2019). It is very difficult to manage all the activities responsible for road construction especially time, cost, and user expectations. If it will not be managed on time it will cause more unsettlement. Hassan (2021) described that social and economic development of in Pakistan also based on the road infrastructure. From 1990-2015, econometric models (VECM) reflected different type of roads and showed the positive effects of infrastructure of roads and said that sustainable investment improve human wellbeing. Financial performance of National Highway Authority showed that it is continuously declining in gross profit 34% while total expenditures increased 46% from 2022-2024 (Profit Pakistan Today, 2025).

Table 1 Financial Performance of National Highway Authority

Financial Performance of National Highway Authority			
Indicator	**Financial Year**		
	2022	**2023**	**2024**
Gross Profit	Rs 45.77 bn	Rs 21.84 bn (↓52%)	Rs 14.28 bn (↓34%)
Overall Income	Rs 74 bn	Rs 78.4 bn (↑6%)	Rs 97 bn (↑24%)
Total Expenditure	Rs 28 bn	Rs 56.5 bn (↑100%)	Rs 83 bn (↑46%)
Net Deficit	Rs 168 bn	Rs 413 bn (↑146%)	Rs 318 bn (↓23%)

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Figure 2 Financial Performance of National Highway Authority (Visual)



Globally used Physics-based material science approaches for the improvement of the durability of road surfaces

We are going to consider the harsh conditions in salt range areas, which include high salinity (leading to corrosion and chemical degradation), temperature variations (leading to thermal cracking), moisture (leading to freeze-thaw damage and infiltration), and heavy traffic loads (leading to mechanical wear and fatigue).

We can use physics-based approaches that focus on the material microstructure design, improving mechanical properties (strength, toughness, elasticity), enhancing chemical resistance (to salts and water), and optimizing thermal properties (to resist thermal fatigue).

Here are some detailed approaches:

Use of Asphalt Binder and Nano Silica-Aerogel Composite

Ghaffari & Sarkar (2025) described that Silica-aerogel significantly enhances asphalt's durability and thermal insulation, with 3% being the identified optimal concentration. The additive increased the asphalt's resistance to rutting and raised its high service temperature. It is important because the thermal conductivity of the asphalt was reduced by up to 15 times with just 3% aerogel, resulting composite asphalt binder is characterized by high strength, low rutting potential, and a long fatigue life.

Identification of a critical stress limit and the Use of Ground Granulated Blast-Furnace Slag (GGBFS)

Identifying a critical stress limit and demonstrating the effectiveness of GGBFS in improving impermeability under load is important for designing more durable roller-compacted concrete (RCC). Faraj, Toufigh, and Ghaemian (2025) defined that Critical Stress Threshold is of 40% of the compressive strength. Below this threshold, permeability decreases as microcracks close, but above it, permeability increases sharply as cracks connect and form fluid pathways. So, using Ground Granulated Blast-Furnace Slag (GGBFS) as an SCM (Supplementary Cementitious Materials) significantly enhanced the RCC's resistance to stress-induced permeability.

Pore-structure engineering and optimized aggregate gradation

Crystal growth pressure depends strongly on pore geometry. Fine, tortuous pore networks with pore radii in a critical range foster internal crystallization; conversely, either very small pores (where salt remains in solution) or open pore systems that allow crystals to grow outward reduce internal pressure. Scherer (2004) explained the damaging pressure exerted by crystal growth is highly dependent on pore geometry. The key is to engineer the pore network within the base/subbase material to avoid the "critical range" of pore radii that trap salts and foster destructive internal crystallization (subflorescence). The use of specifically graded aggregates and controlling fines content to create a fine and tortuous pore structure that discourages the formation of crystals within the pore walls. It is also important to incorporate a coarse layer or geotextile directly beneath the pavement surface acts as a capillary break, holding the evaporation front away from the structurally critical layers and allowing salts to crystallize in non-damaging locations.

Capillary break and active drainage systems

Perkins, Bowders, Christopher, and Berg (2005) described the use of geosynthetics in pavements grew until the 1990s, after which it plateaued. While paving fabrics are the most common type, the use of geosynthetics for reinforcement in base and subgrade layers is slowly increasing. The main barrier to wider adoption is the lack of universally accepted design models. The authors argue for a shift in philosophy, suggesting geosynthetics should be viewed as standard construction materials (like cement-treated bases) to improve performance against rutting and cracking, rather than as a special solution only for problem areas. The strategy of using capillary breaks and active drainage systems is based on the physics of interrupting the upward movement of saline water (capillary rise) and actively removing infiltrated water. This prevents salts from reaching and accumulating in critical structural layers (like the base and subgrade) and shortens the time these layers remain saturated, thereby reducing the potential for salt-related damage. **Approaches** include placing a coarse, hydrophobic layer (e.g., crushed stone) beneath the pavement to act as a capillary break, and using composite geosynthetic drains (geonets with geotextiles) to swiftly evacuate water, keeping the destructive evaporation zone near the maintainable surface. Regular inspection and maintenance of drainage (clearing silts) is critical. Long-term performance depends on preventing clogging, select geotextiles and drainage sizes with expected field clogging rates in mind.

Disintegrated Carbonaceous Mudstone Reinforced with Xanthan Gum

Fu, Zhang, Luo, Zeng, Zhong, Jia, Zhang, and Bian (2025) provided an effective and sustainable method to enhance the stability and durability of DCM (Disintegrated Carbonaceous Mudstone) embankments, which are prone to failure under rainfall. This approach can extend infrastructure service life and reduce maintenance costs, promoting safer and more economical construction. It is investigated that the use of xanthan gum (XG), a biopolymer, to improve the poor mechanical properties (low strength, large deformation, susceptibility to disintegration) of disintegrated carbonaceous mudstone (DCM) used embankments. An optimal XG content of 2.5% more than doubled the Unconfined Compressive Strength (UCS) of the DCM. This treatment significantly enhanced cohesion, internal friction angle, and dynamic rebound modulus, while reducing the permeability coefficient and the XG-modified DCM showed greatly improved resistance to dry-wet cycles. The modification mechanism involves XG filling pores and binding particles into a dense structure through colloidal interactions, cation exchange, and hydrogen bonding.

Flexural behavior of ultrahigh-performance concrete (UHPC)

Wu, Yang, Zhang, Hu, Qi, Lu, Wang, and Yao (2025) investigated the combined, or "coupling," effect of sustained mechanical stress and environmental exposure on the flexural performance of Ultra-High Performance Concrete (UHPC). They demonstrated that the long-term durability of UHPC is highly dependent on the interaction between sustained stress and the environment. While UHPC (ultrahigh-performance concrete) can self-heal in wet conditions, this beneficial effect can be negated by

simultaneous high loads and is severely compromised in chloride-rich environments due to fiber corrosion. The continuous flexural load itself had a negative impact, with higher loads (60%) causing greater reductions in strength and toughness compared to the unloaded control. Exposure to water led to the most significant recovery of flexural strength. This is attributed to ongoing chemical reactions (secondary hydration) that form additional strengthening compounds (C-S-H gel and calcium carbonate), which help heal micro-cracks. Exposure to the NaCl solution caused corrosion of the steel fibers within the UHPC. This corrosion undermined the material's integrity and counteracted any potential strength recovery, leading to poorer overall performance.

Hydrophobic and salt-repellent surface treatments

Hydrophobic treatments use to reduce water and chloride ingress into concrete. It provides experimental evidence on how materials like silane/siloxane-based impregnants lower sorptivity and chloride penetration. Sohawon and Beushausen (2019) investigated the use of silane impregnation cost-effective remedial treatment to extend the service life of concrete structures suffering from premature rebar corrosion due to insufficient concrete cover or poor quality. The silane treatment lines the concrete's internal capillary pores, creating a water-repellent surface that significantly reduces the absorption of water and chloride ions. The treatment was shown to suppress chloride ingress, lower the chloride diffusion coefficient, and reduce capillary absorption in various concrete mixes. Importantly, the silane impregnation also reduced chloride ingress in cracked concrete with crack widths up to 0.6 mm. application. From a physics perspective, slowing nucleation reduces the rate at which localized pressures develop.

Salt-resistant binders: geopolymers and tailored cementitious mixes

Geopolymers and specially modified cementitious matrices often exhibit lower permeability, different pore size distributions, and reduced free calcium hydroxide — affecting salt transport and reaction pathways. From a physical viewpoint, a more The silane impregnation can effectively extend the service life of concrete with inadequate cover, and it can allow for the use of smaller cover depths to achieve the same design life when applied properly.

Using molecular dynamics to simulate the effect of salt ions on the asphalt binder

Use of multi-scale modeling (from atomic to macro-scale) to design composite materials to simulate the effect of salt ions on the asphalt binder and aggregate interface, and then designing a better binder that can withstand the specific environmental conditions. Resin and aromatic components within the asphalt have the strongest attraction to sodium chloride, which helps draw the salt out of the material. Shao, Gao, Zhang, Lv, and Wang (2024) used molecular dynamics simulations to investigate how graphene oxide (GO) influences the self-healing properties of asphalt, both on its own and in combination with polyphosphoric acid (PPA). GO alone actually hinders the self-healing process, but when combined with PPA, it creates a superior composite.

Crystallization inhibitors and molecular scale control

Molecular crystallization inhibitors indicate promise for controlling salt damage in porous stone and concrete. Crystallization inhibitors as a sustainable strategy to control salt damage in both modern and historical porous building materials. Different families of inhibitors work to prevent or mitigate crystal growth, with a focus on their impact on salt transport and crystallization within a porous structure. Implementation for pavements requires dosage studies, environmental safety checks (toxicity and mobility), and cost-benefit analysis for field impermeable, tougher matrix resists both ingress and mechanical stresses. Geopolymers can be engineered for low permeability and high chemical resistance, and they can be fiber-reinforced for improved toughness.Optimize Ordinary Portland Cement (OPC) mixes by adding pozzolans (fly ash, silica fume) to refine pore structure and reduce permeability. Use shrinkage-compensating admixtures to reduce cracking. For asphalt mixes, use polymer modified binders and stone mastic asphalt

(SMA) designs with reduced porosity and improved fatigue resistance. Srinivasan and Sivakumar (2013) presented a comprehensive review of geopolymer binders as a sustainable alternative to conventional cement. The rationale is that traditional cement production is highly energy-intensive, consumes

significant natural resources, and is a major source of global CO_2 emissions.

With the increasing global demand for concrete, geopolymer binders made from industrial by-products are identified as an emerging and promising technology. The review focuses on the various production processes for developing these binders, highlighting their potential for cost-effective construction and reducing global warming.

Fiber reinforcement and composite layer strategies

Fiber reinforced geopolymers show improved fracture toughness and reduced crack growth. Natural fibers are attractive for environmental reasons but may require chemical stabilization to avoid alkaline degradation. Material selection should consider durability under salt exposure and service temperatures. Fibers (steel, synthetic, natural) increase tensile strength and energy dissipation capacity of cementitious matrices, limiting crack widths and thereby limiting pathways and niches where salts can concentrate and crystallize under confinement. Rajak, Pagar, and Linul (2019) explained that fiber-reinforced polymer composites are highly promising materials known for their high strength-to-weight ratio and exceptional properties, including durability, stiffness, and resistance to corrosion, wear, and fire. The performance of these composites is largely determined by their constituent fibers and manufacturing methods.

Multi-scale Material Modeling

Use of multi-scale modeling (from atomic to macro-scale) to design composite materials that can withstand the specific environmental conditions. Using molecular dynamics to simulate the effect of salt ions on the asphalt binder and aggregate interface, and then designing a better binder. This is a computational approach that connects the behavior of a material across different scales of magnitude from the atomic level to the visible, structural level (macro-scale). The core idea is that a material's macroscopic properties (e.g., strength, durability) are ultimately determined by its structure and interactions at the smallest scales. A multi-scale modeling is a powerful design tool that moves beyond trial-and-error, allowing for the rational design of advanced composite materials (like a better asphalt binder) by fundamentally understanding and manipulating their behavior from the atoms up.

Phase Change Materials (PCMs) for Temperature Regulation

Incorporation of microencapsulated PCMs in the asphalt mix to reduce thermal stress. PCMs can absorb and release heat during phase transition, thus reducing the temperature variations within the pavement.

Research methodology

Based on the above list several physics based approaches are directly relevant to improving the durability of road surfaces in the challenging environment of Pakistan's salt range that are categorized by the primary physical challenges. The key challenges in this region include salt weathering (physical and chemical degradation from salt crystallization), temperature fluctuations, and moisture. There are 17 physics based approaches can be categorize in 4 types given below:

1. Effectiveness in Combating Salt Weathering and Moisture Damage

Hydrophobic and salt-repellent surface treatments
Crystallization inhibitors and molecular scale control
Capillary break and active drainage systems
Pore-structure engineering and optimized aggregate gradation
Using molecular dynamics to simulate the effect of salt ions on the asphalt binder

2. Effectiveness in Enhancing Mechanical Strength and Fatigue Resistance

Flexural behavior of ultrahigh-performance concrete (UHPC)
Fiber Reinforcement
Fiber reinforcement and composite layer strategies
Identification of a critical stress limit and the Use of GGBFS
Improved Aggregate-Binder Adhesion

3. Effectiveness in Mitigating Thermal Stresses
Phase Change Materials (PCMs) for Temperature Regulation
Thermal Barrier Coatings
4. Sustainability and Environmental Impact
Salt-resistant binders: geopolymers and tailored cementitious mixes
Advanced Composite Materials
Use of Asphalt Binder and Nano Silica-Aerogel Composite
Multi-scale Material Modeling
Life Cycle Assessment and Durability Prediction Models
These four criteria converted into a set of four criteria that are commonly used in assessments:

Performance Impact: How much does the technique improve the durability and performance of the road?

Implementation Complexity: How complex is it to implement the technique? (Low complexity means easy to adopt, high complexity means requires significant changes or expertise)

Cost-Effectiveness: Is the technique providing good value for the cost? (High cost-effectiveness means high benefit relative to cost)

Technology Readiness: How mature is the technology? (High readiness means it's widely available and proven)
Researcher develop a matrix heatmap with four criteria for each technique and assigned a score for each of these four criteria for each of the 17 techniques.
This is a hypothetical assignment based on the review of literature knowledge.

Performance Impact
High: The technique significantly addresses the intended problem.
Medium: Moderate improvement.
Low: Minor improvement.

Implementation Complexity
High: Requires significant changes in design, construction, or materials; may require specialized equipment or expertise.
Medium: Some changes needed, but can be integrated with existing practices.
Low: Easy to implement with minimal changes.

Cost-Effectiveness
High: Low cost for high benefit.
Medium: Moderate cost for the benefit.
Low: High cost for the benefit.

Technology Readiness
High: Well-established and widely used.
Medium: Proven in research or some projects, but not yet widespread.
Low: Mostly in research phase.
Here the detail of assigning the score for each technique.

Hydrophobic and salt-repellent surface treatments
Performance Impact: High (if effective, can prevent water and salt ingress)
Implementation Complexity: Low (can be applied as a coating)
Cost-Effectiveness: Medium (cost of coating vs. extended life)
Technology Readiness: Medium (some products available, but long-term performance may vary)

Crystallization inhibitors and molecular scale control
Performance Impact: High (can prevent crystal growth damage)
Implementation Complexity: High (requires precise mix design and possibly new materials)
Cost-Effectiveness: Medium (cost of inhibitors vs. reduced damage)
Technology Readiness: Low (mostly in research phase)

Capillary break and active drainage systems
Performance Impact: High (effectively removes water)
Implementation Complexity: Medium (requires design and installation of drainage)
Cost-Effectiveness: High (can be very effective for the cost)
Technology Readiness: High (well-established in civil engineering)

Pore-structure engineering and optimized aggregate gradation
Performance Impact: Medium (reduces permeability but doesn't eliminate it)
Implementation Complexity: Low (part of standard mix design)
Cost-Effectiveness: High (low cost for improvement)
Technology Readiness: High (well-established)

Using molecular dynamics to simulate the effect of salt ions on the asphalt binder
Performance Impact: Low (it's a research tool, not a direct improvement)
Implementation Complexity: High (requires expertise and computational resources)
Cost-Effectiveness: Low (costly for indirect benefits)
Technology Readiness: Low (research phase)

Flexural behavior of ultrahigh-performance concrete (UHPC)
Performance Impact: High (excellent mechanical properties)
Implementation Complexity: High (special mix, placement, and cost)
Cost-Effectiveness: Medium (high cost but high performance)
Technology Readiness: Medium (used in special projects, but not common for roads)

Fiber Reinforcement
Performance Impact: Medium (improves tensile strength and crack resistance)
Implementation Complexity: Low (can be added to mix)
Cost-Effectiveness: High (low cost for the benefit)
Technology Readiness: High (widely used)

Fiber reinforcement and composite layer strategies
Performance Impact: High (composite action can significantly improve performance)
Implementation Complexity: Medium (may require layered construction)
Cost-Effectiveness: Medium (cost of fibers and additional layers)
Technology Readiness: High (composites are well-known)

Identification of a critical stress limit and the Use of GGBFS
Performance Impact: Medium (GGBFS improves durability and strength)
Implementation Complexity: Low (GGBFS is a common SCM)
Cost-Effectiveness: High (GGBFS is often a low-cost waste product)
Technology Readiness: High (well-established for concrete)

Improved Aggregate-Binder Adhesion
Performance Impact: Medium (reduces moisture damage)
Implementation Complexity: Low (adhesion promoters can be added)
Cost-Effectiveness: High (low cost for improved adhesion)
Technology Readiness: High (adhesion promoters are available)

Phase Change Materials (PCMs) for Temperature Regulation
Performance Impact: High (can significantly reduce thermal stresses)
Implementation Complexity: High (encapsulation and mix design challenges)
Cost-Effectiveness: Low (currently expensive)
Technology Readiness: Low (mostly research phase for roads)

Thermal Barrier Coatings
Performance Impact: Medium (reduces temperature fluctuations)
Implementation Complexity: Low (coating application)
Cost-Effectiveness: Medium (cost of coating vs. benefit)
Technology Readiness: Medium (some products available)

Salt-resistant binders: geopolymers and tailored cementitious mixes
Performance Impact: High (excellent chemical resistance)
Implementation Complexity: High (new materials and processes)
Cost-Effectiveness: Medium (could be cost-effective in the long term)

Technology Readiness: Medium (growing use but not standard)

Advanced Composite Materials
Performance Impact: High (tailored for high performance)
Implementation Complexity: High (may require specialized manufacturing)
Cost-Effectiveness: Low (often expensive)
Technology Readiness: Medium (used in some applications)

Use of Asphalt Binder and Nano Silica-Aerogel Composite
Performance Impact: High (improved properties and thermal insulation)
Implementation Complexity: High (nanomaterial dispersion is challenging)
Cost-Effectiveness: Low (high cost of nanomaterials)
Technology Readiness: Low (research phase)

Multi-scale Material Modeling
Performance Impact: Low (indirect, through better design)
Implementation Complexity: High (requires expertise and computation)
Cost-Effectiveness: Low (costly and indirect benefits)
Technology Readiness: Low (research phase)

Life Cycle Assessment and Durability Prediction Models
Performance Impact: Low (indirect, through better design and maintenance planning)
Implementation Complexity: Medium (requires data and modeling expertise)
Cost-Effectiveness: Medium (can lead to cost savings over life cycle)
Technology Readiness: Medium (some tools available, but not universally used)
Researcher converted Low, Medium, High to numerical scores for coloring: Low=1, Medium=2, High=3.
The Favorability Score for each criterion:
Performance Impact: High=3, Medium=2, Low=1
Implementation Complexity: Low=3, Medium=2, High=1 (inverted)
Cost-Effectiveness: High=3, Medium=2, Low=1
Technology Readiness: High=3, Medium=2, Low=1

Table 2 Complete Matrix Heatmap Data

Complete Matrix Heatmap Data

Sr #	Technique	TRL	Complexity	Cost-Effectiveness	Durability Impact	Total
1	Hydrophobic Surface Treatments	M	L	H	H	10
2	Crystallization Inhibitors	L	H	M	H	9
3	Capillary Break & Drainage	H	M	H	H	11
4	Pore-Structure Engineering	H	L	H	M	10
5	Molecular Dynamics Simulation	L	H	L	L	5
6	UHPC Flexural Behavior	M	H	L	H	9
7	Fiber Reinforcement	H	L	H	H	11

8	Composite Layer Strategies	M	M	M	H	9
9	Critical Stress Limit & GGBFS	H	M	H	H	11
10	Aggregate-Binder Adhesion	H	L	H	M	10
11	Phase Change Materials	L	H	L	H	8
12	Thermal Barrier Coatings	M	L	M	M	8
13	Salt-Resistant Binders	M	H	M	H	9
14	Advanced Composites	L	H	L	H	8
15	Nano Silica-Aerogel Composite	L	H	L	H	8
16	Multi-scale Modeling	L	H	L	M	6
17	Life Cycle Assessment Models	M	M	M	M	8

Figure 3 Heatmap of road durability techniques assessment matrix

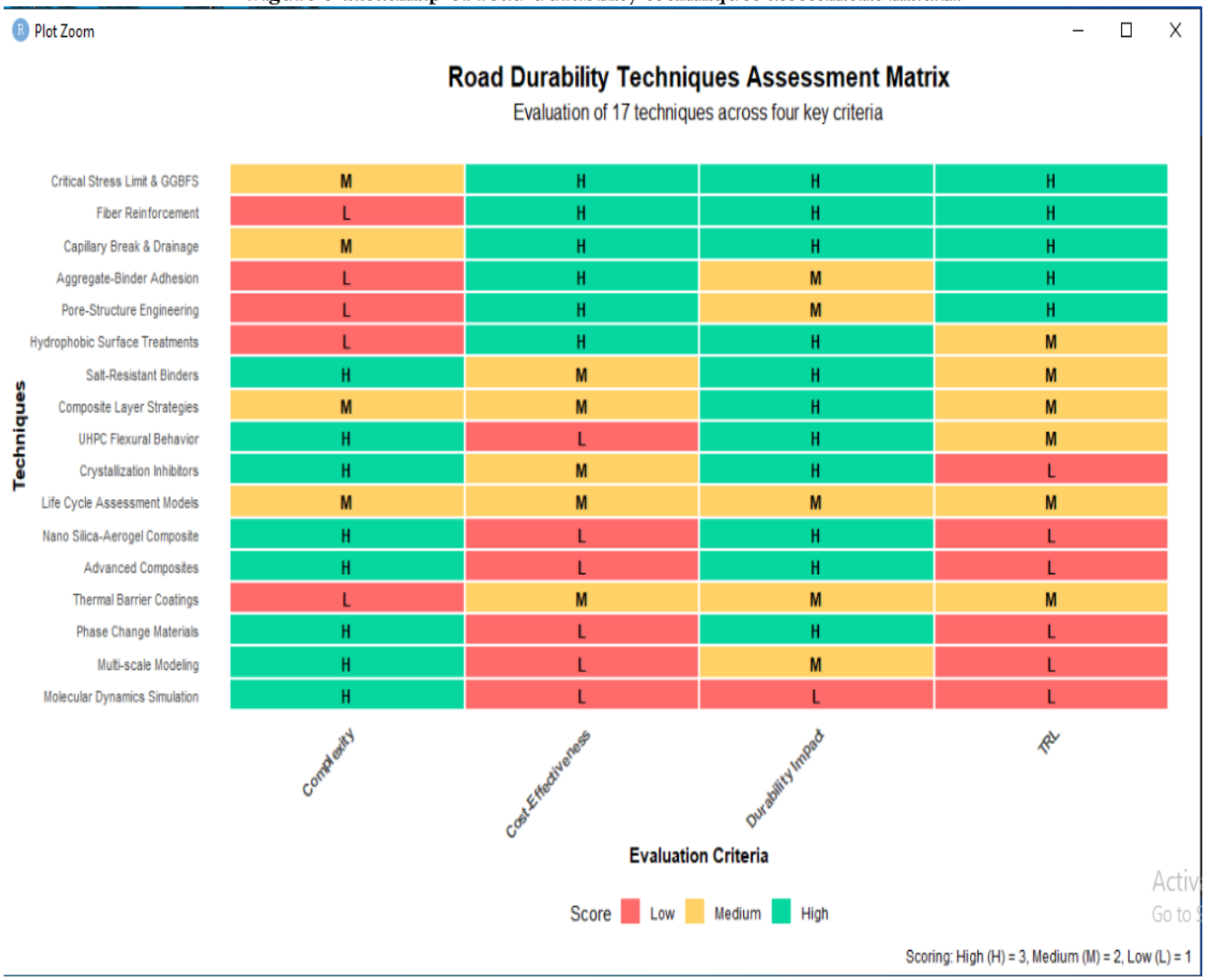


Figure 3 shows a heatmap matrix of Road Durability Techniques Assessment Matrix, evaluating 17 construction techniques across four criteria.

The visualization uses a color-coded system in R Software (red for Low, yellow for Medium, green for High) to represent scores. Techniques are sorted by overall performance, with the top performers like Critical Stress Limit & GGBFS, Fiber Reinforcement, and Capillary Break & Drainage showing mostly green High scores across all criteria.

The matrix reveals a clear performance gradient from top to bottom, with practical engineering solutions dominating the upper section and more research-focused or complex methods like Molecular Dynamics Simulation at the bottom with primarily Low scores. The evaluation appears to focus on practical implementation factors rather than just theoretical benefits.

Mitigation strategies and future considerations

Salt-induced deterioration is fundamentally a coupled physics and chemistry problem: limiting the physical transport of saline fluids, managing where and how salts crystallize, increasing mechanical resistance to internal stresses, and altering binder chemistry to reduce permeability and reactivity are all critical. For Pakistan's Salt Range, a systems approach combining layered pavement defenses (hydrophobic surfacings, capillary breaks, drainage geocomposites), salt-resistant binders

(geopolymers/pozzolanic blends), fiber reinforcement, and targeted use of crystallization inhibitors offers the best path to increase durability and reduce environmental impacts of recurrent road reconstruction. Engineering failures, including rutting, cracking, and rapid pavement degradation, are worsened by swelling-shrinkage cycles, poor water management, and extreme climate variability (Hussain et al., 2019). However, physics-based material science offers promising solutions to these challenges.

Gypsum and nano-composites can enhance soil stability by regulating ions and reducing sodicity (Farooqi et al., 2023). Additionally, precision-engineered matrices and salt-resistant polymers can minimize thermal and moisture damage (Stavi, Thevs, & Priori, 2021). By integrating geosynthetics, thermomechanical modeling, and adaptive drainage systems, engineers can enable predictive maintenance and extend infrastructure lifespan (Hussain et al., 2021; Masood et al., 2023). Stable isotope studies have also provided valuable insights into salt mobilization mechanisms, which are crucial for designing resilient pavements. A holistic, interdisciplinary approach that combines material innovation with environmental modeling is essential for developing sustainable road infrastructure in this geotechnically vulnerable region. To combat salt-induced road damage, sulfate-resistant concrete, polymer-modified asphalt, and enhanced slope drainage have been recommended (Hussain et al., 2021). The National Highway Authority (NHA) has documented frequent maintenance challenges along the M-2 Motorway, particularly near the Khewra Salt Range, where pillared bridges face accelerated corrosion (SMEC, 2022). Research suggests that preventive measures, such as geotextile barriers and sealants, could reduce salt penetration (Hussain et al., 2020). However, long-term solutions require integrated geological and engineering assessments to account for the region's unique evaporite-rich geology (Government of Pakistan's Directorate General of Archaeology, 2016). Future infrastructure projects in the Salt Range must prioritize material resilience and environmental adaptability to mitigate the persistent effects of salt weathering.

Road-scale and systems solutions (combining material and structural design)

In general any single material fixes rarely suffice; combining strategies at the pavement-system level maximizes benefit. Mostly three basic strategies can be used such as layered defense concept, use of local materials and treatment, and maintenance-oriented design for the road scaling and systems solutions.

Layered defense concept

Four types of treatments improve the road surfaces. This layered approach places the evaporation front at the surface and offers serviceable zones for cleaning and inhibitor reapplication.

Surface layer (top): Dense, low-permeability asphalt or geopolymeric overlay with hydrophobic impregnation.

Capillary break layer: Coarse graded layer or geocomposite to stop wicking.

Drainage layer: Geonet/geocomposite leading to edge drains.

Salt-tolerant base/subbase: Treated with stabilization (lime/POZ/geopolymer) and fiber reinforcement if local materials are saline.

Use of local materials and treatment

Where possible, avoid importing large volumes of fresh aggregate. Characterize local salt content in available aggregates/soils and use stabilization (cementitious or geopolymer) to render them usable. Research indicates treated saline soils can be used in road bases with modified design parameters.

Maintenance-oriented design

Design pavements for accessible cleaning of salt crusts (surface washes), scheduled re-application of inhibitors/impregnations, and modular overlays for targeted replacement rather than full reconstruction.

Testing, monitoring and specification recommendations

To implement the physics-based approaches effectively, rigorous testing and monitoring protocols are essential. Some laboratory tests are necessary for the durability of road surfaces in salt range areas. Capillary absorption (sorptivity) and water vapor

permeability of candidate surfacings and coatings. Salt crystallization tests (accelerated cyclic tests using representative salts like Na_2SO_4, NaCl) to measure mass loss, strength loss, and cracking thresholds. Studies on sodium sulfate crystallization are particularly relevant. Permeability and chloride diffusion tests for concrete/geopolymer mixes. Freeze–thaw with salt solution tests where thermal cycles matter. Field monitoring is another requirements for the implementation of physics-based approaches. For this purpose install moisture and salinity sensors at key layer depths to monitor salt ingress patterns and evaluate capillary break performance. Use of infrared or acoustic emission methods to detect early crack formation associated with internal crystallization. Implementation of periodic surface and subsurface sampling for soluble salt content to guide prophylactic maintenance. Move away from purely compressive-strength based acceptance towards durability indices: maximum sorptivity, minimum drainage transmissivity for geocomposites, and acceptable salt loading thresholds for material acceptance.

Environmental and lifecycle considerations

A central justification for improving durability is reducing environmental harm from reconstruction: embodied emissions of materials, transported waste, and habitat disturbance. Physics-based interventions generally reduce life-cycle impacts by prolonging service life, but attention must be paid to the environmental profile of applied products (inhibitors, polymers, alkali activators). When sourced from industrial byproducts, geopolymers can reduce embodied CO_2 of overlays/repairs. However, alkali activator production and transportation must be included in LCA. Evaluation of ecotoxicity and leaching potential ideally choose biodegradable or inert inhibitors and ensure runoff control (catchment/drainage treatment) to minimize ecosystem contamination. Stabilization of local saline soils reduces quarrying transport emissions. But stabilization chemistry must be balanced to avoid creating secondary pollution. A quantitative lifecycle assessments tailored to project scales in the Salt Range (e.g., km of highway) are recommended to prioritize interventions that deliver highest durability per unit environmental cost.

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