

# MACROCELL CORROSION ASSESSMENT OF STEEL IN COLD-JOINTED CONCRETE MIXED AND CURED IN SEAWATER

\* Cheryl Lyne C. Roxas<sup>1</sup> and Bernardo A. Lejano<sup>2</sup>

<sup>1,2</sup>Faculty, De La Salle University, Philippines

\*Corresponding Author, Received: 10 June 2017, Revised: 30 Nov. 2017, Accepted: 20 Dec. 2017

**ABSTRACT:** Previous research works have been devoted to developing sustainable construction materials. This is due to the potential risk of global warming resulting from the abuse and misuse of natural resources. Therefore, this study aims to address this through the use of abundant and by-product resources in the production of concrete, like seawater and fly ash. If these materials were proven comparable to conventional materials, then problems on freshwater scarcity, fluctuating supply of cement and associated pollutants from its production can be addressed. This research specifically concentrates on the effects of varying water to cement ratios and fly ash content on the macrocell corrosion behavior of steel in cold-jointed concrete. Ordinary Portland cement in concrete was partially replaced with fly ash at 30% and 50%. Water to cement (w/c) ratios of 0.30, 0.35, 0.40, 0.45, 0.55 and 0.60 were tested. Rectangular prism specimens were cast to monitor the macrocell corrosion activity of the reinforcements. Results have shown an increasing trend of corrosion rate with increasing w/c ratios regardless of mixing water, with specimens mixed with seawater having higher values compared to freshwater. Generally, the 0.30 w/c ratio resulted to the lowest corrosion susceptibility. In terms of fly ash content, it was found that corrosion rate decreases with increasing fly ash percentage. Fly ash decreases the permeability of concrete, thus making it less exposed to aggressive environments. Cold-joints showed evident corrosion effects as external elements may penetrate through these planes of weakness in the concrete.

*Keywords: Macrocell Corrosion, Seawater, Cold-Joints, Fly Ash, Water To Cement Ratio*

## 1. INTRODUCTION

Concrete is one of the most widely-used construction materials. The strength and durability of concrete are affected by the properties of its constituents, mix proportions, mixing procedure, curing method and exposure to environment. It is primarily composed of cement, sand, gravel, water and some chemical or natural admixtures. However, due to the potential risk of global warming in the planet resulting from the abuse and misuse of natural resources, the availability of these components for the next generation may be inadequate. Thus, a number of research activities have been devoted to developing sustainable construction materials in order to address this issue. This study focuses on the use of abundant and by-product resources in the production of concrete, specifically the use of seawater and fly ash.

The United Nations Water reported that 1800 million people will be living in regions with absolute water scarcity while two thirds of the world's population could be under water stress conditions by 2025 [1]. Although the Philippines falls under the little or no water scarcity category, it is close to the vulnerability state in terms of freshwater availability [2]. Thus, seawater which surrounds the Philippine archipelago, may be used as an alternative to freshwater. Moreover, people

living near coastal areas, where obtaining freshwater might be difficult, may benefit the most. However, the use of seawater, particularly in the construction sector, is not practiced because of its corrosion effects on reinforced concrete structures.

Meanwhile, the Philippines primarily relies on coal powerplants in generating electricity. Coal mainly contributed to the power generation mix at 44.5% in 2015 while the cement industry utilized 15.22% of the country's coal supply in the same year [3]. With the expected increase of 5.7% electricity consumption on the average between 2015 and 2020, the country is set to open 23 new coal-fired powerplants by 2020 [4]. This increase in the demand for electricity requires a corresponding increase in power generation, thus, additional volume of fly ash is produced. Disposal of this enormous amount of ash becomes a problem to most companies in charge of the operations, coupled with the threat of leaching heavy metals and other toxic chemicals. Therefore, the use of fly ash as partial replacement to cement can help address the management and disposal of accumulated fly ash.

During the production of cement, harmful gaseous substances are emitted into the atmosphere, contributing to the global warming effect. Hence, utilization of fly ash can also lessen the amount of cement required in concrete, thereby reducing the

demand for production and consequently reducing pollutants.

The main objective of the study is to investigate the effects of using seawater and fly ash in concrete under the influence of cold-joints on a macrocell corrosion level. Cold-joints are planes of weakness and discontinuity formed when there is a delay in placement of two batches of concrete, i.e., the initially placed and compacted concrete has started to set before the next batch is delivered and placed. Concrete may be difficult to cast monolithically at one time. The delay may result from time gaps in casting or mixing; transportation of concrete from ready-mixed concrete plant to project site; extension of the incomplete construction on next day and inadequate supply of concrete constituents [5]. These cold-joints may become the passageway for aggressive elements that can corrode the reinforcements in concrete and may eventually lead to sudden failure of a structure.

The specific objectives of the study are:

- To determine the effect(s) of different water to cement ratios (w/c) on the macrocell corrosion behavior of steel.
- To determine the effect(s) of different fly ash replacement ratios on the macrocell corrosion behavior of steel.

This paper is organized as follows: First, a literature on corrosion behavior of steel in concrete is presented in order to understand the process and significance of macrocell corrosion assessment. The experimental set-up is discussed next, followed by results and discussion. Finally, conclusions of the research are highlighted.

## 2. CORROSION BEHAVIOR OF STEEL IN CONCRETE

The durability of concrete may be compromised through alkali-aggregate reaction, sulfate attacks, freeze-thaw cycles and corrosion, among others. Corrosion of the reinforcing steel in concrete has become a great concern as this may result to sudden failure of structures. The high alkalinity of concrete ( $\text{pH} \approx 13$ ) provides a thin oxide layer that protects the rebar from chemical reactivity [6]. However, the protective film around the reinforcing steel is destroyed when sufficient chloride ions penetrate the concrete and the pH of pore solution drops to low values due to carbonation [7]. Chlorides may be present in the mixing water and aggregates of the concrete at concentrations higher than 0.4-1.0% by cement weight or may penetrate by through cracks and construction joints. It was found that chloride

induced corrosion rate is higher than carbonation [8].

The corrosion of steel reinforcement in concrete is an electrochemical process as described in [9]. During the corrosion process, two electrochemical reactions occur simultaneously at two different sites of the steel surface namely: the anodic and cathodic reactions. For these reactions to proceed, electric current must flow in the closed loop between the two sites (Fig. 1). An external current also flows through the pores of the concrete as a result of hydroxide ions (negatively charged) moving the cathode to anode, and also ferrous ions (positively charged) moving from anode to cathode. The water in the concrete pores consists of a dilute solution of alkali and calcium hydroxide which serves as vehicle for ionic flow. The reaction of  $\text{Fe}^{2+}$  and  $\text{OH}^-$  forms ferrous hydroxide ( $\text{Fe}(\text{OH})_2$ ) and with further combination with oxygen results to an insoluble product called rust. However, rust is only a byproduct of the corrosion process while actual corrosion means converting metal atoms to ferrous ions dissolved in surrounding aqueous solution.

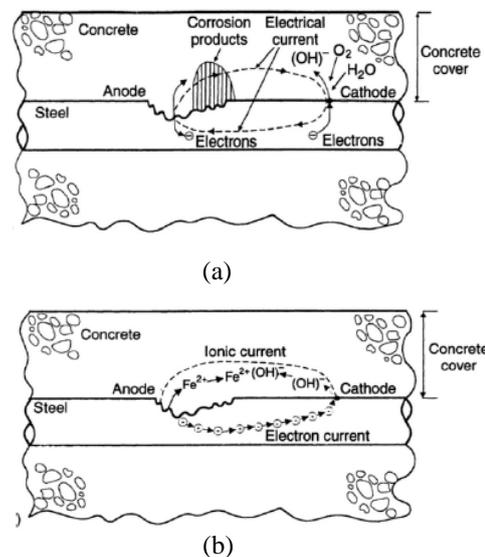


Fig. 1 Corrosion process (a) anodic and cathodic reactions and electric current loop; (b) flow of electric charge in the electric current loop [9]

The loss of metal during corrosion occurs at the anodic sites. The iron atoms are ionized to ferrous ( $\text{Fe}^{2+}$ ) which dissolves in the water solution surrounding the steel. The electrons deposited on the steel raise its electric potential and then flow to a lower potential (cathodic site). At the cathodic

site, the electrons combine with dissolved oxygen and water to form hydroxide (OH<sup>-</sup>) ions. The number of electrons accepted at the cathodic site must be equal to the number of electrons given up at the anodic site. Hence, two iron atoms must be ionized and dissolved at the anodic site for every dissolved oxygen at the cathodic site. Therefore, for the corrosion process to continue, oxygen and water must be present at the cathodic site.

Depending on the different spatial location of anode and cathode, corrosion of steel in concrete can occur as either microcell or macrocell [7]. However, microcell corrosion of reinforcements must normally co-exist with that of macrocell [10]-[11]. In microcell corrosion, the anode and cathode are located adjacent to each other resulting to a uniform iron dissolution over the whole surface [7]. This type of corrosion produces uniform removal of steel and contains anodic and cathodic sites that are microscopic in size [12]. It was found that microcell corrosion is the major corrosion mechanism for steel in concrete after 3 more than years of testing [13]. This type of corrosion is normally present in laboratory tests on small samples of reinforced concrete [10].

On the other hand, in macrocell corrosion, there is a net distinction between the corroding areas of the rebar and the passive surfaces [7]. Furthermore, macrocell corrosion further occurs when the actively corroding bar is coupled to another bar which is passive, which might be due to its different composition or because of different environment [13]. Macrocells are probable on large dimensions of real structures and often due to large active reinforcement areas that are in contact with passive areas [10].

Macrocell corrosion may be affected by the cover depth and the properties or quality of concrete. Increasing the cover depth resulted to lower the corrosion rate in cracked concrete [14]. The cover depth also increases the barrier to various aggressive species and corrosion initiation time [15]. The water to cement ratio significantly influence the macrocell corrosion process [16]. A high water-cement ratio leads to high permeability and a low concrete cover reduces the time for corrosive substances to reach the steel reinforcement [17]. This type of corrosion can be further affected by a non-homogeneous chloride environment and when cracks are induced in the concrete surface [18]. Moreover, macrocell pattern formation prevails and that corrosion rate increases when w/c ratio is low and in the presence of defects in a chloride ion attack condition [8].

Macrocell corrosion investigation of steel in concrete under different w/c ratios and fly ash content mixed with seawater was investigated in this study. Furthermore, the influence of cold-joints was also taken into account. These factors can create a non-homogeneous distribution of chloride ions that may affect the anodic and cathodic transformation of steel through time. As fly ash complements the negative effects of chlorides in the seawater by converting larger pores to finer ones, the study attempts to explain their influence on a macrocell level.

### **3. EXPERIMENTAL SET-UP**

#### **3.1 Material and Specimen Preparation**

Ordinary Portland cement (OPC) Type 1 was used as main binder. Cement was partially replaced by weight with Class F fly ash at 30% and 50%. OPC contained 20.70% silicon dioxide (SiO<sub>2</sub>), 5.00% aluminum trioxide (Al<sub>2</sub>O<sub>3</sub>), 3.36% ferric oxide (Fe<sub>2</sub>O<sub>3</sub>), 62.80% calcium oxide (CaO), 1.7% magnesium oxide (MgO), and 2.66% sulfur trioxide (SO<sub>3</sub>); while fly ash contained 53.30% SiO<sub>2</sub>, 29.10% Al<sub>2</sub>O<sub>3</sub>, 5.44% Fe<sub>2</sub>O<sub>3</sub>, 8.00% CaO, 3.70 MgO, and 0.80% SO<sub>3</sub>. W/C ratio was varied at 0.30, 0.35, 0.40, 0.45, 0.55 and 0.60. Freshwater/tapwater and natural seawater were used as mixing water. The salinity of seawater was measured to be 30.60 ppt.

Concrete mixing was done in accordance to ASTM C192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). Rectangular prism concrete specimens of size 100mm height by 100mm width and 200mm length were cast to investigate the macrocell corrosion activity of the steel reinforcement. Three specimens were cast for each type of specimen. Twelve millimeter diameter deformed steel bars were used as reinforcement. Segmented steel bars (around 60mm in length) were prepared to facilitate the measurement of macrocell current flowing from one element to adjacent elements. Steel bars were submerged in 10% diammonium hydrogen citrate prior to casting to ensure removal of surrounding rust. Lead wires were soldered on both sides of each segment and then attached to one another by epoxy, making sure that no direct electrical connection exists between the elements except through the wires. The cold-joint in the concrete was formed by casting Section A first followed by Section B after 24 hours (Fig. 2). After demolding, each surface of the specimen was covered by epoxy except for the side with the concrete cover of 10mm. This is to ensure the penetration of outside elements through

that surface only. All specimens were then cured by total immersion in freshwater and seawater. For purposes of comparison, control specimens with 0.50 w/c ratio with and without cold-joint were also cast and cured in freshwater. Figure 2 shows the specimen set-up.

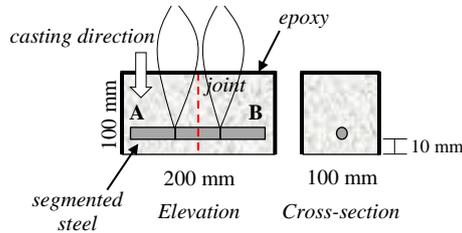


Fig. 2 Specimen set-up

### 3.2 Measurement Methods and Computations

Macrocell currents passing through the segmented steel bars were measured weekly using a zero resistance ammeter. Macrocell corrosion normally occurs in chloride-induced environment and formed along crack and local patch repair areas [19]. Since seawater was used both for mixing and curing concrete with cold-joints, more chloride ions are present for macrocells to occur. Macrocells are characterized by pitting and consists of anodic areas and large cathodic areas situated near or a few distance away from anodes [19]. Formation of macrocells must be considered in designing reinforced concrete structures in aggressive environmental conditions.

The segmented steel bar facilitates the measurement of the actual macrocell current passing from a given element to the adjacent element [18]. Macrocell corrosion current is defined as the total electric current flowing through all steel components taken as a unit. This is given by Eq. (1) considering Fig. 3 [8].

$$I_{macro} = \frac{I_{i-1,i} - I_{i,i+1}}{S_i} \quad (1)$$

Where:  $I_{macro}$  = macrocell current density of steel component  $I$  ( $A/cm^2$ );  $I_{i,j}$  = macrocell corrosion current from steel components  $i$  to  $j$  (A); and  $S_i$  = surface area of steel  $i$ . For a corrosion density of  $100 \mu A/cm^2$ , the corrosion rate of steel is equal to  $1.16 \text{ mm/year}$  [8].

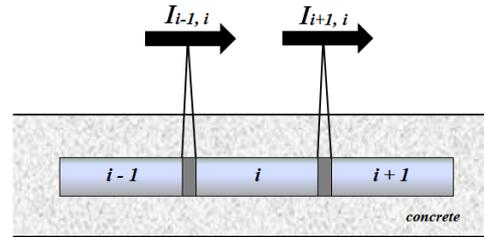


Fig. 3 Macrocell corrosion measurement

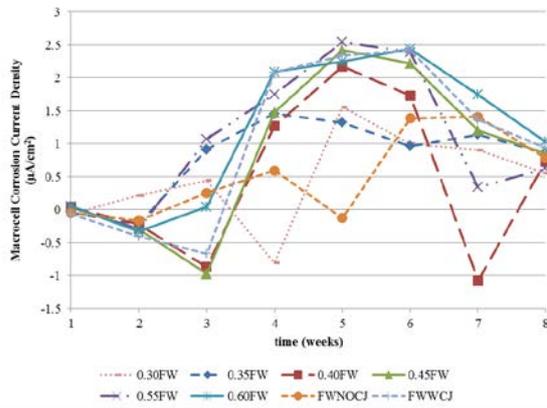
## 4. RESULTS AND DISCUSSIONS

### 4.2 Effect of W/C Ratio

Three samples were cast to investigate the macrocell current variation in concrete specimens under different w/c ratios. These currents were used to compute for macrocell current densities of the steel elements. Figures 4 and 5 show the macrocell current density variation of freshwater and seawater mixed specimens, respectively. A uniform variation of macrocell corrosion throughout the exposure period is not evident. The macrocell current variation is acceptable if it behaves either anodically or cathodically throughout the period regardless of its magnitude [18].

Corrosion rates for freshwater and seawater mixed concrete were calculated and presented in Fig. 6 and Fig. 7, respectively. Generally, the values increased with time. In addition, as the w/c ratio increases, the corrosion rate also increases, except in the case of 0.40 w/c ratio. This can be attributed to the higher permeability associated with higher w/c ratio. Higher w/c ratio leads to greater number and size of pores which increased permeability. Increase in permeability means increase in the ingress of external elements which then corrode the steel bar in concrete. As expected, samples mixed with seawater displayed higher corrosion rates.

Figure 8 illustrates the effect of cold-joints on corrosion. Samples with cold-joints mixed with seawater resulted to higher corrosion rates. Clearly, the presence of cold-joints resulted to an increase in corrosion activity since surrounding elements can easily penetrate the specimen. At eight week, the 0.30 w/c ratio appeared to be the least corrosive regardless of mixing water.



FW-freshwater; SW-seawater; NOCJ-no cold-joint; WCJ-with cold-joint

Fig. 4 Macrocell corrosion current density variation of freshwater mixed specimens under different w/c ratios

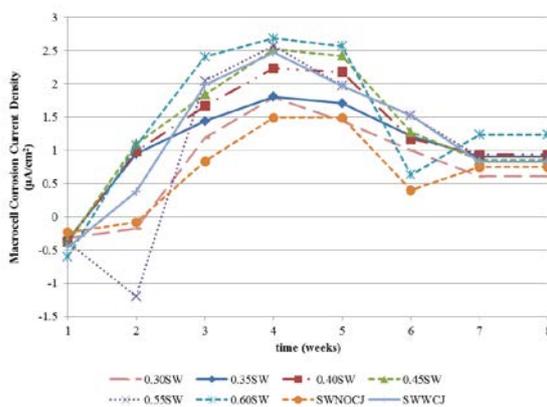


Fig. 5 Macrocell corrosion current density variation of seawater mixed specimens under different w/c ratios

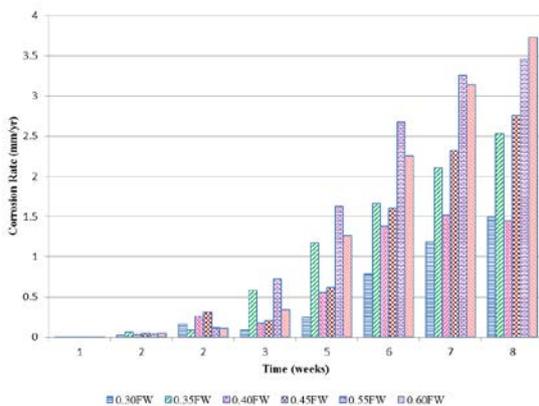


Fig. 6 Corrosion rates of freshwater mixed specimens under different w/c ratios

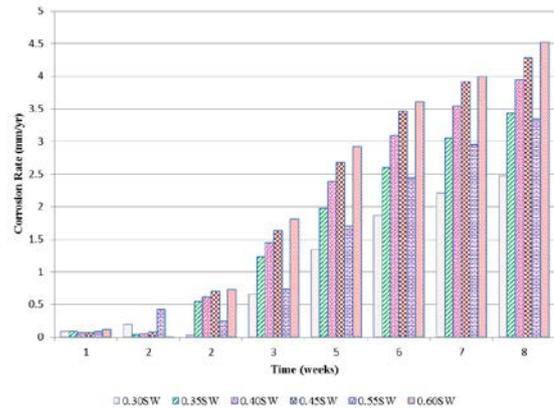


Fig. 7 Corrosion rates of seawater mixed specimens under different w/c ratios

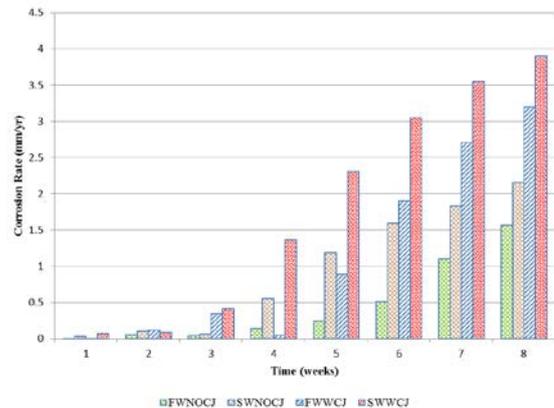


Fig. 8 Effect of cold-joints on corrosion specimens under different w/c ratios

#### 4.2 Effect of Fly Ash Replacement Ratios

Figure 9 shows the corrosion rate with respect to varying fly ash replacement ratios. Similar increasing trends of corrosion values can be observed in samples mixed with freshwater and seawater. Generally, those mixed with fly ash exhibited lower corrosion rates. This can be explained by the fine structure of fly ash that reduces the ingress of elements, thereby improving the permeability of concrete. This then delays the occurrence of corrosion. However, 50% replacement displayed higher value compared to 30% replacement. It can also be seen that seawater adds to the corrosiveness of the steel bar. Reinforcement corrosion is initiated when chloride ions from external environment penetrate the concrete and exceed the critical corrosion-inducing limit [20]. With the chloride content of seawater used for mixing and curing, the electrochemical activity of the steel bars is further stimulated.

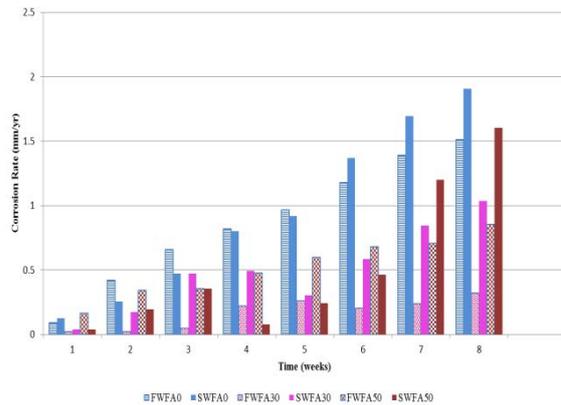


Fig. 9 Effect of fly ash content on corrosion rate

## 5. CONCLUSION

This study highlights the utilization of fly ash and seawater as components of concrete in order to address problems on coal ash by-product disposal and global water scarcity. The effects of these materials, specifically on the macrocell corrosion behavior of steel reinforcement in concrete with cold-joints were investigated.

Specifically, this study investigated the influence of water to cement ratio and fly ash replacement ratios to corrosion rate values. Segmented steel bars facilitated the measurement of macrocell corrosion current activities, with cold-joints acting as corrosion catalysts. The following conclusions summarize the results of this research:

- Using seawater as mixing water showed an increase in the corrosion rate of steel reinforcement compared to specimens mixed with freshwater. Curing specimens with seawater greatly influenced the corrosion rate of the specimens.
- Specimens without cold-joints obtained lower corrosion rates compared to those with cold-joints.
- Corrosion rate increases with increasing w/c ratio. A 0.30 water-cement ratio yielded the least corrosion rate. It may be recommended in terms of the low susceptibility corrosion both for freshwater and seawater mixed concrete.
- Fly ash alters the normal characteristics of concrete when used as partial replacement to cement. It was found that the corrosion rate of steel decreases as fly ash content increases. Specimens containing 30% and 50% fly ash in both freshwater and seawater mixes gained an increase in corrosion resistances. Fly ash decreases the permeability of concrete thus making it less exposed to aggressive environments. Moreover, the fly ash content

caused lesser chloride intrusion to the specimens during curing.

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