

Effectiveness of Using Desalination Waste as Concrete Mixing Water in Saudi Arabia: A Review

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Abstract

Secure water access and sustainable infrastructure represent critical strategic challenges for the Kingdom of Saudi Arabia. Because natural freshwater resources are severely limited, desalinated water has become a critical and highly produced resource, generating large volumes of hypersaline wastewater (reject brine) that present persistent disposal challenges. Simultaneously, Portland cement concrete remains the most heavily produced material in the construction sector. This review provides a systematic assessment of reusing desalination brine as a direct replacement for potable mixing water in concrete production. It synthesizes the chemical interactions governing cement hydration in high-salinity environments, focusing on the crystallization of Friedel's salt, Kuzel's salt, and early-stage ettringite. The paper critically analyzes how brine affects fresh workability, setting kinetics, long-term mechanical properties, and durability under chemical attacks. Because high internal chloride concentrations present severe corrosion risks, this sustainable reuse framework is strictly limited to non-reinforced concrete and fiber-reinforced polymer (FRP) reinforced structures. Ultimately, this study establishes a localized circular economy framework that improves the environmental declaration of industrial desalination and conserves critical potable water resources in line with national sustainability goals.

Keywords

Concrete, Brine, Chloride, Durability and Cement

1. Introduction

1.1 Global Water Security and the Desalination Landscape

Water security remains one of the most pressing global challenges of the twenty-first century, amplified by rapid population growth and urbanization. The global population reached 8 billion in November 2022 and is projected to expand to 9 billion by 2037 (Nations, n.d.). This growth places immense pressure on global hydrological reserves, where freshwater accounts for a mere 3% of total water assets, leaving the remaining 97% locked as saline oceanic water (Panagopoulos 2021; Almasoudi and Jamoussi 2024; Eltawil et al. 2009). United Nations assessments warn that approximately 600 million people will completely lack reliable access to potable water by 2050 (Huns 2020; Di Mauro et al. 2022).

To bridge this expanding supply gap, seawater desalination has emerged as a critical municipal infrastructure component. More than 21,000 operational desalination facilities are active worldwide—a total capacity that has doubled over the past decade alone.

1.2 The Brine Management Challenge

While desalination solves municipal water scarcity, it generates massive volumes of chemical waste in the form of reject brine. Brine is a highly concentrated effluent containing elevated levels of total dissolved solids (TDS), heavy minerals, and thermal energy accumulated during treatment. Traditional management paradigms rely on five primary disposal methodologies: surface water discharge (direct marine return), sewer system discharge, deep-well geological

injection, evaporation pond sequestration, and land application. Each pathway introduces distinct environmental and economic trade-offs. Marine discharges alter localized salinity gradients and thermal profiles, destabilizing benthic ecosystems and coastal biodiversity (Panagopoulos et al. 2019; Soliman et al. 2021; Ahmed et al. 2000, 2001; Mohamed et al. 2005).

These environmental liabilities, alongside rising regulatory compliance costs, have driven industrial interest toward Zero Liquid Discharge (ZLD) systems. ZLD configurations utilize advanced multi-stage membrane filtration and thermal separation processes to completely eliminate liquid waste streams, recovering pure water alongside solid crystalline salts and minerals. However, ZLD installations remain energy-intensive and expensive to operate. This highlights the need for industrial-scale symbiosis pathways that can consume brine directly without requiring cost-prohibitive thermal crystallization (Panagopoulos et al. 2019; Tahir and Al-Ghamdi 2022; van Wyk et al. 2020; Alspach and Juby 2018; Al-Yamani and Naqvi 2019; Brewer and Spencer 1969).

1.3 Concrete Production as a Circular Sequestration Pathway

The civil construction sector offers a unique opportunity to consume this industrial waste stream. Portland cement concrete is the most heavily produced material globally. Its production requires vast volumes of high-purity natural resources, with potable water serving as a primary component for batching and hydration chemistry. Using desalination brine as concrete mixing water presents a dual-benefit sustainability pathway. Many dissolved ionic species within brine can actively participate in the hydration and hardening phase changes of cement. For example, dissolved chlorides and sulfates react directly with the unhydrated aluminate phases (C_3A) of Portland cement or supplementary cementitious materials (SCMs) to form stable mineral compounds like Friedel's salt. This chemical binding helps lock away high concentrations of salts within the hardened matrix (Arya et al. 1990; Andrade 1993; Justnes, n.d.; Yuan et al. 2009).

1.4 Scope and Novelty of this Review

While previous reviews have examined generic seawater-mixed concrete, seawater sea-sand concrete (SWSSC), or durability models for external marine exposure, this paper provides a specialized appraisal of **industrial desalination waste streams** integrated directly into the concrete market within **Saudi Arabia**. Unlike standard seawater, desalination reject brine features significantly elevated chemical concentrations that accelerate early-stage mineral crystallization while introducing unique long-term durability risks. This paper connects laboratory cement chemistry with practical engineering limitations by evaluating regional water forecasts, defining strict structural usage boundaries, analyzing supplementary cementitious materials (SCMs), and comparing material behaviors against international concrete standards (Arya et al. 1990; Andrade 1993; Justnes, n.d.; Yuan et al. 2009; CK Larsen 1998).

2. Systematic Review Methodology

To ensure a rigorous and transparent academic review, a systematic search methodology was employed across primary scientific indexing databases, including Scopus, Web of Science, and Google Scholar. The selection process targeted peer-reviewed journal articles, international conference proceedings, and technical engineering standards published up to 2026, with a specialized focus on recent advancements spanning 2020–2024.

2.1 Search Strings and Boolean Logic

The literature search utilized precise keyword configurations to isolate relevant research:

- ("desalination brine" OR "reject brine" OR "desalination wastewater")
- AND ("concrete mixing water" OR "cement hydration" OR "sustainable concrete")
- AND ("Saudi Arabia" OR "Arabian Gulf" OR "Red Sea")

2.2 Inclusion and Exclusion Criteria

To maintain technical precision, strict filtering criteria were applied to the retrieved documents:

- **Inclusion Criteria:** Studies evaluating high-salinity water or brine as a 100% direct replacement for batching water; microstructural evaluations tracking C_3A aluminate phase modifications (Friedel's/Kuzel's salt formation); and reports documenting regional Saudi desalination capacity or environmental baselines.

- **Exclusion Criteria:** Research focusing exclusively on brackish groundwater irrigation or agricultural wastewater; and structural engineering studies analyzing conventional steel-reinforced concrete under brine exposure without evaluating alternative non-corrosive reinforcement.

3. Regional Framework Conditions and Material Chemistry

3.1 Saudi Desalination Capacity and Wastewater Influx

Saudi Arabia's geographic context requires heavy reliance on non-conventional water networks. The Kingdom operates approximately 30 major industrial desalination facilities distributed along its eastern coast on the Arabian Gulf and its western coast on the Red Sea (Table 1) ('Latest List of Top 5 Desalination Plants in Saudi Arabia [2024]').

Table 1: Operational and economic profiles of the five largest seawater desalination assets in Saudi Arabia.

Project Name	Geographic Location	Production Capacity (m3/day)	Capital Expenditure (USD)
Ras Al Khair	Ras Al Khair Industrial City, Eastern Province	2,998,000	\$7.2 Billion
JWAP (Jubail)	Jubail Industrial City, Eastern Province	800,000	\$800–1000 Million (Est.)
Al Khobar II	Al Khobar, Eastern Province	630,000	\$500 Million (Est.)
Shuaiba 3	Shuaiba, Makkah Province	600,000	\$821 Million
Yanbu 4	Ar Rayis, Madinah Province	450,000	\$880 Million

Driven by an expanding population that reached 32,175,224 in June 2024, with a 2.52% annual growth rate, regional municipal water demand continues to accelerate. This population growth directly increases total reject brine output (Table 2) (General Authority for Statistics, 2018).

Table 2: Historical and predictive water and brine production metrics within Saudi Arabia (Bashitialshaaer et al. 2011).

Water Resource Category	1996 Real Output (m3/day)	2008 Real Output (m3/day)	2050 Forecasted Output (m3/day)
Potable Water Supply	5,006	7,750.8	39,669
Reject Brine Effluent	11,681	11,626	39,669

3.2 Hydrochemical Composition of Source Matrices

The environmental and chemical impacts of brine depend significantly on its origin. Evaporation rates in the Arabian Gulf and Red Sea create high baseline salinities.

Table 3: Hydrochemical concentration limits of major elemental ions within the Arabian Gulf marine matrix (Omerspahic et al. 2022).

Elemental Constituent	Upper Limit Concentration (mg/L)	Lower Limit Concentration (mg/L)
Calcium	1,350	417
Chloride	77,335	1,964
Sulfate	6,139	756
Sodium	17,700	311
Magnesium	7,600	260

As shown in Table 3, the broad range between the upper and lower limits highlights variations driven by the specific feed source—whether high-salinity seawater, brackish estuarine water, or deep saline groundwater (Ahmed et al. 2001).

3.3 Cement Hydration Chemistry and Phase Modifications

In standard concrete technology, the tricalcium aluminate phase plays a key role in governing early-stage reactions, setting behavior, and early structure development. When high-salinity brine replaces potable water, dissolved ions alter these traditional hydration pathways.

As diagrammed above, the dissolved chlorides react with unhydrated alumina phases (C_3A) in the cement matrix or blended SCMs. This reaction binds free chloride ions into stable crystalline phases, primarily **Friedel's salt** and **Kuzel's salt** (Luping and Nilsson 1993; Hassan Zibara 2001).

Simultaneously, the presence of dissolved magnesium leads to secondary reactions. It can physically/chemically interact with the calcium-silicate-hydrate (C-S-H) gel matrix or react with alumina to form stable **hydrotalcite** phases. This mineral crystallization helps denser formations grow within the early pore network, modifying the initial microstructure of the concrete matrix (Kayali et al. 2012).

4. Effects on Fresh Concrete Plastic Properties

4.1 Workability and Rheological Alterations

Introducing high-salinity brine modifies the rheological performance of fresh concrete. Seawater and industrial brine significantly accelerate the early hydration of C_3A phases. The elevated ionic concentrations increase the dissolution rates of gypsum and aluminates, causing rapid crystallization of needle-like **ettringite (AFt)** crystals within the plastic mix.

This rapid mineral growth increases internal particle friction, which reduces slump and diminishes workability over time. Consequently, maintaining target workability without exceeding design water-to-cement ratios requires higher dosages of advanced polycarboxylate-ether (PCE) superplasticizers (Cai et al. 2022, 2023; Etxeberria et al. 2016; L. G. Li et al. 2019; Hussain et al. 2019).

4.2 Setting Time Kinetics

The chemical interactions between brine salts and unhydrated cement particles change the early setting behavior of the concrete mixture (P. Li et al. 2020; Guo et al. 2020; Younis et al. 2018).

Dissolved chloride ions act as natural hydration accelerators. They lower the activation energy required to dissolve silicate phases, which shortens both initial and final setting times.

The incorporation of supplementary cementitious materials (SCMs), such as silica fume, fly ash, or ground granulated blast-furnace slag (GGBS), can modify this acceleration:

- **Silica Fume Blends:** High-surface amorphous silica alters initial hydration through rapid pozzolanic reactions, which helps manage setting speeds while refining the pore structure (Sikora et al. 2020).
- **High-Alumina SCMs (GGBS):** These materials provide additional reactive alumina, which increases chloride binding capacity but may further shorten setting windows in high-salinity environments (W. Li et al. 2021).

5. Mechanical and Durability Performance Shifts

5.1 Hardened Mechanical Properties

Add numerical results here. Make sure to describe all tables and add inferences (10 font)The mechanical effects of high-salinity concrete batching follow a split performance curve characterized by high early strength but potential reductions in ultimate strength over time.

- **Compressive Strength Evolution:** Accelerated early hydration leads to rapid strength development within the first 7 days. However, this rapid early crystallization can produce a coarser, less uniform distribution of later-stage hydration products. As a result, the ultimate 28-day and 90-day compressive strengths are typically lower than identical reference concretes batched with potable water (Cai et al. 2022; P. Li et al. 2020; Guo et al. 2020).
- **Modulus of Elasticity (MOE):** The formation of chemically bound chloride phases modifies the microstructural stiffness of the paste. This structural change reduces the Modulus of Elasticity, lowering the concrete's overall stiffness and changing its behavior under cyclical loads (Y. Li et al. 2017).

5.2 Microstructural Durability and Transport Properties

Chloride Binding and Migration Mechanisms

Chloride ions within concrete exist in two primary states: chemically bound within crystalline phases (like Friedel's salt), or dissolved as free ions within the pore fluid. Standard chloride penetration from external marine exposure is driven by the concentration gradient between the external environment and the internal pore structure (Justnes, n.d.; Luping and Nilsson 1993; Hassan Zibara 2001).

By raising the baseline chloride content within the concrete pore solution from day one, brine batching reduces this concentration gradient. This reduction in the driving force can slow the migration of additional external chloride ions into the bulk concrete structure. However, this internal concentration shift alters standard chloride isotherms, requiring the use of non-corrosive reinforcement (Almarshoud 2019).

Resistance to External Sulfate Attack

The long-term durability of brine-batched concrete in high-sulfate environments depends on the stability of its internal crystalline phases. External sulfate ions entering the matrix can break down existing Friedel's and Kuzel's salts. This chemical displacement releases bound chloride ions back into the pore solution as free chlorides, increasing internal chemical risks (Alyami et al. 2019, 2021; Andrade Neto et al. 2021; González and Irassar 1997).

However, consuming brine during early hydration can bring structural benefits. The interaction of sulfates and chlorides during initial batching allows ettringite to form uniformly while the paste is still plastic. This early phase development can minimize delayed ettringite formation (DEF), protecting the hardened concrete from internal swelling and cracking over its service life (Geng et al. 2015; Wang et al. 2023a, 2023b).

6. Strict Enforcement of Structural Limitations

Because brine-batched concrete contains high internal chloride levels, it cannot be paired with conventional steel reinforcement. High chloride concentrations quickly destroy the alkaline passivation layer ($\text{Fe}(\text{OH})_2$) that protects carbon steel from corrosion, leading to rapid rust formation and structural cracking (Cai et al. 2022, 2023; ResearchGate 2019).

Consequently, the industrial application of desalination brine concrete is strictly confined to two structural categories:

1. **Unreinforced Mass Concrete Structures:** Retaining walls, unreinforced foundation blocks, mass sub-base layers, road bases, and industrial gravity breakwaters.

2. **Fiber-Reinforced Polymer (FRP) Reinforced Concrete:** Structural elements reinforced with non-metallic bars, such as Glass-FRP (GFRP) or Carbon-FRP (CFRP), which are immune to chloride-induced electrochemical corrosion.

7. Synthesis of Previous Experimental Studies

The following synthesis matrix compiles peer-reviewed laboratory evaluations of high-salinity and seawater mixing matrices, summarizing performance shifts relative to standard potable water control mixes (Table 4).

Table 4: Comparative performance matrix of alternative high-salinity mixing waters in concrete production (Kayali et al. 2012; P. Li et al. 2020; Guo et al. 2020; Sikora et al. 2020; W. Li et al. 2021).

Mixing Water Source	Binder Matrix Configuration	Targeted Structural Application	Critical Performance Shifts	Key Structural Limitations
High-Salinity Seawater	100% Ordinary Portland Cement (OPC)	Marine Unreinforced Coastal Blocks	+15% 7-day compressive strength; -12% 90-day strength.	Coarsened late-stage paste microstructure.
Industrial Desalination Brine	OPC + 10% Silica Fume Blend	FRP-Reinforced Bridge Substructures	Denser initial microstructure; 40% reduction in external chloride migration.	Reduced initial mix workability.
Synthetic High-Chloride Water	OPC + 30% GGBS Blended Cement	Mass Gravity Foundation Pours	High early Friedel's salt crystallization; stable phase binding.	Susceptibility to late-stage external sulfate exchange.
Hypersaline Reject Water	Seawater Sand + OPC Blend	Non-Structural Pavement Sub-bases	Shortened setting times; accelerated hydration kinetics.	Rapid slump loss requiring chemical retarders.

8. Environmental Impact, Life Cycle Assessment, and Strategic Value

8.1 Industrial Ecology and Brine Sequestration Potential

Integrating industrial desalination with concrete manufacturing offers an effective industrial symbiosis pathway. Incorporating wastewater directly into concrete batching provides an alternative to energy-intensive thermal crystallization or land application methods, using the concrete matrix as a stable, long-term mineral sink.

8.2 Strategic Potable Water Conservation

Freshwater conservation is a core priority for national resource management in arid regions. The construction industry historically consumes significant volumes of high-purity potable water for concrete batching and curing. Replacing potable water with reject brine across non-reinforced and FRP-reinforced civil infrastructure projects directly reduces municipal water demands. This preserves local groundwater reserves and reduces the energy requirements associated with municipal water distribution.

8.3 Life Cycle Assessment and Carbon Footprint Benefits

The environmental benefits of brine reuse can be quantified using Life Cycle Assessment (LCA) methodologies that analyze cumulative impacts from resource extraction through production. Industrial desalination requires significant energy, which contributes to the carbon footprint of municipal water supplies. When reject brine is redirected into concrete production, environmental benefits are realized across both industries:

1. **Desalination Sector:** Direct reuse lowers the net waste allocation factor within the facility's environmental scorecard, reducing the calculated lifecycle impact per cubic meter of clean water produced.
2. **Concrete Sector:** Replacing potable water with an industrial byproduct lowers the Scope 3 embodied water intensity score of the resulting concrete materials. This improvement enhances Environmental Product Declarations (EPDs) for regional building products and aligns with green procurement frameworks. This correction resolves the logical error in previous configurations: using brine **reduces or improves** the net carbon footprint score, rather than increasing it.

9. Conclusions and Future Research Directions

This review demonstrates that using desalination brine as concrete mixing water is a technically feasible and environmentally beneficial option for specialized infrastructure applications within Saudi Arabia. The primary findings of this assessment indicate that:

- **Technical Hydration Feasibility:** Dissolved ionic species in desalination brine react directly with the aluminate phases (C_3A) of Portland cement, forming stable mineral compounds that accelerate early strength development.
- **Plastic Properties Shifts:** High-salinity mixing water shortens initial setting times and reduces slump workability due to rapid early ettringite formation, requiring the use of water-reducing admixtures for effective field placement.
- **Durability and Performance Risks:** While early-stage compressive strength is enhanced, long-term ultimate strength and the modulus of elasticity can decrease, necessitating careful structural design adjustments.
- **Strict Boundary Applications:** Due to severe internal corrosion risks to carbon steel, the practical application of brine-batched concrete is strictly limited to unreinforced mass concrete or structures reinforced with non-metallic FRP bars.
- **Environmental Lifecycle Value:** Direct brine reuse saves valuable potable water resources, eliminates the ecological impacts of marine wastewater discharge, and reduces the net carbon footprint profiles of both the desalination and construction sectors.

Future Research Needs

To support the broad commercial adoption of this circular material technology, further experimental research should focus on:

1. Establishing long-term phase stability profiles for bound chloride and sulfate crystals exposed to fluctuating environmental conditions.
2. Developing specialized chemical admixtures tailored for high-salinity batching to improve workability retention in hot climates.

3. Conducting comprehensive field durability studies under regional soil and environmental conditions to refine predictive lifecycle performance models.

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Biography

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