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Long-term Performance of Repairs to Reinforced Concrete Exposed to Coastal Conditions

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Abstract. *Reinforced concrete (RC) specimens were treated using different combinations of surface coating and/or patch repair methods and materials, left in a coastal region with frost damage risk, and their properties characterized after 25 years of exposure. Specimens were prepared by chipping away concrete from one section of concrete block with embedded reinforcement bars to expose the bars, followed by patch repair and then surface coating. Four types of material were used for patch repair: cement mortar, styrene–butadiene rubber (SBR) polymer cement mortar, rust-resistant SBR polymer cement mortar, and lightweight epoxy mortar. Two types of material were used for surface coating: multi-layer textured and thin textured coating. Following exposure, cracks were visible only on the surfaces of untreated specimens, apparently due to rebar corrosion; they were absent from all specimens that had undergone surface coating and/or patch repair. In addition, the corrosion resistance of these methods and materials was investigated by measuring and comparing the surface areas of corroded rebar between three segments: the repaired part, the unrepaired part, and the boundary between them. Concrete carbonation and rebar corrosion were greatly dependent on surface coating material, with the multilayer-textured coating especially effective at blocking chloride penetration. In addition, rebar corrosion was more effectively prevented by patch repair with the SBR polymer cement mortar than with the lightweight epoxy mortar.*

Keywords: *Exposure Test, Corrosion, Cracking, Patch Repair Methods, Surface Coating.*

1 Introduction

Various recent initiatives around the world have paralleled our transition to a sustainable society. In the construction industry, efforts have focused on reviewing and optimizing the resource usage of buildings: to this end, priority has been given to improving techniques to repair, renovate, and maintain existing concrete structures to extend their lifespan and ensure their long-term integrity.

Reinforced concrete (RC) buildings are designed with high durability in mind, with purported lifetimes of over 100 years. The fact is, however, that such structures can show signs of degradation such as cracking and peeling very soon after their completion, in as little as 10–20 years. To guarantee the durability and safe usage of RC buildings in the long term, their susceptibility to different deterioration factors present in their environment should be assessed, and used to inform suitable management strategies.

The present study models an RC structure located near the coast, at risk of salt damage from ambient chloride (Sato. K *et.al.* 2002) Specimens were initially treated using a selection of surface coating and/or patch repair methods and materials, left exposed, and then evaluated in terms of several physical characteristics to characterize the durability afforded by each combination. Exposure tests were performed in a coastal region of Hokkaido, the cold, northernmost prefecture of the long Japanese archipelago. Evaluation data from 25-year-old specimens were additionally compared with those of similar specimens exposed for 4.8 and 8 years.

2 Experimental Overview

Table 1 shows the types of materials used in the repairs. Table 2 details the content and properties of the concrete; Table 3 shows its mix composition. The concrete used had a 28-day compressive strength of 30.8 N/mm^2.Figure 1 is a structural schematic of the RC specimens. First, concrete was chipped away from a designated area of the RC slab, which had two reinforcing steel bars ("rebar") embedded in it. Next, this area was patched and its surface coated using a specific combination of materials. Concrete was removed to two different depths ("chipping depth"), defined relative to the embedded rebar: (A) chipping extended below the bar, allowing it to be completely covered with mortar, or (B) chipping reached the same depth as the rebar axis, meaning only half of it was covered with mortar. Figure 2 explains the notation of the specimen IDs in the Results section. Two-symbol IDs denote RC specimens, while three-symbol IDs denote the rebars embedded in them.

Table 1. Repair materials.

Process	Symbol	Type
Patch repair	N	None
	CM	Cement mortar
	PS	SBR* polymer cement mortar
	PI	SBR* polymer cement mortar with anti-rust additive
	LE	Lightweight epoxy mortar
Surface coating	N	None
	L	Thin textured coat
	S	Multi-layer textured coat

*SBR: styrene–butadiene rubber

Table 2. Concrete content and properties.

Materials	Properties
Cement	Ordinary Portland cement Density: 3.16 g/cm^3
Fine aggregate	River sand Density 2.62 g/cm^3, F.M.2.64
Coarse aggregate	Crushed hard sandstone Density 2.64 g/cm^3, F.M.6.71
Air entraining agent	Natural resinate
Rebar	Round steel bars with mill scale and acetone defatting: φ13 mm, SR235 (SR24) (JIS G 3112)

Table 3. Concrete mix composition.

Target slump (mm)	Target air content (%)	W/C (%)	S/a (%)	Water	Cement	Fine aggregate	Coarse aggregate	AE (*cement weight (%))
				kg/m^3				
180	4.0	65.0	48.0	185	285	862	940	0.020

These 'repaired' specimens were left at the exposure test site for predetermined lengths of time (43.025N, 140.53E, ~40 m from coastline: Figure 3). At each timepoint, several specimens were broken apart and the rebar inside removed to measure the surface area affected by corrosion ("corrosion area") and the weight lost due to corrosion ("corrosion mass loss"). Carbonation depth and chloride penetration were measured in the broken concrete in parallel. Figure 4 shows the mean monthly temperatures of the region where the specimens were left exposed.

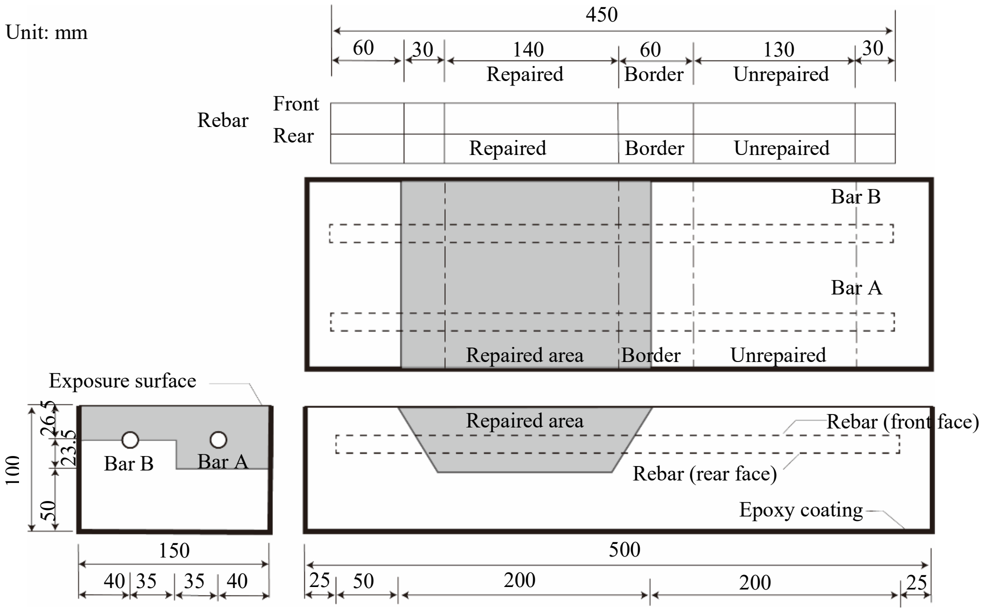

Figure 1. Schematic of RC specimen.

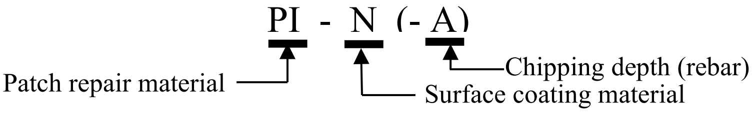

Figure 2. Specimen notation.

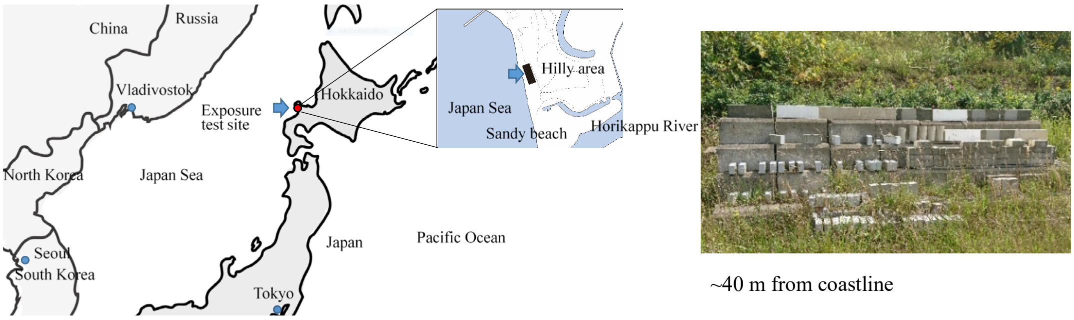

Figure 3. Exposure test site.

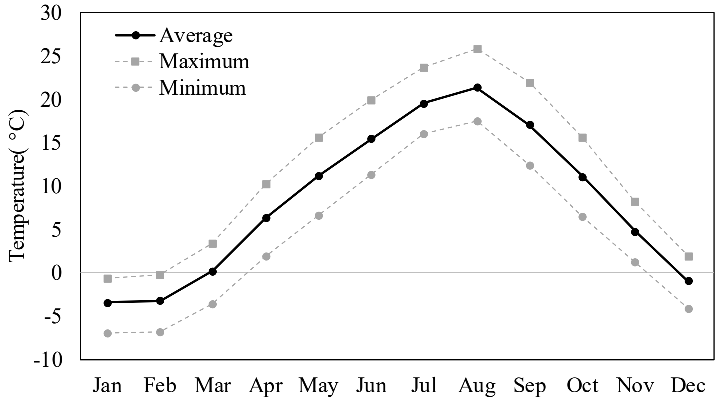

Figure 4. Mean air temperature by month at exposure test site.

3 Results and Discussion

3.1 Carbonation Depth

Figure 5 shows the measurement data for carbonation depth. Carbonation depth was most affected by the presence of surface coating itself, consistently measured deeper in specimens whose surfaces had not been coated at all (-N). When present, multilayer textured coating (-S) provided superior protection to thin textured coating (-L): specimens treated with it experienced almost no carbonation at all, irrespective of patching mortar type, evidencing its excellent resistance to carbonation.

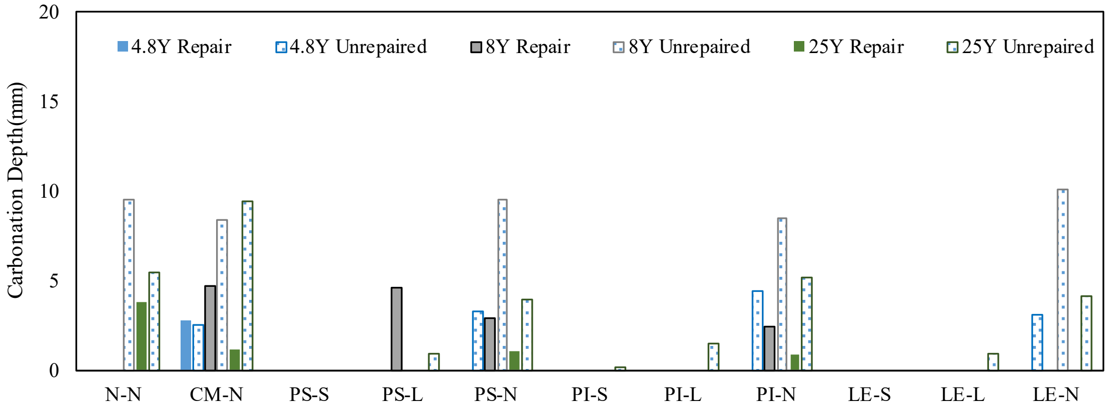

Figure 5. Carbonation depth.

3.2 Rebar Corrosion

Once removed from concrete, steel rebar was first visually graded, and then its degradation quantified by tracing and measuring the surface area of the regions affected by corrosion. Figure 6 contains photos of two bars affected by corrosion taken from a representative specimen (CM-N). Corrosion behavior clearly differs greatly between the repaired and unrepaired regions: interestingly, in the repaired part, it seems dependent on chipping depth (*i.e.* A versus B rebar).

|← Repaired →| ← Border→ |← Unrepaired→|

CM-N Bar A Front		
CM-N Bar B Front		

Figure 6. Rebar corrosion (CM-N, 25 years).

Next, rust was removed from the extricated bars by immersion in 10% di-ammonium citrate. Each bar was sectioned into three parts according to Figure 1 (Repaired, Border, and Unrepaired), and the corrosion mass loss calculated for each part (Nishimura N. *et al.*,2012, Kakegawa, M.*et al.*,2012). Corrosion speed was then calculated based on the mass loss using the following equation (Sato K. *et al.*,2002).

$$\Delta Ws = \frac{\Delta Wc \times W_0}{\varphi \times l \times \pi \times t} \tag{1}$$

Where ΔWs is the rebar corrosion speed (10-6g/mm^2/y), ΔWc is the mass loss due to rust (%), W_0 is the initial weight of the rebar (g), φ is its diameter (13 mm), l is its length in the part under analysis (mm), and t is the exposure length (year).

Figure 7 depicts correlations of rebar corrosion speed in the unrepaired versus border and repaired sections. Corrosion was effectively prevented by the repair techniques utilized, by and large proceeding at slower speeds in repaired than unrepaired rebar. Corrosion speed was quite high in the border region after eight years of exposure following repair with the rust-resistant SBR polymer cement (PI). This behavior could be attributable to a macrocell formed by a major differential in corrosion potential between the repaired and unrepaired parts due to the anti-rust additive in the mortar. However, the same tendency was not apparent in the 25-year-old specimens repaired using the same material, suggesting this variation likely originated in individual differences between specimens.

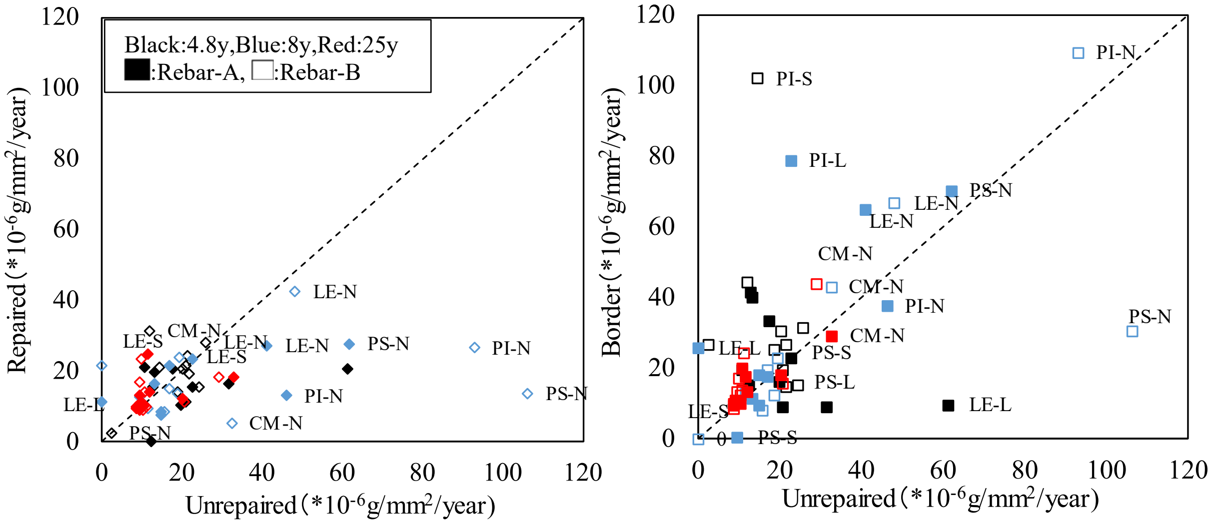

Figure 7. Rebar corrosion speed.

Figure 8 separately depicts the associations between the rebar corrosion area (itself affected by chipping depth) and corrosion mass loss by type of patching material. Specimens not treated by patch repair or surface coating (N-N-) experienced major mass loss, directly proportional to

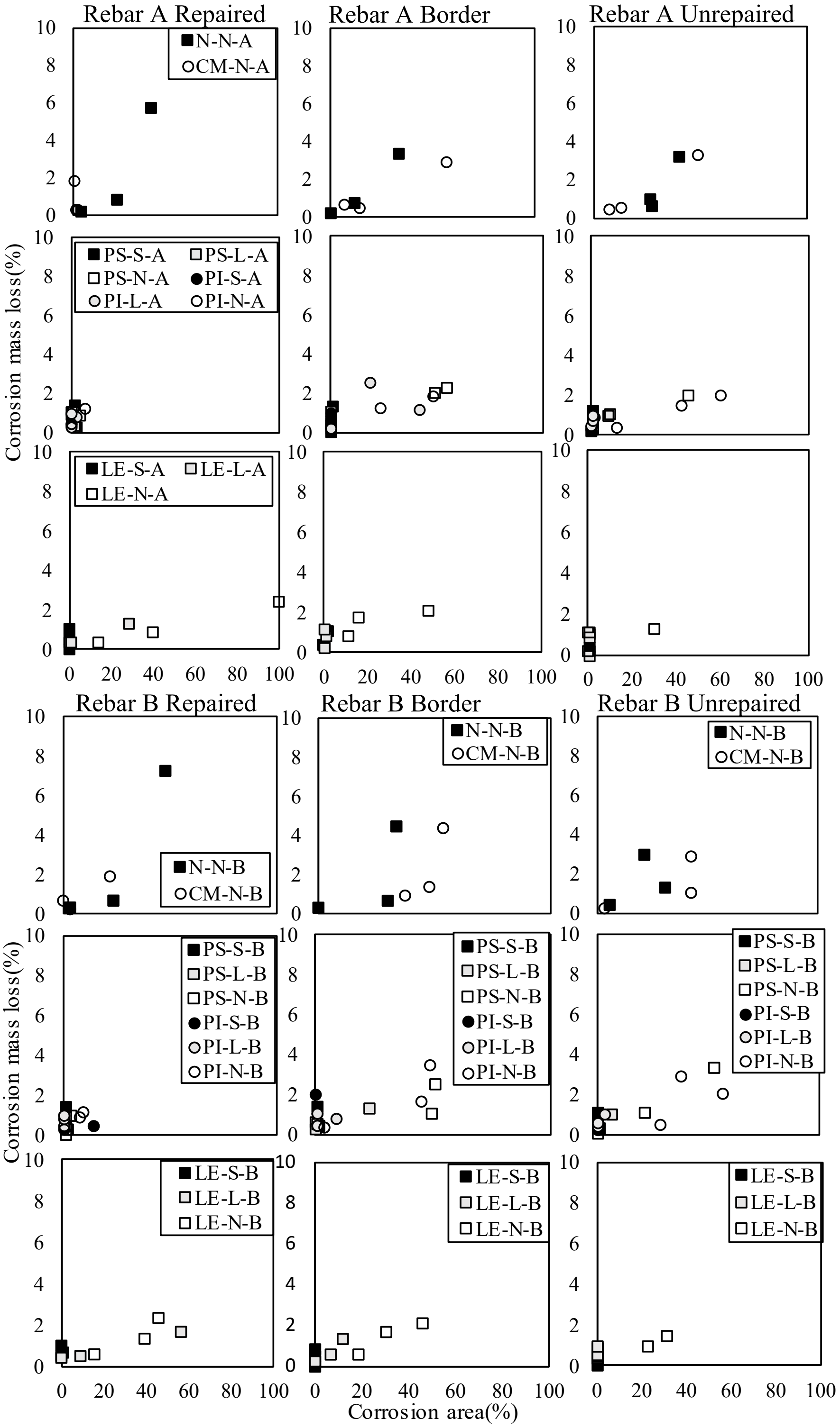

Figure 8. Rebar corrosion area versus mass loss by repair material and chipping depth.

corrosion area. In addition, corrosion progressed not only along the surface of rebar, but also towards its interior. When cement mortar was used for patch repair (CM-), the corrosion area and mass loss of the repaired region tended to be greater for B rebar than for A rebar. This suggests that chipping away enough concrete so that the entire area surrounding the rebar can be coated with patching mortar should effectively protect against corrosion. In addition, the corrosion area and mass loss of the repaired region were lower when SBR-type polymer cements (PS, PI) were used as the patching mortar than for lightweight epoxy (LE), evidencing the former materials' superior ability to protect against corrosion in patch repairs. Corrosion was prevented rather poorly by LE: when it was used, corrosion tended to spread widely across the rebar surface in the repaired region. No matter which material was used for patch repairs, the usage of multi-layer textured coating (-S-) was associated with significant drops in both corrosion area and weight loss, suggesting this material effectively resists corrosion and block the penetration of chloride ions. The only difference between PI and PS is the presence of an anti-rust additive in the former. Figure 8 shows that both materials well protect against rebar corrosion in the repaired region, with only marginal benefits afforded by the anti-rust compound.

However, specimens repaired using PI or PS tended to experience greater rebar corrosion along the border and non-repaired parts, especially in the absence of finish: this suggests the occurrence of macro-cell corrosion due to differential susceptibility to chloride penetration between the repaired and unrepaired segments. Notably, the multi-layer textured finish was the thickest of all types tested, achieving high chloride resistance and little penetration in the border and unrepaired segments on the whole. This characteristic may be why serious rebar corrosion was never really observed in the border and unrepaired parts of specimens coated with it.

4 Conclusion

This study's findings illustrate how the corrosion resistance of a repaired RC structure is affected by the materials chosen for patch repair and surface coating, as well as by chipping depth, based on experimental data from exposure tests lasting ~25 years. They can be summarized as follows:

- Carbonation was most effectively prevented by the multi-layer textured coating material.
- Corrosion protection was greater when concrete chipping extended below the rebar than merely to the same depth.
- Rebar corrosion, as with carbonation, was most effectively prevented by the multi-layer textured coating material.
- Rebar was more resistant to corrosion following patch repair with SBR polymer cements than with lightweight epoxy. However, when surface coating was not performed, macrocell corrosion may have been triggered by a high differential in chloride environment between the boundary/unrepaired and repaired regions.

Going forward, the authors plan to analyze chloride penetration depth in order to further scrutinize its relationship with rebar corrosion.

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