The performance of corrosion protection measures on the chloride ingress of concrete in a solar salt environment

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Abstract

Solar salt production at Rio Tinto Dampier Salt Limited (DSL) sites involves the progressive evaporation of seawater to precipitate salt, followed by washing, drying, and exportation. This process exposes concrete assets to high chloride concentrations, leading to chloride ingress and subsequent reinforcement corrosion. This study aims to test various corrosion protection measures including crystalline and hydrophobic admixtures, silane-based penetrative coatings, waterproof membranes, and protective coatings against chloride ingress through accelerated laboratory and site-based exposure testing. Experimental results will provide DSL personnel with a performance database for protection measures, supporting current maintenance and future asset commissioning. This aims to extend asset lifespan, deferring future cost expenditure on repair and maintenance. To date, preliminary results (based on weight change) indicate that crystalline and hydrophobic admixtures offer the highest resistance to ingress, closely followed by silane-based penetrative treatments and protective coatings.

1. Introduction

Dampier Salt Limited (DSL), a 68%-owned subsidiary of Rio Tinto, is the world's largest exporter of seaborne salt, producing 10.3 million tonnes annually through solar salt operations in Dampier, Port Hedland, and Lake MacLeod. Operations involve the precipitation of salt from seawater via evaporation, followed by washing, drying, and exportation. This process exposes concrete assets to high chloride concentrations allowing for chloride ion penetration into the concrete matrix. Capillary action, diffusion, and permeation transport ions to the surface of embedded steel reinforcements, initiating corrosion processes, significantly reducing the asset's service life. This issue is prevalent across all three sites operated by DSL, contributing to site shutdowns for maintenance and asset replacement.

This study aims to evaluate the performance of several corrosion protection measures including crystalline and hydrophobic admixtures, silane-based penetrative coatings, waterproof membranes, and protective coatings. These measures will undergo both on-site and accelerated laboratory testing, with results guiding DSL in safeguarding future assets and mitigating damage to existing ones. Ultimately, this approach could enhance system efficiency and reduce both downtime and operational costs.

1.1 Transport Methods

Chloride ion transfer into the concrete matrix typically occurs through capillary action, diffusion, and permeation (Li et al., 2019). Capillary absorption occurs when liquids penetrate the concrete's capillary pores due to surface tension and negative pressure, typically in partially dry concrete (Mengel et al., 2019). The high evaporation rates in the Pilbara accelerates this process by quickly drying surfaces, reducing the surface tension between the liquid in the pores and the surface. Diffusion is common in newer assets, where chloride ions move through the concrete's pore network, following a concentration gradient until equilibrium is reached (Christodoulou et al., 2013). Permeation is driven by pressure differences and allows the greatest volume transfer, influenced by factors such as porosity, moisture content, and concrete defects (Mengel et al., 2019).

1.2 Crystalline Admixtures

Crystalline admixtures (CAs) consist of a diverse blend of particles varying in sizes and compositions, including cement, fillers, pozzolans, slags, and sands (Antón et al., 2024). Diversification within the mix of CAs allows them to exhibit high hydrophilicity. Upon contact with water, CAs also react to form insoluble crystalline precipitates, sealing cracks and pores within the concrete matrix reducing ingress via capillary action and permeation.

1.3 Hydrophobic Admixtures

Hydrophobic admixtures are chemicals which form a thin water-repellent polymer within the pores and capillaries of concrete. By lining these pathways, they render the entire concrete mass water-resistant, minimising water absorption through capillary action. Additionally, polymers in the admixture interact with infiltrating water, forming a physical plug that blocks pathways, preventing further water ingress.

1.4 Silane Based Penetrative Surface Coatings

Due to its small molecular size of approximately 0.4 to 1.5 nm (Sika, n.d.), silane effectively penetrates voids and capillaries within the concrete matrix. This makes it suitable for dense substrates, such as the high-durability concrete mix used in testing. Upon impregnation molecules polymerise, lining voids and capillaries and reduce absorption through capillary action.

1.5 Waterproof (Polyurethane) Membrane

Waterproof membranes (WM) are flexible coatings used to protect surfaces against ingress. By fully sealing the concrete surface, the membrane masks imperfections, including pores and capillary networks extending from the surface. The application of a WM offers three main benefits: increased surface contact angle, reduced permeability, and resistance to capillary ingress.

1.6 Protective Coatings

Protective coatings (PCs) can be either polymer-based or cementitious, both forming continuous films that limit the penetration of substances into concrete matrix (Coffetti et al., 2021). Polymer-based coatings such as epoxy resins, acrylics, and polyurethanes resist carbon dioxide, chloride ions, oxygen, and water ingress, key factors in concrete degradation. They also allow water vapour to escape from the concrete matrix, reducing the risk of delamination. Multiple layers are often applied for optimal protection, facilitating easy maintenance and application on existing structures.

2. Process

2.1 Sample creation

Two mix designs were used in sample creation, Business as Usual (BAU) and High Durability (HD). BAU is a standardised concrete mix, previously used by DSL and serves as a standalone control sample, with a minimum compressive strength (f'c) of 40 MPa. HD follows an updated DSL concrete specification with a higher minimum compressive strength (f'c 50 MPa). Based on the C2 exposure classification of Bridge Code AS 5100.5 (Standards Australia, 2017), it serves as the base for all tested protection measures.

Six 100 mm cubic samples were cast for each protection measure, including control samples for both mix designs. Admixtures were incorporated into the HD mix prior to casting while other measures saw HD samples cast, cured, then treated in accordance with respective technical data sheets. Additionally, three AS 1012.9 (Standards Australia, 2014), compliant cylinders (200 mm long x 100 mm diameter) were cast for 28-day compressive strength testing of both control mixes and admixture types.

2.2 Testing Background

Samples were divided across two fronts of testing: laboratory accelerated and site exposure. Each protection measure saw four samples transported to the DSL Dampier site, retaining two at the University of Western Australia (UWA) for accelerated testing. This distribution saw 28 samples being placed on site, with 14 remaining at UWA.

2.3 Short and Long term site exposure testing

Site exposure samples were positioned under DSL's Dampier site conveyor transfer tower, a key location for chloride exposure due to salt spillage and wash down. Samples were secured on grid mesh using cable ties (Figure 1, left), ensuring uniform exposure while allowing for drainage and easy insertion and removal. Two samples per protection measure will be subjected to short-term site exposure testing, limited to the duration of this study. Remaining samples will remain on site for a long-term study conducted by DSL, aimed at assessing natural chloride ingress over a five-year period.

2.4 Lab accelerated testing

The two remaining samples per protection measure at UWA will be subjected to accelerated laboratory testing. This process involves simulating the wetting and drying cycle that occurs on site. Samples will be fully submerged in brine sourced from the DSL Dampier site (Figure 1, right) for two days followed by three days of oven drying at 40ºC then weighed for water intake. This cycle is continuously repeated until analysis of results in early October.

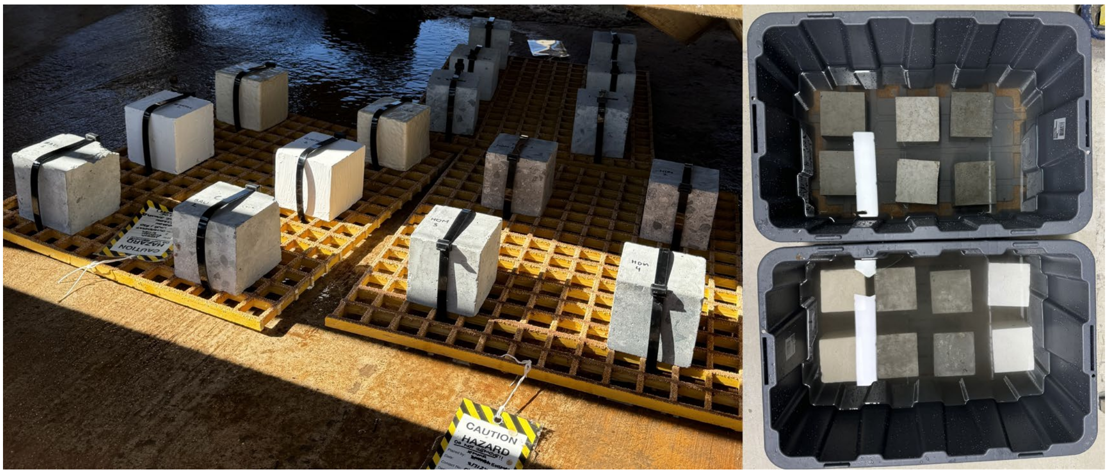

Figure 1 Site exposure samples secured on a grid mesh jig (left); lab accelerated samples submerged in brine (right).

2.5 Analysis Methodology

Chloride ingress will be evaluated by Duratec in accordance with BS 1881 P124 (British Standards Institution. n.d.). Using a 15mm masonry drill bit, powder samples will be collected at depths of 0-5mm, 10-15mm, and 20-25mm from the surface of cubical samples, then titrated with silver nitrate to determine chloride concentration. This process will be conducted on three samples per measure, one exposed to short-term site testing and both accelerated testing samples.

3. Results and Discussion

3.1 Compression test results

The BAU and HD samples achieved minimum compressive strengths of 42.4 MPa and 49.8 MPa, respectively. Although the HD sample slightly fell short of the 50 MPa minimum requirement, it remains within the acceptable range according to AS 1379, which allows for a standard deviation of up to 4.2 MPa (Standards Australia, 2007). Hydrophobic and Crystalline mixes exhibited reduced compressive strengths of 44.27 MPa and 45.27 MPa, representing decreases of 11.1% and 9.1%, respectively, when compared to the 49.8 MPa result of the HD cylinders. These reductions render the Hydrophobic and Crystalline mixes non-compliant. While achieving maximum compressive strength was not the primary objective of this project, inconsistent mixing, inaccurate measurement of additives, or uneven curing conditions could have led to variations in the concrete's composition and performance.

3.2 Ingress results (by weight)

To date samples have undergone ten testing cycles, amounting to 50 days of testing. Plotted results in Figure 2 show the average weight change of samples throughout this period. All protection measures exhibited similar trends in weight variation, with greater weight loss during each drying phase than the weight gained during the preceding immersion stage. This cumulative effect led to a continuous reduction in overall weight, indicating progressively drier concrete over time.

Crystalline and Hydrophobic admixtures showed the most promising results with the greatest weight loss observed across the 50-day period. On average, Crystalline samples exhibited a net weight loss of 22g, slightly outperforming the Hydrophobic samples, which saw a net loss of 18.8g. Silane-treated samples performed comparably to those coated with a protective layer, which also required a silane-based primer for application, possibly influencing these results. Waterproof Membrane samples exhibited the least weight loss, behaving similarly to BAU samples which despite receiving no treatment, showed a negative weight gain. In contrast, HDM samples demonstrated significant weight fluctuations, with immediate water intake observed.

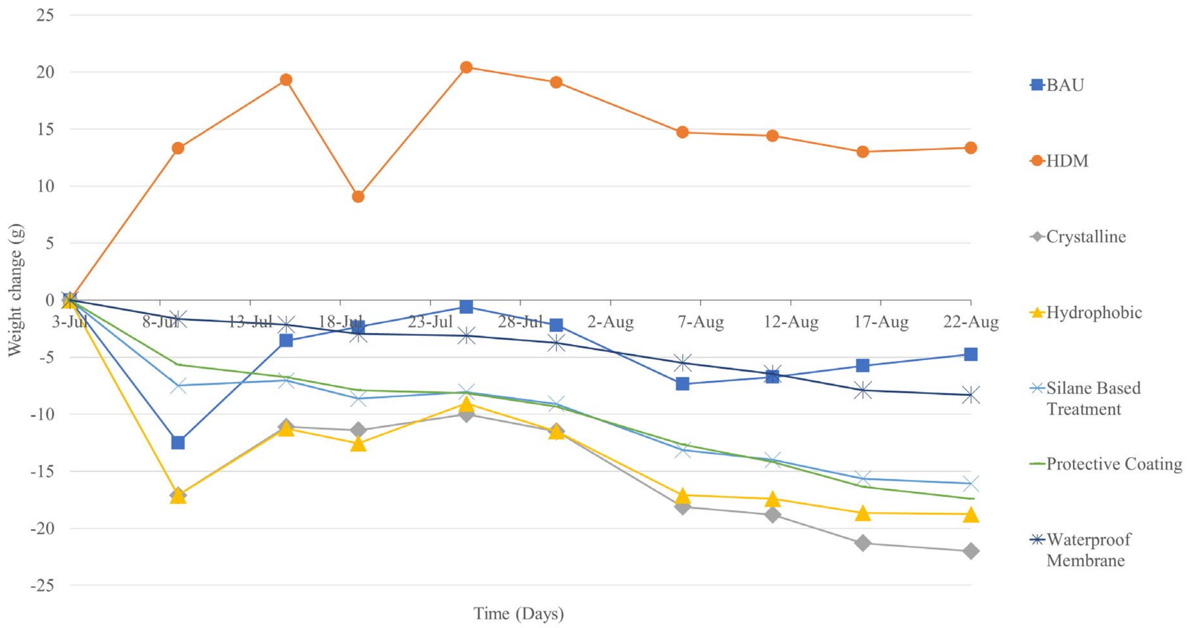

Figure 2 Average weight change of samples across 50 days of lab testing.

3.3 Cost analysis

Costs are estimates provided by suppliers and are subject to change based on quantity and future market fluctuations. These estimates do not include expenses related to sourcing concrete mixes or labour costs; they are intended as rough guidelines for the protection measures alone. When considering costs, externally applied measures require prior curing, surface preparation, and a specialised crew, increasing expenses and downtime. In contrast, internally mixed measures incur no additional labour costs, and curing is included in the standard 28-day process.

Estimates are also provided for each measure if creating or covering a 1m^3 (6m^2) concrete block.

Externally applied measures:

[1] Protective coating (with silane-based primer): \$18/m^2 (\$108 to cover 6m^2).
[2] Silane-based penetrative surface treatment: \$23/m^2 (\$138 to cover 6m^2).
[3] Waterproof membrane: \$27/m^2 (\$162 to cover 6m^2).

Internally mixed measures:

[1] Crystalline Admixture: \$80-\$90/m^3 (\$80-90 to create 1m^3).
[2] Hydrophobic Admixture: \$120-\$150/m^3 (\$120-150 to create 1m^3).

4. Conclusions and Future Work

The initial findings demonstrate that all corrosion protection methods effectively resist water ingress, resulting in drier concrete with noticeable weight loss. Admixtures proved the most effective, with the hydrophobic admixture reducing weight by 0.83% and the crystalline admixture by 0.96% compared to the initial sample weights. While admixtures are effective for new structures, they are less suitable for existing ones.

For pre-existing assets, protective coatings with a silane-based primer or direct silane-based surface treatments are recommended. While both methods perform similarly, protective coatings may be more cost-effective and offer additional benefits, such as accommodating concrete expansion and sealing cracks in older structures. For new assets, the optimal approach might involve combining crystalline admixtures with externally applied protective coatings. This combined method requires further testing and a cost-performance analysis, which could be a future project for DSL. Final chloride ingress results, expected in October, will be essential for validating these assumptions, as analysis on weight gain alone does not provide a comprehensive assessment.

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