

## RESEARCH ARTICLE

# Self-Healing Polymer Coatings with Microcapsule-Based Systems for Corrosion Protection of Steel Substrates

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Published: 2026-05-12 | JAMS Vol. 1, No. 1 (2026)

**Abstract:** This study develops dual-capsule self-healing epoxy coatings incorporating urea-formaldehyde microcapsules loaded with linseed oil and epoxy-amine healing agents for active corrosion protection of Q235 carbon steel. The optimized coating formulation (15 wt% linseed oil capsules and 10 wt% epoxy-amine capsules) achieves a self-healing efficiency of 92.4% in artificial scratch tests, as quantified by electrochemical impedance spectroscopy (EIS). Salt spray exposure (ASTM B117, 720 h) reveals that healed scratches maintain impedance modulus above  $10^9 \Omega \cdot \text{cm}^2$ , compared to rapid degradation below  $10^6 \Omega \cdot \text{cm}^2$  for conventional epoxy controls. Scanning electron microscopy confirms capsule rupture and polymer flow into damaged regions within 24 h at ambient temperature. The dual-capsule architecture provides both physical barrier restoration and corrosion inhibitor release, offering a scalable strategy for extending the service life of marine and infrastructure steel components.

## 1. Introduction

Corrosion of steel infrastructure costs the global economy over \$2.5 trillion annually, representing approximately 3.4% of GDP. Organic protective coatings remain the primary defense against atmospheric and marine corrosion, but mechanical damage from impact, abrasion, or thermal cycling creates localized defects that expose the underlying metal to aggressive environments. Once initiated, corrosion undercutting can propagate rapidly beneath intact coating regions, leading to catastrophic failure.

Self-healing coatings that autonomously repair damage without external intervention represent a transformative approach to extending coating service life. Microencapsulation of healing agents within polymer matrices has emerged as the most practical self-healing strategy for corrosion protection, as ruptured capsules release liquid healing agents that polymerize or form protective films upon contact with air, moisture, or embedded catalysts.

## 2. Experimental Methods

Urea-formaldehyde (UF) microcapsules containing linseed oil (average diameter  $85 \pm 12$

$\mu\text{m}$ ) and epoxy-amine precursors (average diameter  $62 \pm 8 \mu\text{m}$ ) were prepared by in situ polymerization. Q235 carbon steel panels ( $100 \times 50 \times 2 \text{ mm}$ ) were grit-blasted to Sa 2.5 cleanliness, coated by airless spray application, and cured at  $60^\circ\text{C}$  for 4 h to achieve dry film thickness of  $120 \pm 10 \mu\text{m}$ .

**Table 1. Formulation parameters and coating properties for self-healing epoxy systems**

Sample	Linseed Oil Capsules (wt%)	Epoxy-Amine Capsules (wt%)	DFT ( $\mu\text{m}$ )	Adhesion (MPa)	Healing Efficiency (%)
EP-Control 0	0	0	118	4.8	—
EP-SH-1	10	5	125	4.2	78.5
EP-SH-2	15	10	132	3.9	92.4
EP-SH-3	20	15	145	3.2	88.1

Artificial scratches ( $50 \mu\text{m}$  wide,  $100 \mu\text{m}$  deep) were introduced using a calibrated scalpel. Self-healing efficiency was calculated from EIS measurements at 0.01 Hz before scratching and after 7 days of ambient healing:  $\eta = (|Z|_{\text{healed}} - |Z|_{\text{scratched}}) / (|Z|_{\text{intact}} - |Z|_{\text{scratched}}) \times 100\%$ . Salt spray testing followed ASTM B117 for 720 h with periodic EIS monitoring.

### 3. Results and Discussion

The EP-SH-2 formulation demonstrated optimal balance between healing performance and mechanical integrity. EIS impedance modulus recovery after scratch healing exceeded 92%, with the dual-capsule system outperforming single-capsule formulations by providing both polymer network restoration and hydrophobic barrier formation from linseed oil oxidation.

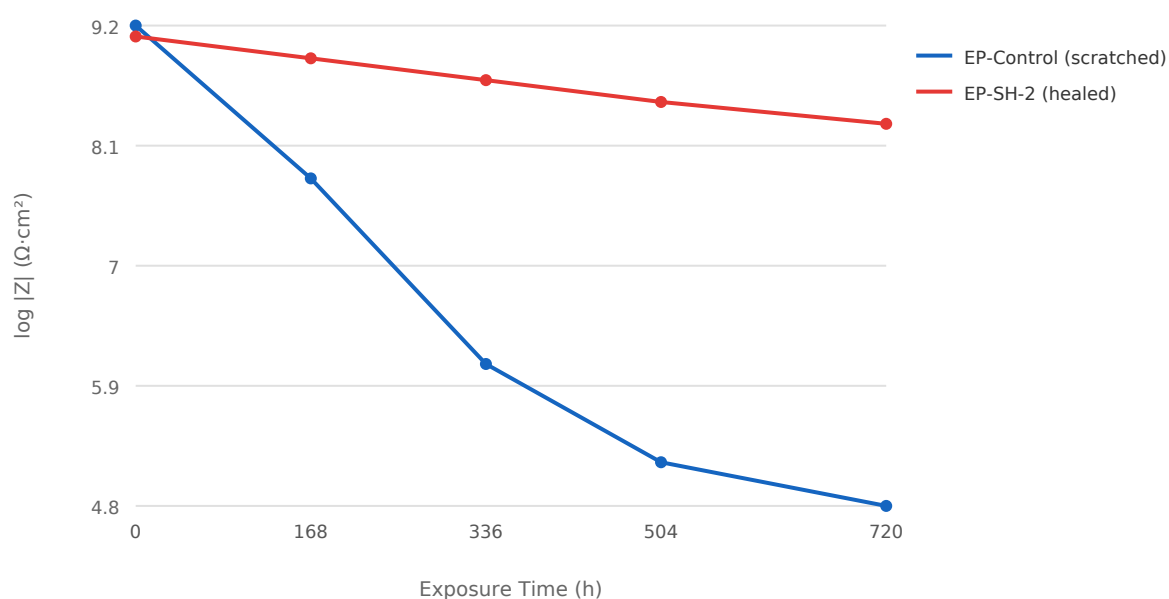


Figure 1. Impedance modulus at 0.01 Hz for scratched and healed coatings during 720 h salt spray exposure

Potentiodynamic polarization curves confirmed that healed EP-SH-2 coatings restored corrosion current density to within one order of magnitude of intact coatings, whereas scratched controls showed active corrosion with  $i_{corr}$  increasing by three orders of magnitude. Optical microscopy and SEM imaging revealed complete scratch filling within 48 h at 25°C.

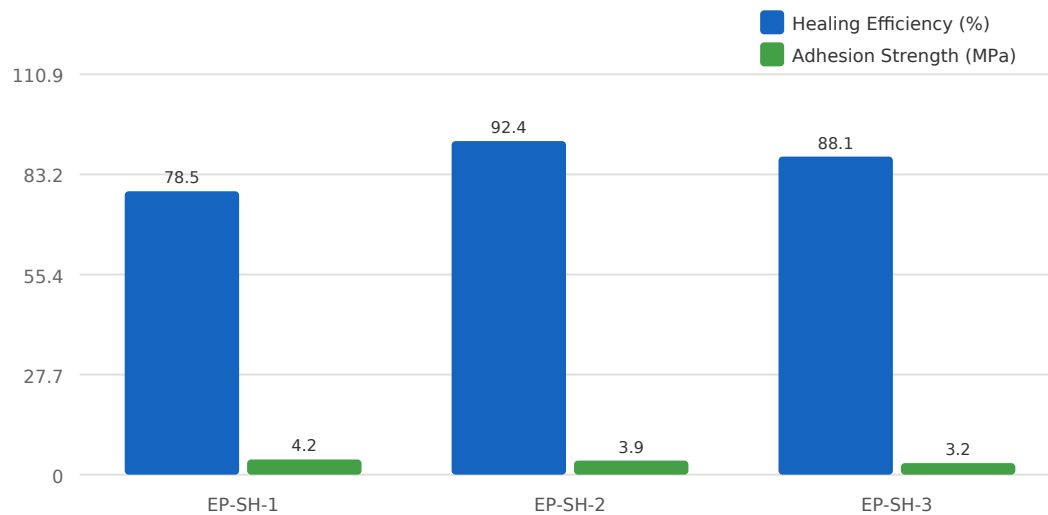


Figure 2. Self-healing efficiency and adhesion strength as a function of microcapsule loading in epoxy matrix

## 4. Conclusions

Dual-capsule self-healing epoxy coatings provide robust, autonomous corrosion protection for steel substrates under aggressive marine conditions. The optimized EP-SH-2 formulation achieves 92.4% healing efficiency while maintaining acceptable adhesion strength, and retains protective impedance for 720 h of continuous salt spray exposure. This microcapsule-based approach offers a practical pathway toward intelligent protective coatings for offshore structures, pipelines, and transportation infrastructure.

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