Comparative Study on the Corrosion Characteristics of Carbon Steel in Various Chloride-Containing Environments Simulating of Coastal Condition

Seoeun Jang [ab], Hyunkyung Choi [a], Gwang- Min Sun [a], Hyun Ho An [c], Nam-Chul Cho [b], Jaeyeon Kim [b], GyuHo Kim [b], Young Rang Uhm [a*]
[a]*Korea Atomic Energy Research Institute, HANARO Utilization Division, Republic of Korea, Daejeon 34057*
[b]*Kongju National University, Department of Cultural Heritage Conservation Science, Republic of Korea, Gongju 32588*
[c] *Konyang University, Department of Biomedical Materials, Republic of Korea, Daejeon 35365*
[*]*Corresponding author: uyrang@kaeri.re.kr*

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1. Introduction

The durability of reinforced concrete (RC), a key structural material for various structures located in coastal areas such as factories, thermal and nuclear power plants, and high-rise buildings, is essential for securing long-term stability. Chlorides, acting as a major aggressive factor in marine environments, penetrate into concrete and cause critical corrosion of the reinforcing steel. Since rebar corrosion is influenced by various environmental factors, model experiments reflecting the diversity of these coastal environments are absolutely necessary for the safety of structures.

This study made a significant discovery while establishing a chloride corrosion model for iron cultural heritage artifacts in coastal areas. It was found that the chloride corrosion trend of pseudo-specimens, manufactured to emulate Joseon Dynasty gray cast iron (characterized by a carbon content exceeding 3%), could show similarities to the corrosion patterns of carbon steel extensively used in modern structures, such as nuclear power plants. This similarity suggests that historical iron heritage corrosion research can provide crucial insights for improving the durability of modern structures.By comparing corrosion characteristics in various chloride-containing solutions and exposure environments, this study aims to provide fundamental data to prevent structural deterioration in factories, thermal and nuclear power plants, and high-rise buildings . In particular, comparative research on the corrosion trends of gray cast iron pseudo-specimens and modern carbon steel structures can serve as an important reference point for evaluating the long-term durability of structures exposed to coastal environments.

Through this research, we can gain a deeper understanding of the carbon steel corrosion mechanism in marine atmospheric environments and ultimately contribute to extending the lifespan and ensuring the safety of critical infrastructure located in coastal regions.

2. Materials and Methods

2.1 Materials

In this study, two pieces of carbon steels measuring 5 cm × 5 cm were prepared for seperate corrosion experiments. One piece was placed in contact with 1M NaCl solution at the center, and the other piece was placed in contact with 0.33 M $FeCl_3 \cdot 6H_2O$ solution; both were maintained for 10 days, subsequently air-dried for 20 days. Afterwards, a total of 4 corrosion product samples were obtained from two pieces and subjected to scientific analyses. Table 1 presents the names of the samples according to the corrosion solution and exposure environment.

Table I: Sample description

Sample	Corrosion solution	Exposure environment
N_Imm	NaCl	solution immersed
N_Inter		solution-air interface
F_Imm	$FeCl_3 \cdot 6H_2O$	solution immersed
F_Inter		solution-air interface

Fig. 1. Carbon steel specimen after corrosion testing

2.2 Methods

Each sample was first phase-identified by Raman spectroscopy in the bulk state. Since Raman spectroscopy can be biased towards localized information limited to the surface of the investigated point, XRD analysis was additionally performed on the powder form scraped from each area to cross-verify the crystalline phase. Finally, Mössbauer spectroscopy was performed for precise identification and quantification of iron-containing phases based on the XRD and Raman analysis results.

3. Results

3.1 Corrosion experiment using NaCl solution

Raman spectroscopy revealed the presence of akaganeite in N_Imm and N_Inter exhibited a spectrum similar to magnetite. XRD analysis confirmed that akaganeite was the dominant phase in N_Imm with a minor presence of goethite, while N_Inter was found to have akaganeite and magnetite as the main phases. Quantitative evaluation via Mössbauer spectroscopy indicated that N_Imm contained approximately 23.7% goethite and 76.3% akaganeite with superparamagnetic goethite, whereas N_Inter contained 23.8% magnetite(maghemite), 35.9% goethite, and 40.3% akaganeite with superparamagnetic goethite.

3.2 Corrosion experiment using $FeCl_3 \cdot 6H_2O$ solution

Raman and XRD analyses only confirmed the presence of Akaganeite in F_Imm and F_Air, and no differences were revealed between them. Mössbauer analysis of the F_Inter section showed a doublet likely originating from akaganeite, along with a minor sextet. To clearly identify these phases, further low-temperature experiments are necessary.

Table II: Corrosive factors and Analyzed Corrosion Product of Each Sample

Sample	Corrosive factor	Product
N_Imm	dissolved oxygen high humidity chloride-rich nearly neutral pH	Akaganeite Goethite
N_Inter	atmospherically supplied oxygen presence of moisture chloride-rich	Magnetite (Maghemite) Akaganeite Goethite
F_Imm	dissolved oxygen high humidity chloride-rich strongly acidic pH	Akaganeite
F_Inter	atmospherically supplied oxygen presence of moisture chloride-rich	Akaganeite

4. Conclusions

4.1 Comparison according to the type of the corrosion solution

The most significant difference between the two solutions is their acidity. pH measurements indicated that the NaCl solution was close to neutral of pH 5.20, whereas the $FeCl_3 \cdot 6H_2O$ solution was strongly acidic with a pH of 1.18. The difference in acidity directly affects the type of stable compounds formed. According to the Pourbaix diagram that illustrates the stable states of iron as a function of pH and corrosion potential in a chloride-containing environment, the formation of iron oxide and hydroxide films is difficult in acidic environments. This tendency was also corroborated in this study: the presence of Magnetite(maghemite) and Goethite was clearly observed in the NaCl experiment, whereas such phases were scarcely detectable in the $FeCl_3 \cdot 6H_2O$ experiment. Furthermore, in the $FeCl_3 \cdot 6H_2O$ experiment, not only oxygen but also ferric iron in the solution acted as a reducing agent, leading to a more active corrosion reaction.

4.2 Comparison according to the of exposure environment

O_2 and H_2O are the primary factors that cause iron corrosion. In this sense the most significant environmental difference between the immersed area and interfacial area is the degree of O_2 supply. At the immersed area, iron oxidation occurs due to dissolved oxygen in the solution. In contrast, at the interfacial area, oxygen is continuously supplied from the atmosphere, resulting in the rapid formation of corrosion products. Furthermore, the galvanic cell structure, where the oxygen-rich atmosphere acts as a cathode and the oxygen-limited immersed area acts as an anode, can further accelerate corrosion. Actually, although the types of corrosion products differ between the two experiments, the interfacial area clearly exhibits the abundant amount of corrosion products. In the case of the NaCl solution, magnetite was predominantly formed due the adequate supply of oxygen by the presence of moisture. And in the case of the $FeCl_3 \cdot 6H_2O$ solution, akaganeite, which is known to form readily in acidic, chloride-rich environments, was predominant.

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