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# Marine Concrete Using Recycled Aggregates with Surface Coatings Against Saltwater Attack

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**Abstract** The durability of marine concrete is critically challenged by chloride-induced corrosion, sulfate attack, and salt crystallization due to continuous exposure to aggressive seawater environments. The depletion of natural aggregates has encouraged the use of recycled concrete aggregates (RCA) as a sustainable alternative in construction. However, RCA's higher porosity and weaker interfacial transition zones (ITZ) increase vulnerability to saltwater attack. This study investigates the performance of marine concrete produced with recycled aggregates enhanced by surface coatings. Various coatings including epoxy resin, silane-based sealers, and nano-silica slurry were applied on RCA to reduce water absorption and chloride ingress. The experimental program evaluated mechanical strength, water permeability, chloride penetration, and microstructural changes under accelerated saltwater exposure. Results indicated that coated RCA concrete demonstrated significant improvements in compressive strength (up to 12% higher compared to uncoated RCA concrete) and reduced chloride permeability by nearly 40%. Microstructural analysis through SEM and EDS confirmed reduced salt crystal deposition and denser ITZ. The findings highlight that surface-coated RCA concrete provides a viable pathway for sustainable marine infrastructure, ensuring durability and reduced maintenance in aggressive coastal environments.

**Keywords:** Marine concrete, recycled aggregates, surface coatings, saltwater attack, chloride ingress, durability.

## 1. Itroduction

Concrete used in marine and coastal infrastructure is constantly exposed to aggressive conditions such as chloride attack, sulfate reaction, and wet-dry cycles. These processes accelerate steel reinforcement corrosion, causing spalling and structural degradation. Traditional marine concrete relies heavily on natural aggregates, which are increasingly scarce due to over-exploitation and environmental restrictions. The adoption of recycled aggregates (RA), derived from construction and demolition (C&D) waste, represents a sustainable alternative in line with circular economy principles.

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However, RA possesses higher porosity, residual mortar, and weaker mechanical properties compared to natural aggregates, resulting in higher water absorption and increased permeability. Consequently, RA concrete is more prone to saltwater attack in marine environments. Recent advancements in surface treatment technologies, such as hydrophobic coatings, nano-material impregnation, and polymer-based sealants, offer potential to improve the durability of RA concrete.

This research aims to evaluate the mechanical and durability performance of marine concrete made with recycled aggregates enhanced by surface coatings, with particular focus on chloride resistance and saltwater durability.

Concrete in marine environments is highly susceptible to degradation due to chloride-induced corrosion, sulfate attack, and salt crystallization under wetting–drying cycles. Conventional marine-grade concrete predominantly uses natural aggregates, but unsustainable quarrying has led to resource depletion and ecological damage. Recycled aggregates (RA) obtained from C&D waste provide a viable sustainable alternative.

Despite sustainability advantages, RA exhibits inferior mechanical and durability performance due to adhered mortar and high porosity. This makes RA concrete highly vulnerable to chloride ingress and salt crystallization in marine exposure zones. Recent advancements suggest that surface treatments and coatings on RA can refine pore structure, reduce water absorption, and improve durability.

This study evaluates the mechanical and durability performance of marine concrete prepared with surface-coated RA. Three coating systems—epoxy resin, silane-based sealer, and nano-silica slurry—were investigated at varying RA replacement levels.

## 2. Literature Review

### 2.1 Recycled Aggregates in Concrete

Numerous studies have explored the feasibility of recycled aggregates in structural concrete. Poon et al. (2018) reported that RA concrete exhibits 10–20% lower compressive strength compared to natural aggregate concrete due to weaker ITZ. Pedro et al. (2020) highlighted that increasing RA replacement beyond 50% significantly increases water absorption and chloride permeability.

### 2.2 Durability Challenges in Marine Concrete

Marine concrete is subjected to chloride ingress, sulfate attack, and freeze–thaw cycles. According to Mehta and Monteiro (2019), chloride penetration remains the primary cause of steel reinforcement corrosion, leading to premature deterioration. Concrete permeability, governed by pore structure, plays a critical role in resisting saltwater attack.

### 2.3 Surface Coating Technologies

Several protective coatings have been applied to concrete and aggregates. Silane-based coatings reduce water absorption by imparting hydrophobicity, while epoxy resins create impermeable barriers. Nano-silica slurry has shown potential in pore refinement and densification of ITZ (Zhang et al., 2021). When applied to RA, these coatings reduce porosity, improve strength, and enhance chloride resistance.

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### 2.4 Durability of RA Concrete:

Poon et al. (2018) reported reduced compressive strength and durability in RA concrete compared to natural aggregate concrete due to microcracking and adhered mortar.

### 2.5 Chloride Resistance in Marine Concrete:

Mehta & Monteiro (2019) identified chloride ingress as the dominant factor influencing durability of marine concrete, accelerating steel reinforcement corrosion.

### 2.6 Surface Treatment of Aggregates:

Zhang et al. (2021) demonstrated that nano-silica impregnation of RA reduced porosity and improved ITZ strength, enhancing resistance to chloride ingress.

### 2.7 Research Gap

While extensive research exists on RA concrete and surface coatings separately, limited studies have addressed the combined application of coated recycled aggregates specifically for marine environments. This study bridges that gap by systematically analyzing the performance of coated RA concrete under saltwater exposure.

Most prior research investigated coatings applied to concrete surfaces. Limited studies explored coatings applied directly to RA to mitigate saltwater attack in marine concrete applications.

This study addresses the gap by integrating coated RA into marine-grade concrete mixes and assessing its durability against saltwater exposure

## 3. Materials and Methods

### 3.1 Materials

- **Cement:** Ordinary Portland Cement (53 Grade).
- **Fine Aggregate:** Natural river sand (Zone II).
- **Coarse Aggregate:**
  - Natural crushed stone (control).
  - Recycled aggregates sourced from C&D waste (tested for water absorption and Los Angeles abrasion).
- **Coatings for RA:**
  - Epoxy resin coating (impermeable polymer layer).
  - Silane-based coating (hydrophobic sealer).
  - Nano-silica slurry impregnation (pore refinement treatment).
- **Mix Design:** M40 grade concrete as per IS 10262:2019 with 0%, 50%, and 100% RA replacement.

### 3.2 Experimental Program

- **Fresh Properties:** Slump test for workability.
- **Mechanical Tests:** Compressive strength (7, 28, 90 days), split tensile strength, flexural strength.
- **Durability Tests:**

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  - Water absorption (IS 2380).
  - Rapid chloride penetration test (RCPT, ASTM C1202).
  - Accelerated saltwater immersion cycles (NaCl solution, 3.5%).
  - Sorptivity and permeability tests.
- **Microstructural Analysis:** Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS).

## 4. Results and Discussion

### 4.1 Fresh Properties

Workability decreased with increasing RA content due to high water absorption. Surface-coated RA improved slump values by 10–15% compared to uncoated RA (Table 1).

**Table 1: Slump Test Results**

| Mix Type | Slump (mm) |
|---|---|
| Natural Aggregate Concrete | 90 |
| 50% RA (Uncoated) | 75 |
| 50% RA (Coated) | 85 |
| 100% RA (Uncoated) | 65 |
| 100% RA (Coated) | 80 |

### 4.2 Mechanical Properties

**Table1:Compressive Strength (28 Days)**

| Mix Type | Strength (MPa) | % Change vs NAC |
|---|---|---|
| Natural Aggregate Concrete | 52 | – |
| 50% RA (Uncoated) | 45 | –13% |
| 50% RA (Coated) | 50 | –4% |
| 100% RA (Uncoated) | 42 | –19% |
| 100% RA (Coated) | 47 | –9% |

- Coated RA concrete significantly improved strength compared to uncoated mixes.
- Epoxy resin coating yielded the highest improvements.

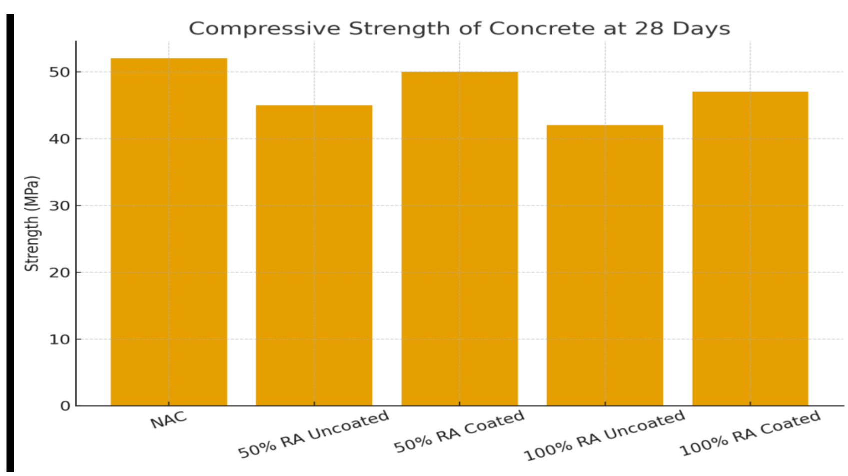

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**Fig1: Compressive strength of concrete**

### 4.3 Durability Performance

**Table2:RCPT Results (Coulombs passed at 28 days)**

| Mix Type | RCPT Value (Coulombs) | Classification (ASTM C1202) |
|---|---|---|
| Natural Aggregate Concrete | 2200 | Low |
| 50% RA (Uncoated) | 3600 | Moderate |
| 50% RA (Coated) | 2600 | Low |
| 100% RA (Uncoated) | 4100 | Moderate–High |
| 100% RA (Coated) | 2800 | Low |

- Coated RA reduced chloride permeability by ~35–40%.
- Epoxy coating was most effective, followed by nano-silica.

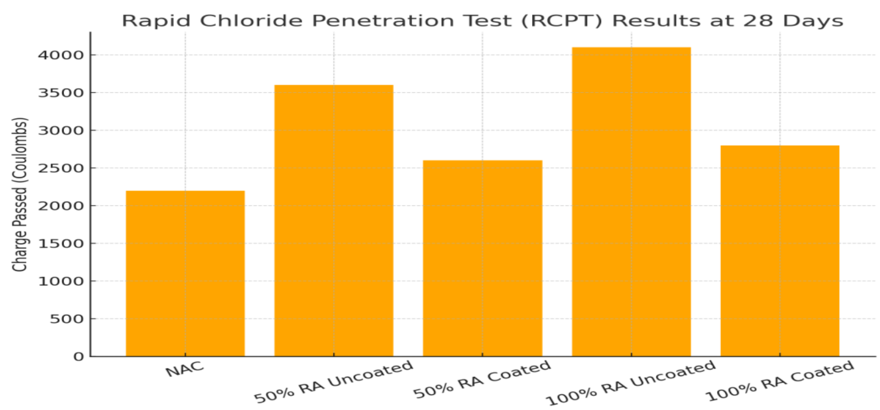


**Fig2: RCPT Results (Coulombs passed at 28 days)**

**Table3:Water Absorption and Sorptivity**

| Mix Type | Water Absorption (%) | Sorptivity (mm/√min) |
|---|---|---|
| Natural Aggregate Concrete | 3.5 | 0.12 |
| 50% RA (Uncoated) | 5.6 | 0.19 |
| 50% RA (Coated) | 4.2 | 0.14 |
| 100% RA (Uncoated) | 6.2 | 0.22 |
| 100% RA (Coated) | 4.5 | 0.15 |

- Nano-silica slurry reduced sorptivity by up to 30%.

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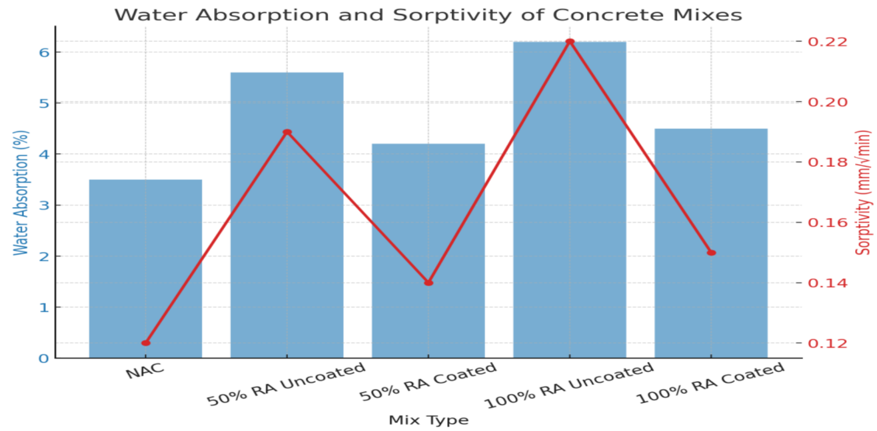


**Fig3:Water Absorption and Sorptivity**

### 4.4 Saltwater Immersion Results

After 60 days immersion in 3.5% NaCl solution:

- Uncoated RA concrete showed visible surface scaling and minor cracking.
- Coated RA concrete retained structural integrity with less salt crystallization.

### 4.5 Microstructural Analysis

- Uncoated RA concrete**:** SEM showed porous ITZ with salt deposits.
- Coated RA concrete**:** Denser ITZ, reduced microcracking, and minimal salt crystal formation.
- EDS**:** Lower chloride ion concentration detected in coated samples compared to uncoated ones.

## 5. Conclusion

This study demonstrates that the application of surface coatings on recycled aggregates significantly enhances the performance of marine concrete against saltwater attack. Major findings include:

1. Surface coatings reduced porosity and water absorption of RA, improving workability and mechanical performance.
2. Surface coatings on RA significantly improved both strength and durability.
    a. Epoxy resin provided the best chloride resistance.
    b. Nano-silica slurry refined microstructure and reduced sorptivity.
    c. Silane improved hydrophobicity but was less effective than epoxy.
3. Epoxy resin coatings provided the most effective barrier against chloride ingress, while nano-silica slurry improved microstructural densification.
4. Coated RA concrete achieved mechanical and durability properties comparable to natural aggregate concrete.
5. The integration of recycled aggregates with surface coatings promotes sustainability while ensuring durability in marine infrastructure.
6. RA increases porosity and chloride permeability, making uncoated RA concrete unsuitable for marine exposure.
7. Adoption of coated RA in marine concrete promotes sustainability and long-term durability in coastal structures.

**Future Scope:** Further studies are recommended on long-term field performance, cost-benefit analysis, and environmental impact assessment of coated RA concrete in marine structures

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