Behavior of High-Nickel Type Weathering Steel Bars in Simulated Pore Solution and Mortar under Chloride-Containing Environment

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Abstract

Weathering steel (WS) is known to develop higher corrosion resistance than ordinary steel under atmospheric conditions due to the formation of a protective, dense rust layer. This aspect, however, has not been studied so far in cement-based materials, which are characterized by high alkalinity and limited oxygen. To address the need for durable RC structure in extreme environments, it is necessary to study the behavior of WS in concrete. Here, a basic investigation was conducted to compare the short-term behavior of a newly developed WS with 1% Ni (NT) to conventional WS with 1% Cr (CT) and carbon steel (PC). One set of steel bars was exposed to solutions with varying air and pH to simulate concrete condition under chloride-containing environment. Another set was embedded in mortar under wet-dry cycle. Corrosion degree based on mass loss, coupled with half-cell potential, and corroded area was obtained. Results indicate that alkalinity or low oxygen appreciably reduces the corrosion rate of steels regardless of composition. These conditions make the corrosion behavior of NT comparable with other conventional steels. It is recommended to explore using longer time and wider cracks in future studies to achieve clearer difference between the steels.

1. Introduction

Weathering steel (WS) is a collective term for an array of low-alloyed steels that exhibit resistance to corrosion due to the development of a dense and chloride-expelling rust layer when the material is exposed to atmosphere (Morcillo et al. 2014). They have low carbon content of 0.2% by weight or less, and small addition of one or several metals other than iron (e.g. Cu, Cr, Ni, P, Si, etc.), totaling to a maximum added alloys of 3 to 5 wt.% (Cano et al. 2018). Weathering steel is a promising alternative to carbon steel because of small addition of expensive and corrosion-resistant metals, while providing better mechanical properties (Cheng et al. 2014). WS was initially designed to contain chromium (Cr) content up to 1% by weight. However, a decade-long laboratory and field experiments from 1980’s to 1990’s in Japan revealed that this amount is not enough to combat corrosion in salt-rich, coastal regions (Kihira et al. 1999; Itou et al. 2000; Usami et al. 2003). These studies have shown that at salt (NaCl) deposition rates above 0.05 mg/dm\(^2\)/day, corrosion rate in conventional and Cr-added WS will exceed a certain limit, leading to the formation of voluminous and loosely adhering rust. Hence, a new alloy design needs to be developed for environments with high airborne salt.

Extensive characterization studies in recent years (Kimura et al. 2004, 2005; Wu et al. 2017) provided evidence on the improved anti-corrosive behavior of WS with small addition of nickel (Ni). Ni was found to facilitate the growth of Fe\(_2\)NiO\(_4\) in the rust layer by substituting the position of iron (Fe). As a result, the inner rust layer becomes more negatively charged than the ferric oxyhydroxide (FeOOH) compounds commonly found in the rust of Cr-type WS, promoting the approach of Na\(^+\) ions near the steel instead of Cl\(^-\) (Kimura et al. 2005). It is precisely this repelling of chlorides that gives the newly developed WS greater resistance compared to conventional WS under high salt concentration.

While both mentioned WS have been extensively studied under open exposure and alternating wet-dry conditions, their performance in highly alkaline and low-oxygen environment (i.e., concrete confinement) remains relatively unexplored. To illustrate the purpose of this study further, Fig. 1 depicts an RC storm water drainage cover that was broken up in 2016, then subjected to natural environment of a precast-concrete plant in Kawasaki City, Kanagawa, Japan for two years. High-Ni WS was used as reinforcements. Interestingly, the reinforcements did not exhibit appreciable corrosion after two years, as shown. It is thought that high-Ni WS is effective for RC that is partially damaged or cracked. However, this observation gives no information on high-Ni WS durability when concrete cover is still intact.

WS resistance is due to the development of a dense and stable rust layer, not on the thin passive film that forms at early stage of concrete life (Shi et al. 2018). To this effect, WS is generally allowed to corrode under chloride-rich environment. However, when it does cor-

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rode, the rust that appears will act as a barrier against further chloride intrusions. Furthermore, there is a thin region in steel-concrete interface (SCI), existing over a distance of μm to cm from steel surface, that is composed of air voids, macro-cracks, crevices, slips and separations (Angst et al. 2017). Unlike the corrosion products in carbon steels, which are expansive and loose, rust in WS is well-adhering and dense (Kimura et al. 2005). It is hypothesized that existing spaces in SCI may provide room for rust layer to develop as the rust is densified through Ni-addition. The resulting composite would therefore provide better protection against further damage after corrosion initiation, compared to carbon-steel RC. In view of the above premises, a basic study on the newly developed WS when embedded in concrete – characterized by an alkaline and low-oxygen condition – is therefore necessary. Since high-Ni WS was developed to promote corrosion resistance against elevated NaCl deposition rates (≥ 0.05 mg/dm²/day), this study is vital to understand its application for coastal structures (e.g. RC bridge decks and piers).

This paper discusses the results of an experimental program that provides preliminary data on the behavior of newly developed WS with 1.0% Ni by weight, relative to conventional WS with 1.0% Cr by weight, and ordinary carbon steel. First, a series of steel bars were submitted to liquid test (Benito et al. 2019) with varying amount of oxygen and pH to simulate the conditions inside a concrete with chlorides. This experiment aims to determine which environment in general will permit a reasonable degree of protection. Then, the study proceeded to embedding the same steel types in mortar specimens.

2. Materials and experimental Details

2.1 Simulated pore solution

The chemical compositions of steels tested are listed in Table 1. PC is the control specimen specified in Japan Industrial Standard (JIS G 3505) with carbon content of 0.8% or less. CT contains about 1.0% Cr by weight and low Ni, while NT has 1.0% Ni by weight with almost no Cr. Both are low-alloyed steels conforming to JIS G 3114, the standard that specifies the minimum mechanical properties for WS in Japan. Plain round bars with 5 mm diameter were purchased. They were cut to lengths of 50 mm, and their ends polished using SiC paper No. 120 to remove the sharp edges. One steel bar was assigned to each exposure period lasting 14, 21, 30, 60, 90, 120, and 150 days. Solutions were prepared according to different conditions provided in Fig. 2, and is explained more deeply in proceeding sections.

2.2 Mortar test

Ordinary Portland cement with a density of 3.15 g/cm³...
was used as the binding material. Standard sand that complies with JIS R 5201 was used as fine aggregates having an air-dried density of 2.61 g/cm³, and absorption of less than 0.2%. Steel bars with the same composition as listed in Table 1 were also acquired with dimensions of 5 mm diameter and 200 mm length.

Based on literature, the formation of protective rust layer happens only when steel does not retain water on its surface, or undergoes periodic drying (Moricillo et al. 2019). To increase the rate of supplying and draining of water, and to permit rapid chloride migration, the absence (case N) and presence of crack (case C) were considered. The use of cracked specimens is justified since RC elements do sustain tensile cracks, which subject the embedded steel bars to a slow process of wetting and drying. Hereafter, specimens will be designated according to symbols presented in Fig. 2. For each condition stated, two trial samples were allotted for 60, 90 or 120 days of exposure time, summing to 36 mortar specimens casted in total.

3. Experimental procedure

3.1 Simulated pore solution

WS is generally used in atmosphere where air is fairly present. Concrete, on the other hand, has reduced oxygen access, which can change depending on its density and water content. Different levels of oxygen were investigated to compare the behavior of studied steels under these two opposing conditions. To change the oxygen content, four levels of exposure were set based on the amount of air that will interact with steel bars. These are: continuous liquid immersion (IM), cyclic wetting and drying with short (SF) and long frequency (LF), and continuous aeration (AE). SF case consisted of 3 days of complete immersion in solutions followed by 4 days of drying; while LF consisted of 7 days wetting, and 7 days drying. Continuous aeration (AE) was made possible by simple electronic aerators that introduce air flow rate of about 1.0 L/s.

Acidic and alkaline solutions were also considered to compare the rust development of WS in environment similar to atmosphere and concrete, respectively. Water containing 3.5% NaCl by weight was prepared to simulate an environment with low pH (case A). A separate set of 3.5% NaCl solutions were added with NaOH at 0.1 mol/L so that a chloride-contaminated alkaline solution is achieved (case B). The chemical composition of the pore water will affect the composition of corrosion products; however, since this study is a basic investigation, the focus is mainly on pH level, and NaOH was selected because of its high solubility and ease to keep the desired high pH value. All solutions were put in 500 mL polypropylene bottles and were replaced every 2 weeks to maintain their alkalinity and salinity as rusting progressed. Specimens were arranged so as not to create contact during immersion. All NaCl solutions were measured to have an average pH value of 6.05 ± 0.59, while it was 13.10 ± 0.21 for the remaining NaCl and NaOH solutions. Acidic pH was observed in NaCl solutions probably as a result of stirring, which can capture free CO₂ from the surroundings. Finally, the entire test was carried out in closed room of constant conditions at 20°C and 60% RH. Figure 3 is a photograph of laboratory setup shown together with schematics of different corrosion methods.

After about 14, 21, 30, 60, 90, 120, and 150 days, the assigned steel bars were retrieved and cleaned according to the procedure outlined in ASTM G1 (2003). First, corrosion products were cleaned manually by a combination of light scraping and sanding using SiC paper No. 400 in water. It was followed by immersion in a solution of 16% ferric ammonium citrate, initially boiled at 70 to 90°C for 20 minutes. Finally, samples were further scraped to remove the remaining rust, rinsed in reagent acetone, and weighed. The mass loss due to corrosion...
was converted to an average value through Eq. (1), regarded as an average of mass change over the corroded area.

\[
C = \frac{m_i - m_f}{2\pi R^2 + 2\pi RL}
\]

(1)

where \(C\) = corrosion degree (g/dm²), \(m_i\) = mass of the rebar before exposure (g), \(m_f\) = mass of the rebar after removing the rust products (g), \(R\) = radius of steel bars equal to 0.025 dm, \(L\) = measured length of the steel bar (dm).

### 3.2 Mortar Test

#### 3.2.1 Specimen Preparation

The schematic of specimens made for this study is presented in Fig. 4. Mortars were cast in cylindrical plastic molds made up of rigid polyvinyl chloride pipe with nominal inner diameter of 150 mm. Molds were cut into 50 mm heights and drilled with 6 mm diameter hole passing their diameter. The configuration was selected because of two reasons. First, plastic molds could restrict the transport of moisture to vertical direction, and thus fluid transport due to wetting and drying can occur mainly over the top and bottom faces. Secondly, the installation is simpler because the steel bar is firmly secured without the need for spacers.

The form height was selected to permit a cover of 22 mm. This distance is considered to be within the range influenced by wetting and drying action (Chrisp et al. 2002), and over which corrosion activity of embedded steel is sufficiently detectable by half-cell potential mapping (Elsener 2002). Protruding ends of steel bars were completely coated with epoxy resin. For the 120-day specimens only, one end was connected to an electric wire using copper tape, which will serve as the positive terminal for potential measurement. This part was similarly covered with epoxy resin.

The proportions used for mixing, together with resultant physical properties of mortar in fresh and hardened state, are given in Table 2. A water-cement ratio of 0.60 was selected based on previous microstructural studies on mortars (Stefanoni et al. 2019), showing that this ratio produces a porosity just less than what is required for the microstructure to behave like a bulk solution. In this way, the pore structure is not so open to resemble a liquid solution but not low enough to hinder wetting and drying action.

Mixing followed a stepwise procedure using an automatic rotary mixer with 20-liter capacity as outlined in Fig. 5(a). Mortars were first poured into the prepared molds in two layers with each layer rodded and lightly compacted [Fig. 5(b)]. After 24 hours, the specimens were moist-cured by wrapping them in wet cloth, and sprinkling them with water every week for 28 days under 20°C and 60% RH [Fig. 5(c)]. After curing, half of the specimens were cracked by applying a compressive load in a manner similar to Fig. 5(d). The load was applied until a crack appears in the direction perpendicular to the axis of steel, and over the entire depth of mortars (Fujiwara et al. 2017). Because the cracks induced were practically small relative to the length of exposed area of steel, the influence of crack on corrosion degree was assumed to be the same for all bars.

| W/C (%) | S/C | Unit weight (kg/m³) | Flow (mm) | Air (%) | Density (kg/m³) | \(f'_c\) (MPa) |
|---|---|---|---|---|---|---|
| 60 | 3.0 | 290 | 484 | 1452 | 169 | 3.3 | 2,254 | 48.41 |

Table 2 Mortar mix proportions and physical properties.
3.2.2 Exposure condition
Only wetting and drying scenario was employed in this study to simulate the conditions in the field. The samples were submitted to exposure immediately after cracking. Each cycle is composed of 3 days complete immersion in 3.5% NaCl solution, followed by 4 days drying in closed room of constant temperature (20°C) and relative humidity (60%), which lasted for 120 days. Within this period, the specimens were kept slightly elevated so that water and air could freely circulate at the bottom of mortars. Note that pH of 3.5% NaCl was not recorded since this is not a variable of interest in this part of study, but similar condition as in solution test can be conveniently assumed. Lastly, solution is replaced every month to maintain its salinity.

3.2.3 Half-cell potential
Half-cell potential (HCP) measurement was conducted on 120-day specimens following ASTM C876 (2009), with saturated copper/copper sulfate electrode (CSE) as reference half-cell. Although HCP method is not quantitative, various researchers (Pourbaix et al. 1980; Shi et al. 2018) used it to compare the possibility of corrosion in WS. This method allows us to monitor the corrosion risk of the bars non-destructively. Measurements were made immediately after the specimens were taken out of the solution after wetting stage, and just before they were immersed after drying stage. The electrode was placed on three adjacent points of uncracked mortars to measure the potential over the entire length of bar. However, for the cracked mortars, the electrode was placed only at two points, about 1 to 5 mm from the crack segment (see Fig. 6). Placing the electrode directly above the crack was avoided to prevent fluctuations of potential due to water percolating through the crack (Dasar et al. 2017). Finally, the average value measured from two separate samples was obtained, and termed as corrosion potential ($E_{corr}$) in the following sections.

![Flow of experiment](image)

**Fig. 5** Flow of experiment: (a) step-wise mixing procedure and the rotary mixer used; (b) casting; (c) curing; and (d) cracking method.

![Half-cell potential measurement assembly](image)

**Fig. 6** Half-cell potential measurement assembly.
3.2.4 Rust coverage
The specimens were broken up using sledge hammer to recover the bars after the assigned periods. The surface area of the bars within the mortar was covered with transparent adhesive tape to trace localized rust and coloration using a fine-tip marker. The tape was detached, and laid flat in a white paper to be captured and analyzed. The extent of rust, corresponding to the areas marked in the tape, was expressed as a fraction of the original exposed area within the mortar by Eq. (2).

\[ r = \frac{A_{corr}}{A_0} \]

where \( r \) = rust coverage (%), \( A_{corr} \) = corroded areas marked in the tape (mm\(^2\)), \( A_0 \) = surface area of the bars measured within the mortar (mm\(^2\)).

3.2.5 Corrosion degree
The steel bars were then cleaned following a similar procedure applied in solution test. When the bars were recovered, significant rusting was found to occur at the end portions covered with epoxy. To consider only the area embedded in mortar, both ends were cut to retain only a length of about 140 mm. Then, the actual length and mass of these newly cut bars were measured, and Eq. (3) were applied as the estimate of corrosion degree. The said expression similarly assumes that mass loss is uniform over the exposed lateral surface area of newly cut bars.

\[ C = \frac{m_o \left( \frac{L_o}{L_c} \right) - m_{fc}}{\pi D L_o} \]

where \( C \) = corrosion degree of steel bars inside the mortar (g/dm\(^2\)), \( m_o \) = initial mass of original length (g), \( L_o \) = actual length after cutting (dm), \( L_c \) = original length before cutting (dm), \( m_{fc} \) = final mass of the cut length (g).

4. Results and discussion
4.1 Simulated pore solution
4.1.1 Influence of alkalinity and oxygen level
Figure 7 plots the corrosion degree with time, arranged according to steel type. Under the same oxygen (air) content, alkaline pH (case B) suppressed the damage by 30 to 90% compared to acidic pH (case A) across all exposure conditions. This result was expected since dissolution of iron at pH > 11.5 favors passive products to form, mainly as FeO\(_2\) (maghemite) or Fe\(_2\)O\(_4\) (magnetite) (Hansson 1984). These products are stable on the surface of steel, unlike iron ions (Fe\(^{2+}\) or Fe\(^{3+}\)) that are continuously released when pH is acidic. Continuous dissolution under low pH may explain why the curves present linear increase until 90 days of exposure, then became steady thereafter, whereas those in alkaline water remained leveled down throughout the test. Gradual stability of corrosion curves in acidic pH can be associated with the decrease of oxygen penetration as rust thickness increases with time.

Furthermore, corrosion degree appreciably increases if air supply increases. This result is also expected since oxygen supports the cathodic reaction. It is rather worth mentioning that the effect of oxygen on corrosion degree is more pronounced in acidic solution. For instance, when pH is alkaline, an increase of oxygen exposure from completely immersed state (IM) to wet-dry cycle (SF or LF) hardly changed the corrosion degree; whereas in solution of acidic pH, corrosion increased by 3 to 4 times for the same levels of oxygen. This result shows

\[ \text{Exposed time (days)} \]

Fig. 7 Change of corrosion degree with time as a function of alkalinity, corrosion method and steel type. See Fig. 1 for symbols used (Benito et al. 2019).
that appropriate combination of oxygen and pH is necessary for rust development even for WS.

4.1.2 Influence of steel type
Considering the result of Fig. 7 again, it is found that Cr-added steel (CT) recorded the highest resistance only when the solution is continuously aerated (AE). Corrosion degree in CT decreased by an average of 60% relative to other types in acidic case (AE-A), but the reduction was only 30% in alkaline case (AE-B). Previous studies postulated that Cr can interact with multiple oxygen ions (O$_2^-$) to form chromium-oxygen ion complexes of the form CrO$_x$$_{3-2x}$. These ions can fill the spaces of rust in Cr-added steels that densifies its structure, restricting the growth of rust layer (Yamashita et al. 2004). While this is apparent for AE, it is not so clear in other cases. It can be said that CT suppresses the corrosion degree more visibly when oxygen is abundant (AE condition).

On the other hand, Ni-added steel (NT) slightly leveled off the rust growth only when it was subjected to acidic drying. The material showed an average decrease of 19% in long-frequency (LF-A), and 33% in short-frequency wet-dry (SF-A) relative to other types after 150 days. The beneficial role of periodic drying to develop the protective layer in Ni-containing WS is a prevalent concept in literature (Itou et al. 2000; Usami et al. 2003). Acidic water can dissolve the metal to start the corrosion process during wetting, while the rust is stabilized when wetting transitions to drying (Kimura et al. 2005). Drying also provides a washing action on rebar surface, giving rise to a uniform rust coating that can repel chlorides away from steel. Figure 8 gives the morphologies of corroded samples after 120 days of test, from which this supposed coating on NT is observed. It is worth noting that dense and thin rust layers, corresponding to IM through SF, are relatively blacker; while AE with thick and loose rust shows red coloration.

NT did not show any difference compared to other types in environment that remains permanently wet (AE cases), is alkaline (SF-B and LF-B) or has low oxygen (IM cases). The first item is explained by the fact that corrosion layer grows rapidly at continuous contact with chloride-containing water by imbibing large amount of moisture. This condition forces some portion of rust to separate from the metal, making the layer difficult to stabilize (Matsushima et al. 1974).

Moreover, in the range of pH and oxygen content usually found in hardened cement paste, the whole cathodic reaction (reduction of oxygen in water) shifts to lower current values (Stefanoni et al. 2019). Thus, corrosion rate is reduced regardless of steel composition since the process is controlled, in large part, by the cathodic reaction. This inhibiting effect impedes iron, and important alloys (Ni or Cr) to oxidize and grow into phases known to develop the protective rust, namely α-FeOOH (Kimura et al. 2003) and Fe$_2$NiO$_4$ (Kimura et al. 2005) for Cr- and Ni-bearing steel, respectively. Thus, corrosion progression in WS will only approach that of plain carbon steel. This hypothesis is supported by the fact that the rust morphology in all rebars, under alkaline and low oxygen scenarios, does have striking similarity in terms of color, uniformity, and areal extent (Fig. 8).

The superior resistance of WS arises from the formation of a suitable rust with dense structure. Cr and Ni addition are known to stabilize such layer in atmospheric settings, lowering its corrosion rate than carbon steel. The result presented here indicates that the formation of the layer is impeded, and, therefore, the corrosion resistance was comparable with plain carbon steel in an environment that is continuously wet, has high pH or has very low oxygen.

4.2 Mortar test
4.2.1 Half-cell potential
The variation of $E_{corr}$ with time is displayed in Fig. 9.

|    | AE | SF | LF | IM |
|----|----|----|----|----|
| B-PC | ![Image](B-PC.png) | ![Image](B-PC.png) | ![Image](B-PC.png) | ![Image](B-PC.png) |
| B-CT | ![Image](B-CT.png) | ![Image](B-CT.png) | ![Image](B-CT.png) | ![Image](B-CT.png) |
| B-NH | ![Image](B-NH.png) | ![Image](B-NH.png) | ![Image](B-NH.png) | ![Image](B-NH.png) |
| A-PC | ![Image](A-PC.png) | ![Image](A-PC.png) | ![Image](A-PC.png) | ![Image](A-PC.png) |
| A-CT | ![Image](A-CT.png) | ![Image](A-CT.png) | ![Image](A-CT.png) | ![Image](A-CT.png) |
| A-NH | ![Image](A-NH.png) | ![Image](A-NH.png) | ![Image](A-NH.png) | ![Image](A-NH.png) |

Fig. 8 Macro-morphology of corroded bars after 120 days of exposure in different pore solutions. (Benito et al. 2019).
Note that the x-axis has been changed to logarithmic scale to amplify the effect of time. Immediately after the first wetting time, $E_{\text{corr}}$ dropped to values below -300 mV vs. CSE. Thereafter, the parameter took a wide range of values between -200 and -600 mV CSE, which coincide with the range of uncertain and 90% corrosion risk as per the ASTM criteria. $E_{\text{corr}}$ also remained nearly constant with time. Crack barely influenced the absolute values of $E_{\text{corr}}$ throughout the test. This result is apparently the case for all steel types. Crack supposedly brings the potential to lesser negative values as it tends to increase the oxygen content near the steel. A negligible difference in $E_{\text{corr}}$ has been observed between case N and C, however, indicating that only small corrosion has occurred in cracked mortar.

There is, nonetheless, a systematic pattern on the trend of $E_{\text{corr}}$. It drops during wetting, followed by a rise after drying. This behavior is associated with two processes: changes in moisture content inside the mortar that controls the oxygen accessing the rebar (Elsener et al. 2003), or changes in effective concentration of dissolved metals in the water-filled pores (Ribeiro et al. 2012). When mortar is saturated, oxygen concentration in its pores decreases since gas does not easily dissolve in water. At the same time, water entering the mortar dilutes the concentration of metallic ions dissolved in pores. Both processes bring the steel potential field to more negative values. When mortar undergoes drying, oxygen penetrates its pores while water simultaneously leaves the pores, improving the concentration of metallic ions. These conditions shift $E_{\text{corr}}$ to higher values compared to those during wetting. Hence, repeating this cycle yields a periodic drop and rise of $E_{\text{corr}}$ as mortar undergoes wetting and drying.

It is worth noting some variations in case C that are not present in case N. In particular, a sudden drop of potential to as low as -600 mV CSE is observed in cracked mortar with PC steel beginning at day 30, corresponding to wetting stage (Fig. 9). For the same period, CT and NT stayed equally at -370 mV CSE. During the dry periods, PC still exhibited the lowest potential at about -390 mV CSE, followed by -300 mV CSE and -240 for NT and CT, respectively. Hence, PC can be considered slightly at risk of corrosion more than the other types in cracked case. Clearer distinction between the types might be achievable with longer exposure.

It was also observed that the change of potential from wetting to drying, and vice-versa, is markedly evident in cracked mortars. This behavior may have been due to the greater tendency of water to go near and away the rebar level in cracked matrix. PC is also observed to have the greatest potential shift from wetting to drying and vice versa compared to other steels in cracked cases. This increase can be likely attributed to Fe$^{3+}$ on its surface. According to previous studies, unalloyed carbon steel favors oxide products to form with richer Fe$^{3+}$ than those in nickel (Tian et al. 2020) or chromium-bearing (Liu et al. 2016) steels. The concentration of this ion dictates the rebar potential according to Nernst equation (Stefanoni et al. 2019). Since ionic concentration changes as a result of

![Risk of corrosion as per ASTM C876: No Crack (N)](image)

![Risk of corrosion as per ASTM C876: Cracked (C)](image)

Fig. 9 Change of $E_{\text{corr}}$ with time arranged according to steel type.
water going in and out of mortar (Ribeiro et al. 2012), a higher shift of potential in PC may have resulted from a higher number of charged particles with higher equilibrium potential, i.e., Fe$^{3+}$.

4.2.2 Surface condition

Figure 10(a) shows the actual state of different steel bars after 90 and 120 days of wet-dry cycle. As observed, all the steels present comparable surface condition, containing only few localized rusts and some coloration due to rust stains. These rusts were detected to cover only less than 5% of the exposed surfaces [Fig. 10(b)]. Clearly, no severe corrosion has occurred. Similar to IM-B case of solution test, this observation is attributed to the fact that corrosion of steel is restricted in an environment of high pH and low oxygen. Consequently, localized rust tends to form regardless of steel type within the period of wet-dry cycle considered.

Fig. 11 relates the values of $E_{corr}$ with the actual degrees of damage given by the corroded area and the corrosion rate. There is negligible correlation found between the parameters. Such weak correlation, and the fact that $E_{corr}$ lies within uncertain and 90% corrosion risk as shown in Fig. 9, is in agreement with very few rusted areas observed in Fig. 10. From these results, steel type appears to have no remarkable influence.

4.2.3 Progress of degree of corrosion

Since $E_{corr}$ reflects only the corrosion risk, average mass loss allows for the assessment of corrosion kinetics quantitatively. The plot of the parameter with time (Fig. 12) suggests no observable difference between cracked and uncracked mortars, consistent with the result of corrosion potential. This may have been due to limited oxygen or chloride that accessed the rebars through the cracks. Figure 12 also reveals that NT actually sustained higher mass loss in mortar by as much as 70% than other types at the end of the test. To expound this data further, Fig. 13 was prepared to compare the result in mortars with those in chloride-contaminated alkaline solutions. It is apparent that the sequence of steel type in terms of corrosion degree is not the same across the experi-

![Table: Surface condition comparison](image)

Fig. 10 (a) Surface macro-morphology, and (b) rust coverage of steel bars in different conditions after 90 and 120 days of wet-dry cycle.

![Graph: Correlation between $E_{corr}$ and parameters](image)

Fig. 11 Relationship of $E_{corr}$ with average corrosion rate and rust stain coverage.
mental conditions considered. In particular, NT showed the highest damage in sound mortar at 2.1 g/dm² [Fig. 13(a)]. However, the trend is not consistent with the result in alkaline liquid phase of similar condition, i.e., continuous immersion [IM-B, Fig. 13(b)]. The trend is also not consistent for cracked mortar [Fig. 13(c)] and its corresponding liquid test condition, i.e., cyclic wet-dry [SF-B, Fig. 13(d)]. The measured values were compared with those in aerated alkaline solution [AE-B, Fig. 13(e)], whose corrosivity is much more severe. As observed, the difference between the steel types becomes far less apparent. In other words, the average corrosion in both sound and cracked mortars was very low (≤ 2.1 g/dm²) that the distinctions between the steel types given in Figs. 13(a) and (c) are actually insignificant. This is because open air (oxygen), in addition to water, is necessary for the formation of protective rust in weathering steels (Morcillo et al. 2014, 2019).

Results for uncracked mortar [Fig. 13(a)] and for IM-B solution [Fig. 13(b)] were compared because both cases do not permit air near the steel bars, thus allowing only localized pits to occur. This was indeed the case considering the observed surface appearances in Figs. 8 and 10. However, since the rusts that formed were few and localized in the said cases, no difference between steel types could be deduced. On the other hand, the result of cracked mortars to SF-B and AE-B solution were compared because, under these cases, air interacts with rebars, although at different degrees. In AE-B solution [Fig. 13(e)], even though abundant air is present, the rebars are permanently in contact with water, which accelerates the growth of rust products in all steels. The rusts are forced to absorb water, and thus, produce thick and loose layer (Matsushima et al. 1974). Meanwhile, under frequent wet-dry cycle or SF-B solution [Fig. 13(d)], water is deposited and drained periodically,
5. Conclusions

1) High-Cr type WS (CT) showed 30 and 60% corrosion reduction compared to other steels under basic and acidic case, respectively, only when it was put continuously in chloride-containing water with abundant air. There is no difference, however, when oxygen is low.

2) High-Ni WS (NT) reduced the corrosion degree by 19% to 30% relative to other steels under acidic and cyclic wet-dry state, consistent with its weathering application. It appears that dense and chloride-repelling rust is favored by faster wet-dry cycle.

3) NT did not reduce the corrosion degree in environment that remains continuously wet, is highly alkaline, or has low oxygen. The first item is explained by the fact that continuous immersion in chloride-containing water accelerates the corrosion process drastically, resulting in rust products that absorb water. Whereas, in a solution of high pH or low oxygen, corrosion rate is inhibited so that the desirable dense and uniform rust film does not form. Consequently, the corrosion behavior of WS approaches that of carbon steel.

4) Although all steels in intact mortar assumed similar $E_{corr}$ values, plain carbon steel (PC) were slightly more active than WS in cracked mortar. Furthermore, the change of potential from wetting to drying and vice versa is highest in PC, which may have been caused by the difference in concentration of ferrous ions on surface of each steel.

5) Besides water, air plays a role in forming the protective rust in Ni-type WS. Thus, wet-dry condition seems to be more favorable for NT than mortar embedment. Only localized rust has formed in mortar after 120 days of wet-dry cycle, covering only 5% of the total surface area. NT sustained higher corrosion by about 70% than other types but the values are merely 2.1 g/dm² or lower, which can be considered insignificant given that only few products have formed. In summary, within the scope of this study, the behavior of NT in mortar remains practically the same as those of conventional steels.

6) In addition to possible development of rust layer, the result of the study can be advanced by determining the effect of Ni or Cr on the critical chloride content and time of corrosion initiation of WS. Future research may also be done focusing on advanced electrochemical measurements and microstructural analysis of rust products of WS in mortar or concrete.

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