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INFLUENCE OF SEAWATER ON THE STRENGTH OF RC BEAMS AND CORROSION BEHAVIOR OF STEEL

* Bernardo A. Lejano[1] and Cheryl Lyne C. Roxas[2]

[1,2]Faculty, De La Salle University, Philippines

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ABSTRACT: The effects of seawater on the strength performance of reinforced concrete (RC) beams were investigated. Four RC beams measuring 150 x 200 x 800 mm were constructed. Two beams were constructed with concrete mixed with freshwater and the other two were constructed with seawater. Center point loading test was conducted on the beams specimens. Load, deflection, and strain of each beam were monitored and recorded. It was found that the difference between the strength test values obtained by using freshwater and seawater were minimal. However, formation of rust in steel when seawater was used was very evident. Hence, the effects of seawater on the corrosion behavior of steel were investigated. Mortar specimens with cold-joint were used as medium to facilitate the investigation of corrosion. Ordinary Portland cement (OPC) Type 1 was used as binder for the mortar and was partially replaced with fly ash at 30% and 50%. Rectangular prism specimens of dimensions 40mm by 40mm by 160mm were cast for macrocell corrosion measurements and compressive strength determination. From the test results, the following were observed: (a) Specimens with fly ash were observed to have lower corrosion rates compared with the ones without fly ash; (b) Specimens mixed with freshwater resulted to the higher strength both at 7th-day age and 28th-day age; (c) Regardless of the type of water used in making the mortar, specimens cured in seawater achieved higher later strength values.

Keywords: Seawater, Corrosion, Reinforced Concrete, Mortar, Fly Ash

1. INTRODUCTION

Seawater is still currently not allowed to be used in construction as stipulated in the National Structural Code of the Philippines (NSCP) [1] and most of the other codes all over the world. However, there are already studies [2] - [5] that indicate the possibilities of using seawater as a substitute for potable water in concrete; whether for mixing, curing, or both. Results are varying and sometimes contradicting. Studies of Otsuki et al. [2], indicate the countermeasures that can be applied to eliminate the disadvantages that seawater presents. These studies indicate the possibility of using seawater in concrete; but still more studies must be conducted to further validate the usage, especially in reinforced concrete. Establishing criteria in using seawater in reinforced concrete members would benefit places with abundant seawater resources, such as the Philippines.

To investigate the effect of seawater when used in making reinforced concrete (RC) beam, the structural performance of two RC beams constructed with seawater were compared to two control RC beam specimens constructed with freshwater. This is done by testing the RC beams as simply supported beams with center-point loading. The findings of this comparison are presented in this paper. It was observed that the major effect of seawater is in corroding the reinforcing bars. It is also believed that exposing the RC beam to seawater environment would affect the corrosion behavior of the reinforcing bars.

As a consequence, the effects of seawater on the corrosion behavior of steel in mortar were investigated. In addition, fly ash was also investigated as a possible concrete ingredient that can possibly lower the corrosion rate of steel in concrete. Fly ash is a pozzolan, hence it reacts with calcium hydroxide that is produced during cement hydration resulting to the conversion of larger pores into finer pores [6]. This produces a more compact concrete thereby blocking the flow of seawater or other chemical attacks. As a result, the corrosion risk of reinforced concrete structures in chloride rich environments, such as seawater, can be lowered by fly ash to a satisfactory level [7].

In this study, steel is assumed to undergo macrocell corrosion. Corrosion happens when chemical reaction, specifically oxidation, occurs in steel. The presence of this chemical reaction can be monitored through the flow of electricity when steel bars enclosed in concrete are arranged forming a macrocell circuit, that is, an anode and a cathode that are separated from each other. Usually, the passive film that is formed on the steel surface due to the alkalinity of concrete is broken down due to the presence of chemicals or other environmental factors.

Mortar specimens were used in this research to make it easier to measure to macrocell corrosion, as the presence of coarse aggregate could complicate the flow of electric current. Macrocell corrosion can be further affected by chloride environment especially when concrete surface has cracks [8]. Since macrocell corrosion may occur at any time to any reinforced concrete structure, it is important to have good awareness of this corrosion process. As seawater is known to increase the probability of corrosion of steel, it is important to determine under what conditions this will happen and what are the possible remedies or solutions that may be applied.

To address the above mentioned problems, the main objective of this phase of study is to determine the effects of seawater on the corrosion density and corrosion rates and the possible countermeasures that fly ash can provide to the macrocell corrosion. In addition, the effects of seawater and fly ash to the compressive strength of mortar are also investigated to provide more information.

2. METHODOLOGY

This research may be divided into two parts. The first part is the testing of RC beams to evaluate the effect of seawater on their structural performance. The second is the macrocell corrosion test to study the corrosion behavior of steel and find possible way of counteracting it.

2.1 Test of RC beams

Four RC beams with dimensions of 150 x 200 x 800 mm with target concrete strength of f'c= 21MPa were prepared. Two RC beams used freshwater as mixing water while the other two RC beams used seawater, which will be termed as "freshwater beam" and "seawater beam", respectively. The seawater used was obtained near seashore at waist-deep with salinity of 30.2 ppt. Other components such as size of aggregates, size of steel reinforcing bars, type of cement, and water to cement ratio were held constant to make the beams identical except for the water used. Cylindrical concrete specimens were also prepared so as to determine the strength of concrete at the day of testing of the beams. The diameter of the longitudinal steel reinforcement is 8mm and the stirrup is 6mm. The cross-section detail of the beam is shown in Fig, 1 and the longitudinal dimensions and reinforcing details of the beam is shown in Fig.2.

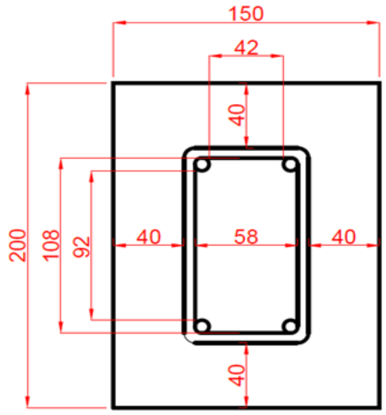

Fig.1 Cross section of the RC beam specimens

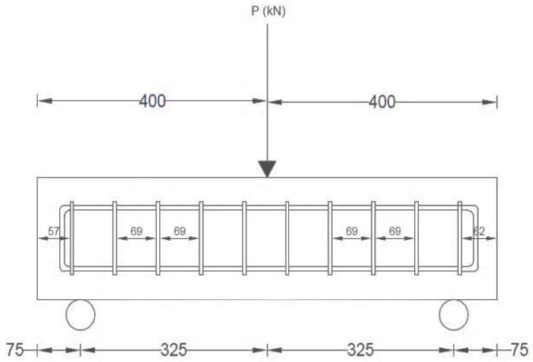

Fig. 2 Longitudinal details of the beam specimens

Testing for the flexural strength of the RC beam was conducted at 56 days after casting. Center point loading on a simply supported beam was adopted. A hydraulic jack was used to apply the load and monitored with a load cell. Clip gages and displacement transducers were used to monitor the strains and deflection, respectively, at the midspan of the beam. Shown in Fig. 3 is the test setup. After the beams were tested, the reinforcing bars were recovered by opening up the beam for evaluation of the effect of seawater.

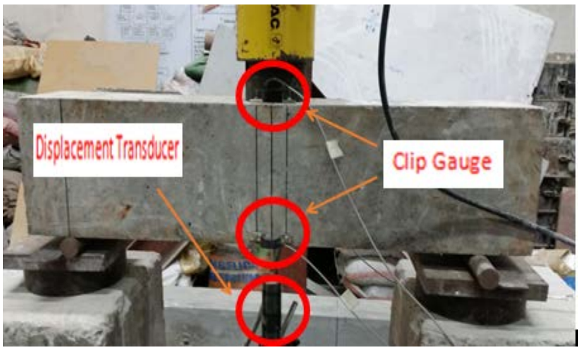

Fig. 3 Experimental test setup of RC beam

2.2 Macrocell Corrosion Test

For the macrocell corrosion test, rectangular prism or block specimens measuring 40mm by 40mm by 160mm were used. The water cement ratio used in making the specimens is 0.5 and the cement-sand ratio is 1:2. Fly ash as partial substitute for cement at 30% and 50% by weight was implemented. The seawater used had a salinity of 30.6 ppt. ASTM Type 1 Portland cement was used in combination with class F fly ash. Presented in Table 1 are the specimen codes assigned for the different type of specimens. The specimens were cured in either freshwater or seawater, but the macrocell corrosion test was done only for the specimens that were cured in seawater. To provide more information about the effect of seawater on mortar, compressive strength tests were conducted at the 7th and 28th day age of mortar.

Table 1 Codes used for specimen

Specimen Code	Fly ash (FA) %	Mixing Water	Curing Water
FA0FW-FW	0	FW	FW
FA30SW-FW	30	SW	FW
FA50SW-FW	50	SW	FW
FA0FW-SW	0	FW	SW
FA30SW-SW	30	SW	SW
FA50SW-SW	50	SW	SW

Note: FW=Freshwater, SW=Seawater

For the macrocell corrosion test, reinforcing steel bars, 12 mm in diameter, were arranged in mortar block so that anode and cathode are spatially separated resulting in a flow of electric current over the spatial distance [9]. A 100 mm long deformed bar was cut into three equal lengths and were placed in the mortar blocks as illustrated in Fig. 4. The bars were cleaned by soaking them in 10% diammonium hydrogen citrate to remove rust. Electrical wires were soldered on both ends of the cut steel bars to be connected to the ammeter that will measure the electric current. The divided bars were longitudinally joined together using epoxy. The assembled steel bars were placed in the mortar block maintaining a mortar cover of 10 mm from the surface. Cold-joint was made in the mortar block to ensure penetration of seawater. To do this, only half of the mould was first filled with mortar. Then, the mortar was allowed to set for a whole day before filling the mould to its full capacity. Fig. 5 shows the resulting corrosion specimen with cold-joint. The mortar blocks were then sealed with epoxy on all sides except on the side nearest to the steel bar, the one with 10 mm mortar cover.

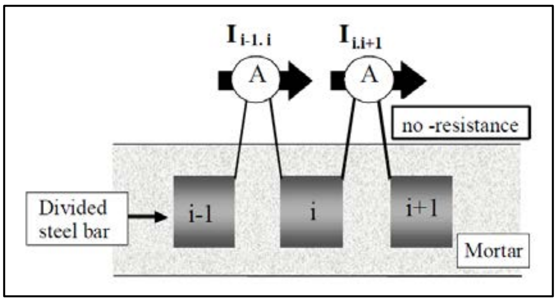

Fig. 4 Macrocell current density measurement [12]

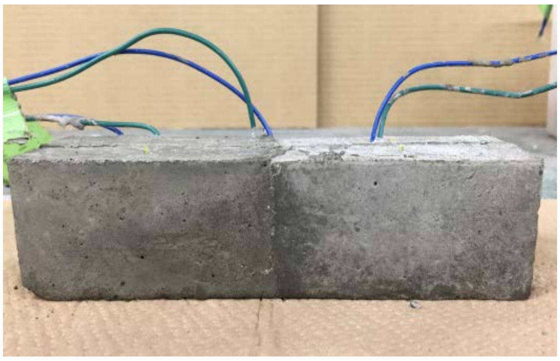

Fig. 5 Corrosion specimen with cold-joint [15]

Cold-joints are incorporated in the specimens to provide a possible passage for the seawater used in curing. This will provide additional chloride ions to reach the steel aside from the ones that are already present in the mortar. The high alkalinity of the mortar creates a thin layer of iron oxide that provides resistance to further oxidation by preventing oxygen from reaching the steel [10]. However, the introduction of chloride ions, oxygen and water into the mortar destroys this protective oxide layer.

As mentioned earlier, macrocell corrosion monitoring was done only to steel in specimens cured in seawater. A zero resistance ammeter (ZRA) was used to measure weekly the macrocell current (refer to Fig. 4). Then the macrocell current densities were calculated from the measured macrocell currents. Macrocell corrosion current is defined as the total electric current flowing through all segmented steel bars in the mortar blocks taken as a unit. The macrocell current density formula is given in Eq. 1 [11]:

$$a_i = \frac{I_{i-1,i} - I_{i,i+1}}{S_i} \tag{1}$$

where: a_i = 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.

To evaluate the macrocell corrosion electricity, a graph is made by plotting the macrocell current density against time. An example is shown in Fig. 6. The macrocell current densities are plotted for a period of 8 weeks (56 days). The macrocell corrosion electricity is obtained by integrating the area under the curve in the graph shown in Fig. 6.

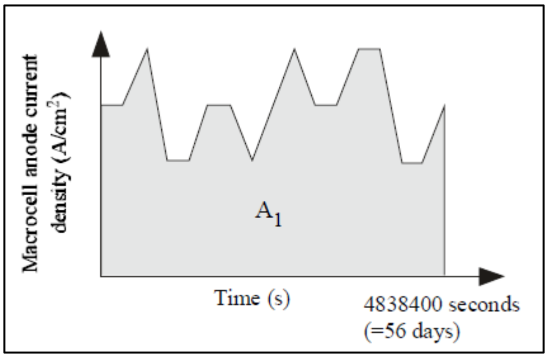

Fig. 6 Macrocell corrosion electricity [11]

According to Miyagawa et al. [12], the corrosion rate may be evaluated as follows: If the maximum corrosion electricity is below 20 Coulomb/cm^2 in 56 days the corrosion rate is considered “low”, that is, 0.05 mm/year. If it exceeds 50 Coulomb/cm^2 in 56 days, the corrosion rate is considered “high”, that is, 0.12 mm/year. He also predicted that for “low” corrosion electricity in 30 years, the yield strength of the reinforcing steel may decrease to about 70% of the original strength, while for “high” corrosion electricity, the yield strength may decrease to as low as 35% of the original strength.

3. TEST RESULTS AND FINDINGS

At the time of testing of the RC beam specimens, the concrete strength was measured using concrete cylinders. The average strength of concrete with freshwater is 27.17 MPa and the strength with seawater is 23.94 MPa, indicating that that the compressive strength of concrete with seawater is 11.88% lower than concrete with freshwater.

The yield strength (fy) of reinforcing bars recovered from the tested RC beam specimens was determined. Freshwater beams had an average fy=499.5 MPa and seawater beams had fy=495.7 MPa. The difference is only 0.76% indicating that the strength of the steel reinforcing bars has not been significantly affected by the seawater. Hence, the decrease in strength of the beam may be due only to the slight decrease in concrete strength.

Fig. 7 shows the visual difference of the steel reinforcement bars taken from the seawater beam specimens and from the freshwater beam specimens. Rust can be clearly observed on the steel reinforcements from the seawater beam specimens while no rust can be observed on the steel from the freshwater beam specimens.

Fig. 7 Steel bars from “freshwater beam” (top), steel bars from “seawater beam” (bottom)

The load-strain strain curves of the tested beams are shown in Fig. 8. Curves labeled starting in “F” are for freshwater beams while those starting in “S” are for seawater beams. It can be seen that the curves are almost identical. Differences are very minimal.

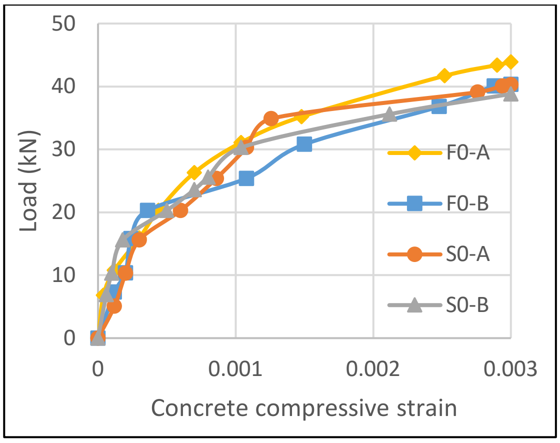

Fig. 8 Load-strain relationship of the RC beams

Tabulated in Table 2 are the important values obtained from the test of beam, specifically at the ultimate condition, that is, when the strain of concrete reached 0.003. The average ultimate load obtained from the freshwater beams is a little bit higher than that of the seawater beams. The difference is only 6.10%. The midspan deflection was also almost the same for the two types of beams. The difference is only 12.9%.

Table 2 Values from tests of RC beam specimens

At ultimate condition (strain=0.003)	Specimen Type	
	Freshwater beam	Seawater beam
Ult. Load (kN)	42.11	39.54
Deflection (mm)	0.986	1.113
Mn_{expt} (kN-m)	6.84	6.42
Mn_{calc} (kN-m)	6.72	6.45
Expt/Calc	1.018	0.995

Comparing the nominal flexural strengths (Mn), the flexural strength of freshwater beams is higher than compared to seawater beams as presented in Table 2. However, the difference between the two groups is again very minimal. The percentage difference is 6.14% only. The comparison between experimental and theoretical nominal moments (Mn_{expt}, Mn_{calc}) yielded very good agreement. The theoretical values were calculated using the formulas stipulated in the code (NSCP).

The test results from the loading test of RC beam specimens indicate that there is very small difference in the structural performance between RC beam specimens with freshwater and that with seawater. The major effect is only in the corrosion of the steel bars, which in the long run may contribute to the deterioration of the structural integrity of the beams.

The macrocell corrosion rate evaluation of steel in mortar provides an insight on the possible corrosion of steel in beams with seawater and exposed to seawater environment. Fig. 9 shows the macrocell current density of the middle steel element for each specimen type.

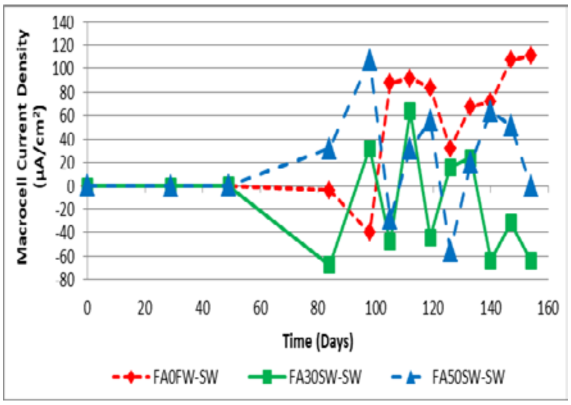

Fig. 9 Macrocell current density variations

Although Fig. 9 does not consistently show anodic or cathodic macrocell current densities, it is only an indication that macrocell corrosion measured is non-uniform. The anodic and cathodic reactions may fluctuate throughout the investigation period [8]. Based on corrosion rate calculation of Miyazato [11] and Miyagawa et al. [12], the macrocell corrosion electricity may be calculated from Fig. 9 and can be converted to macrocell corrosion rate. It is evaluated for the period of 8 weeks (56 days), starting on the 98th-day up to 154th-day of current measurement, when the current measurements are significantly large.

Presented in Fig. 10 is the plot of the macrocell corrosion rates of the mortar specimens for the investigation period of 8 weeks. The corrosion rate is calculated per period (per week) so that corrosion development could be observed over the investigation period. The specimens without fly ash (FA0FW-SW) are observed to have the highest corrosion rate. Moreover, the corrosion rate is consistently increasing during the 8-week period and the corrosion rate at the end of the 8-week period is 0.08mm/(8week) which may be projected to one year as 0.51mm/year. For the specimen with 30% fly ash (FA30SW-SW), the corrosion rate is lowest, picking up only at the end of the 8-week period. The corrosion rate at the end of the 8-week period is 0.01mm/(8week) or 0.09mm/year. The lower corrosion rate of specimens mixed with fly ash can be explained by the fine structure of fly ash preventing the penetration of chlorides. However, in the case of the specimen with more fly ash, that is, at 50% cement replacement (FA50SW-SW), the corrosion rate turned out to be higher than the specimens with smaller amount of fly ash. This indicates that the amount of fly ash used as corrosion countermeasure may have a limit and may be at cement replacement lower than 50%. Furthermore, it seems that using seawater as mixing water is a lesser corrosion risk than exposing mortar to chloride-rich environment. Moreover, the existence of cold-joints may have also increased the corrosion activity as surrounding seawater can easily penetrate the mortar.

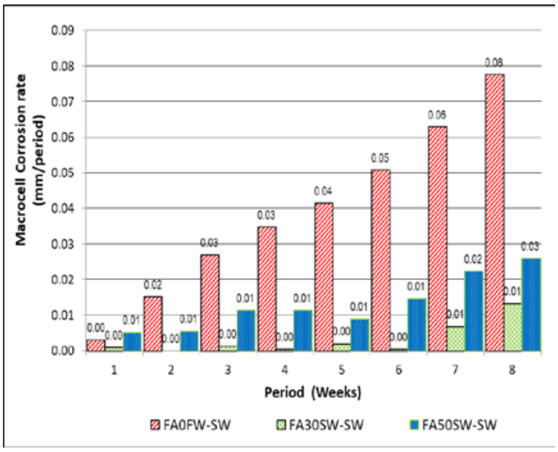

Fig. 10 Macrocell corrosion rate of the specimens

Regarding the strength investigation of the mortar specimens, the results of the compressive strength test indicate the usual trend that the compressive strength increases with time, as shown in Fig. 11. The strength increased from 7th-day to 28th-day. Furthermore, the compressive strength of specimens mixed with freshwater exhibited higher than those mixed with seawater. This is the same observation in the RC beam test. In general, the increase in fly ash replacement percentage resulted to the decrease in compressive strength of mortar, which was similarly observed by Lim et al. [13].

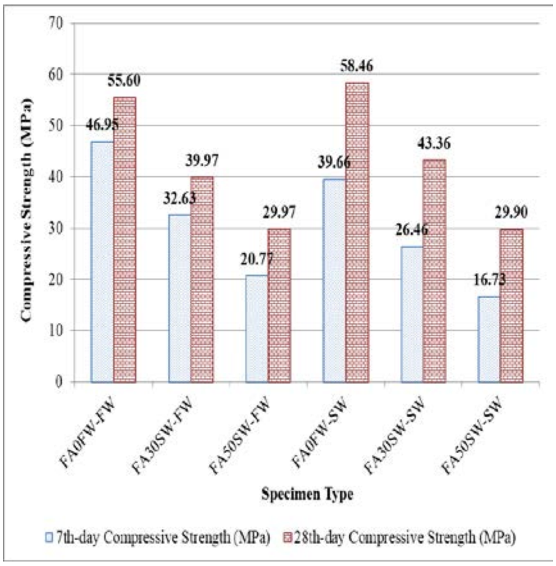

Fig. 11 Day 7 and day 28 compressive strengths

Regardless of the mixing water, specimens cured in seawater resulted to higher 28th-day compressive strength, except for the specimens with 50% fly ash replacement. Results of this study corroborated that mortars with fly ash immersed in seawater tend to have higher compressive strength [14]. However, it seems that the 30% fly ash replacement is the best among the values considered because the increase in strength is higher when cured in seawater.

4. CONCLUSION

Rust was clearly observed on the steel reinforcement recovered from the RC beam specimens mixed with seawater. However, in terms of strength, the steel was not significantly affected.

Although there was a slight strength reduction in concrete with seawater, in general, the seawater did not have any significant effects on the flexural strength of the beam for the period covered in the study. Since the strength performance of RC beams with seawater was not significantly affected, seawater may be used in short term general and minor construction purposes. However, the behavior of reinforced concrete with seawater must still be studied further on a long-term basis.

To provide insights on the effects of seawater on the corrosion of steel reinforcement in concrete, the effects of seawater and fly ash to the macrocell corrosion behavior of reinforcement in mortar were investigated. Rectangular prism mortar specimens with segmented steel bars were used as specimens. The macrocell corrosion currents were measured every week for a period of 8 weeks in order to compute for the corresponding macrocell corrosion density and corrosion rates. From the results, the following were concluded:

The specimens cured in seawater did not show consistent anodic or cathodic current densities throughout the exposure period, indicating non-uniform corrosion

Mortar specimens with fly ash were observed to have very much lower corrosion rates compared with the ones without fly ash which can be explained by the fine structure of fly ash that reduces the ingress of aggressive elements. However, it was observed that less corrosion rate is obtained when the cement replacement with fly ash is at 30% than when the fly ash is at 50%.

Mortar specimens mixed with freshwater resulted to higher strength both at 7th-day age and 28th-day age. The compressive strength decreases as the fly ash replacement percentage increases. Regardless of the mixing water, mortar specimens cured in seawater seemed to achieve higher 28th-day compressive strength.

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6. REFERENCES

[1] NSCP 2010, “National Structural Code of the Philippines 6th Ed.”, Chapter 4 – Structural Concrete, Vol. 1, 2010, pp. 13-14, pp.

[2] Mohammed T, Hamada H, & Yamaji T, “Performance of seawater-mixed concrete in the tidal environment”, Cement and Concrete Research, Volume 34, Issue 4, April 2004, pp. 593–601.

[3] Otsuki N, Furuya D, Saito T, and Tadokoro Y, “Possibility of sea water as mixing water in concrete”, 36th Conference on Our World in

Concrete & Structures, Singapore, August 14-16, 2011.

[4] Wegian FM, "Effect of seawater for mixing and curing on structural concrete", The IES Journal Part A: Civil & Structural Engineering, Vol. 3, No. 4, November 2010, pp.235–243.

[5] Olutoge FA and Amusan GM, "The effect of sea water on compressive strength of concrete", International Journal of Engineering Science Invention, Vol. 3, Issue 7, July 2014, pp. 23-31.

[6] Manmohan D and Mehta PK, "Influence of pozzolanic slag and chemical admixtures on pore size distribution and permeability of hardened cement paste", Cement Concrete Aggregates, Vol. 3, Issue 1, July 1981, pp. 63-67.

[7] Millard SG and Bungey JH, "In-situe assessment of reinforcement corrosion in concrete structures", IABSE Report, 1989.

[8] Nanayakkara O and Kato Y, "Macro-cell corrosion in reinforcement of concrete under non-homogeneous chloride environment", Journal of Advanced Concrete Technology, Vol. 7, No. 1, February 2009, pp. 31-40.

[9] Subramaniam K and Bi M, "Investigation of steel corrosion in cracked concrete: Evaluation of macrocell and microcell rates using Tafel polarization response", Corrosion Science, Volume 52, Issue 8, August 2010, pp 2725-2735.

[10] Madlangbayan M, Otsuki N, Nishida T and Baccay M, "Corrosion behavior of steel bar in chloride contaminated mortars with fly ash", Philippine Engineering Journal, Vol 26, No 2, 2005, pp. 13-24.

[11] Miyazato S, and Otsuki N, "Steel corrosion induced by chloride or carbonation in mortar with bending cracks or joint", Journal of Advanced Concrete Technology, Vol. 8, No. 2, June 2010, pp.135-144.

[12] Miyagawa T, Takewaka K, Demura K, Masuda Y and Moriwake A, "Technical committee report on the rehabilitation of concrete structures" Proceedings of the Japan Concrete Institute, Vol. 20, No. 1, 1998, pp. 39-48. (in Japanese)

[13] Lim ED, Roxas CLC, Gallardo R and Otsuki N, "Strength and corrosion behavior of mortar mixed and/or cured with seawater with various fly ash replacement ratios", Asian Journal of Civil Engineering, (BHRC), Vol. 16, No. 6, Jan. 2015, pp 835-849.

[14] Donatello S, Palomo A and Fernández-Jiménez A, "Durability of very high volume fly ash cement pastes and mortars in aggressive solutions", Cement and Concrete Composites, Vol.38, 2013, pp.12-20.

[15] Roxas C and Lejano B, "Influence of Fly Ash and Seawater to the Strength and Macrocell Corrosion Behavior of Steel in Mortar with Cold-Joint", Proceedings of the 9th ASEAN Civil Engineering Conference (ACEC) 2016, Universiti Teknologi Brunei, Brunei Darussalam, 14 - 15 November 2016, pp. 115-125