Effects of bleeding on corrosion of horizontal steel bars in reinforced concrete column specimen

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Abstract. The durability of reinforced concrete proved to be predominantly controlled by the resistance against ingress of harmful substances including chloride ions, carbon dioxide, and moisture. The corrosion of steel bars taking place especially in a marine environment was likely to be severe, which depends on the availability of oxygen and moisture consumed by cathodic reactions. This study aims to investigate the effects of bleeding on the corrosion of horizontal steel bars placed in reinforced concrete column specimens. This was examined through electro-chemical tests including the half-cell potential, polarization resistance, and corrosion current density carried out using specimens in which corrosion was induced via dry and wet (NaCl 10%) cycles. The presence or absence of copper slag fine aggregate and fly ash replacement were taken up as experimental factors. The results suggested that the corrosion of horizontal steel bars in the upper part of the column concrete specimen was adversely affected even for the case of OPC specimens with relatively lower bleeding water. This was attributed to less resistance against the ingress of corrosive substances especially in those locations. In the case of fly ash mixtures, the corrosion resistance was significantly improved owing to lower oxygen permeability measured via cathodic polarization technique.

1. Introduction

Conventionally, RC structures have been considered to be maintenance-free because it is highly durable. In recent years, a decrease in the durability of reinforced concrete (RC) structures caused by corrosion of steel bars has become a major social problem. RC structures are widely used for infrastructure such as tunnels and bridges. The durability of RC structures is adversely affected by corrosion of steel bars when exposed to aggressive environments, such as chloride and acid attack [1]. Indonesia is an archipelagic state and many provinces are located at the coastal area of each island. It is inevitable that corrosion of steel bars embedded in concrete occurs, which tends to be caused by chloride ion from the sea environment during the service time. This is also the case for the RC structures that have used protection for the chloride attack. The use of sea sand and antifreezing admixture also has led to the corrosion of steel bars in landed areas. Therefore, the durability of RC structures especially the corrosion of steel bars has become one of the major durability issues in Indonesia.
Recently, the use of industrial by-products as construction materials has been promoted in a sustainable approach [2]. For example, the amount of coal ash which produces fly ash (FA) generated from electric utilities such as coal-fired power plants is about 8.5 million tons in Japan and about 300 thousand tons in Shikoku according to data published in 2011 [3]. On the other hand, about 2 million tons of copper slag fine aggregate (CUS) are also produced through copper refining in Shikoku. Much research for utilizing these materials as concrete materials has been intensively conducted. According to past research [4], it was reported that bleeding water tends to increase in fresh concrete mixed with CUS because of its high density 3.55 g/cm$^3$. On the other hand, it has been suggested that bleeding water could be reduced by the addition of FA, and the longer strength development is expected by the pozzolanic reaction [5].

Corrosion resistance of steel bars is a very important materials property among the durability of concrete structures [6]. Among them, chloride induced corrosion of steel bars is known to be most severe leading to higher deterioration rate. Chloride attack is mainly caused by the ingress of chloride ions from the outside into cover concrete under marine environment. When the chloride ion concentration at the depth of steel bars exceeds thresholds e.g. 1.2 kg/m$^3$ [7, 8], the passive film is destroyed and the corrosion of steel bars occurs. Various nondestructive tests have been developed and studied for assessing the corrosion properties, as it is difficult to directly observe the corrosion processes of steel bars embedded in concrete by visual observation. Electrochemical methods such as half-cell potential method and polarization resistance method [9, 10] are promising because corrosion of steel bars in concrete proceeds through electrochemical reactions by consuming water and oxygen [11-13]. When corrosion of steel bars occurs, an anodic reaction in which iron ionizes and a cathodic reaction in which oxygen is reduced progresses on the surface of the reinforcing bar to form a corrosion cell. In the cathodic reaction, oxygen is consumed on the surface of the steel bars, and it was reported that the rate of oxygen permeability is an influencing factor greatly affecting the corrosion of steel bars in concrete [14, 15]. In addition, the electrical resistivity of cover concrete is a significant factor contributing to the corrosion processes when macro-cell formation occurs.

Pores modified by the bleeding water may have a large influence on the durability with respect to ingress of harmful substances and corrosion processes owing to chloride attack or carbonation. Bleeding in a form of segregation is unavoidable for column specimens cast from the height of 1.5 m at most, thus leading to the formation of vulnerable zone around the horizontally placed steel bars. The bleeding affects the integrity of reinforced concrete owing to larger gaps or voids formed at the steel and concrete interface. According to past investigation, the bleeding of fresh concrete qualitatively aggravated the durability of horizontal steel bars embedded in concrete structures [16, 17].

Reinforced concrete column specimens cast using various types of aggregate including crushed limestone, sandstone, and pit sand obtained in regional resources. The presence or absence of CUS and FA replacement were taken up as an experiment factor. This study examined the corrosion resistance of horizontally placed steel bars due to the ingress of chloride ions in concrete column specimens cast with CUS and/or FA replacements, whereby bleeding rate is varied. In particular, a detailed investigation was carried out on the variations of Cl$^-$ concentrations with height and depth, corrosion current density, and oxygen permeability on horizontal steel bars affected by segregation especially with bleeding water in column specimens.

### 2. Methodology

#### 2.1 Specimen overview

Reinforced concrete column specimens of the cross section 300x300 mm and the height of 1500 mm were cast from a height of 1.5 m with water to binder ratio (W/B) of 60% for OPC mixtures. For the case of FA mixtures, W/B was specified as 52.5%. Figure 1 shows the schematic of the reinforced concrete column specimen. They were cured in room conditions controlled at 20oC
until the age of 28 days [18, 19]. Segmented steel bars comprising D32 deformed steel bars were
embedded in the height of 250, 750, and 1250 mm from the bottom surface. The smaller
specimens with dimensions of 300x132x100 mm were cut out from the column specimen and
used for chloride induced corrosion tests.

![Figure 1. Reinforced concrete column specimen](image)

### Table 1. Mix proportions of concrete specimens

| Mixtures | W/B (%) | W | C | FA | Fine aggregate (g/m³) | Coarse aggregate (g/m³) | Chemical admixtures |
|----------|---------|---|---|----|-----------------------|------------------------|---------------------|
|          |         | S1 | S2 | S3 | S4 | G1 | G2 | G3 | AEA- WRA | AEA |
| FACUS 60 | 52.5    | 165 | 251 | 63 | - | 166 | 169 | - | 731 | 931 | - | 1886 | 629 |
| FACUS 30 | 52.5    | 165 | 251 | 63 | - | - | 604 | 366 | - | 469 | 462 | 943 | 2200 |
| CUS60    | 60      | 165 | 275 | - | - | 179 | 183 | - | 731 | - | 955 | - | 1650 | - |
| OPC      | 60      | 165 | 275 | - | - | 448 | 457 | - | - | 955 | - | - | 4125 | 1375 |

### Table 2. Properties of aggregate

| Fine aggregate (S) | Types                                      | Specific gravity (SSD) | Absorption capacity | Fineness modulus |
|--------------------|--------------------------------------------|------------------------|---------------------|------------------|
| S1                 | Crushed sand obtained from sandstone       | 2.61                   | 1.06                | 2.92             |
| S2                 | Crushed sand obtained from limestone       | 2.66                   | 0.58                | 2.47             |
| S3                 | Crushed sand obtained from pit sand        | 2.62                   | 1.05                | 2.51             |
| S4                 | Cooper slag fine aggregate                | 3.55                   | 0.04                | 2.28             |
| G1                 | Crushed sandstone                          | 2.63                   | 1.15                | -                |
| G2                 | Crushed sandstone                          | 2.65                   | 0.49                | -                |
| G3                 | Crushed sandstone                          | 2.61                   | 0.66                | -                |
Table 1 shows mix proportions of concrete mixtures tested in this experiment. Ordinary Portland Cement (OPC) with a specific gravity of 3.14 was used as the binder in accordance with JIS Type-II. Four types of fine aggregates and three types of coarse aggregates were used as summarized in Table 2. The specified slump and air content for the experiment were 8.0 cm and 4.0% respectively.

2.2. Electro-chemical measurements
Chloride-induced corrosion test using salt water at a concentration of 10% was carried out through dry and wet cycles under room conditions controlled at 20°C. The specimens were left under room conditions (dry conditions for 4 days and 3 days for the wet conditions). Half-cell potential and polarization resistance were measured at the end of each wet period.

2.2.1. Corrosion current density
The potential of the steel bars in concrete was measured by half-cell potential method. This method examines the corrosion possibility of steel bars in concrete based on the half-cell potential of steel bars depending on the severity of corrosion of steel bars in concrete. It is shown that there is a high possibility that corrosion of steel bars is occurring as the value of the half-cell potential is relatively low. The classification criteria adopted is in accordance with ASTM-C876 [20] and is reproduced in Table 3.

| Corrosion Potential (Ecorr) (mV vs. CSE) | Probability of corrosion |
|-----------------------------------------|--------------------------|
| <-350 mV                                | 90%                      |
| (-350 mV) - (-200 mV)                   | Uncertain                |
| >-200 mV                                | 10%                      |

Table 4 Corrosion current density criteria for reinforcing bar in concrete (CEB) [21]

| Corrosion Current Density (i_corr mA/cm²) | Corrosion State   |
|------------------------------------------|-------------------|
| <0.2                                     | Passive           |
| 0.2-0.5                                  | Low corrosion     |
| 0.5-1.0                                  | Moderate          |
| >1.0                                     | High corrosion    |

Half-cell potential and polarization resistance were measured from the same surface on which the water was provided and subsequently removed. The electro-chemical measurements consist of working electrode (embedded steel bars), counter electrode (steel plate), and a reference electrode were electrically connected during the measurement. The reference electrode is comprised of Ag/AgCl saturated KCl and the potentials based on Cu/CuSO4 were inferred by the readings. A classification criteria for the corrosion current density according to European Concrete Committee (CEB) is shown in Table 4. Microcell corrosion current density was calculated based on the polarization resistance measured using stern-geary constant as 0.026.
2.2.2. Oxygen permeability
Cathodic polarization tests were carried out using a potentiostat similar to the polarization resistance measurements. The current density was measured when DC current was impressed based on the rate of 1 mV/s. The current density when the potential difference became -860 mV was assumed to reach the limiting current density. The rate of oxygen permeability consumed on the surface of the steel bar embedded in the concrete was calculated based on the Eq. (1) [22].

\[
\frac{dQ}{dt} = -\frac{i_{\text{lim}}}{nF}
\]

(1)

where \(\frac{dQ}{dt}\): the rate of oxygen permeability (mol/cm\(^2\)/sec); \(i_{\text{lim}}\): limiting current density (A/cm\(^2\)); \(F\): Faradays constant (96,500 coulombs/mol); and \(n\): the number of electron exchanged equal to 4.

2.2.3. Chloride ion concentration
Chloride ions are measured using coulometric titration method. The samples were taken by drilling the specimens at the depths: 0-15 mm; 15-30 mm; 30-45 mm; 45-60 mm; 60-75 mm from the concrete surface. The chloride ion concentration in each powder sample was calculated based on the Eq. (2).

\[
C = \frac{W_1 \times S}{W_2 \times 100} \times E
\]

(2)

Where \(C\): the content of chloride ion (kg/m\(^3\)); \(W_1\): the weight of heated distilled water (g); \(W_2\): the weight of sample (g); \(S\): chloride ion concentration (%); and \(E\): the density of concrete (kg/m\(^3\)).

3. Result and discussion

3.1. Compressive strength
Compressive strength was measured in accordance with JIS A 1108 using cylindrical specimens with a diameter of 100 mm and height of 200 mm. As can be seen in Figure 2, the compressive strength was comparable among the mixtures tested at the age of 28 days. On the other hand, the compressive strength measured at the age of 91 days is higher than those measured at the age of 28 days in the cases of the FA specimens. This is because long-term strength enhancement by pozzolanic reaction was obtained.

![Figure 2. Compressive strength](image-url)
3.2. Bleeding test

The bleeding tests carried out in accordance with JIS A 1123-2012 were conducted twice for each specimen. Figure 3 shows the results of the bleeding test in which (1) and (2) were represented the results of two times carried out. From the figure, it can be seen that the amount of bleeding in the case of CUS60 mixtures is much larger than that measured in the OPC mixture. The amount of bleeding water in the case of the OPC and the CUS60 mixtures were 0.33 cm³/cm² and 1.0 cm³/cm² respectively. CUS with a higher density used for the CUS60 mixture resulted in larger amount of bleeding water as expected. On the other hand, the amount of bleeding water in the case of the FA mixtures was 0.55 cm³/cm² and 0.32 cm³/cm² for the FACUS60 and the FACUS30 respectively. Compared to the result in the case of the CUS60 mixture, it was confirmed that the amount of bleeding water was reduced in the FACUS60 and the FACUS30 mixtures, which is attributed to the FA replacement leading to more resistance against segregation. The results seemed to suggest that the excessive bleeding water may affect the integrity between horizontal steel bars and cover concrete when the mixture cast in column specimens from the height of 1.5 m.

![Figure 3. Amount of bleeding water up to 600 minutes](image-url)

![Figure 3. Half-cell potential vs. time for (a) OPC and (b) CUS60](image-url)
3.3. **Half-cell potential**

Figure 4 shows the half-cell potentials measured in the OPC, the CUS60 and the FA specimens up to 49 cycles. The potentials were varied in upper, middle and lower of the specimens. In the case of the OPC specimen, the values of half-cell potential after 2 cycles of dry and wet exposure were observed to be lower than -350 (mV vs. CSE). Also, the half-cell potential values measured in the specimens taken from the height of 1250 mm decreased significantly after 200 days of the monitoring and were lower than -700 (mV vs. CSE). For the case of the CUS specimens as shown in Figure 4(b), corrosion of steel bars was not observed in the specimen.
taken from the concrete in the height of 1250 mm. In addition, corrosion of steel bars was likely to occur in the upper parts (1250 mm) of the FACUS30 and upper parts (1250 mm) and middle parts (750 mm) of the FACUS60 because the half-cell potential were lower than -350 (mV vs. CSE). On the other hand, corrosion of steel bars was observed to be not severe in the lower (250 mm) in both of FACUS30 and FACUS60 because the half-cell potentials were close to -200 (mV vs. CSE).

3.4. Corrosion current density

The results of the microcell corrosion current density measured by the AC impedance method based on polarization resistance in each specimen are shown in Figure 5. In the cases of the OPC and the CUS60 mixtures, the corrosion current density was likely to increase from the early stages thus indicating severe corrosion in the specimen. The results were consistent with the results of half-cell potentials. It should be noted that the corrosion current density measured in the OPC specimens was varied in upper/lower sides of steel bars. Next, the middle (750 mm) and the lower (250 mm) specimens of the CUS60 mixture showed higher corrosion current density. In contrast, lower corrosion current density in the upper specimens was observed during the test. The result is different from the corrosion observed in the OPC specimens. Although the reason for this is not clear, it will be examined based on the rate of oxygen permeability in Section 3.5 and chloride ion concentration in Section 3.6.

On the other hand, the corrosion current density decreased for 336 days of the testing for the cases of the FA specimens, which was consistently observed both in FACUS30 and FACUS60 specimens. As shown in Fig. 5 (c) and (d), the microcell current density showed relatively higher values up to 2 cycles and was subsequently reduced after that. The results are consistent with the results of half-cell potential which showed more positive values during testing periods. From this fact, it assumed that FA specimens having smaller amount of bleeding owing to higher resistance against material segregation could densify the pore structure by the pozzolan reaction around steel bars and protected the steel bars from the ingress of chloride ions. The result seemed to suggest that smaller amount of ions and water consumed in the corrosion processes could reach the depth of steel bar and it will be discussed in Section 3.5 and 3.6.

3.5. Oxygen permeability (cathodic polarization)

The rate of oxygen permeability was measured at the age of 180 days. As can be seen in Figure 6, among the specimen tested, the rate of oxygen permeability was smaller for FA mixtures both for upper and lower parts of concrete. In addition, the results indicate that the rate of oxygen permeability in the FA mixtures was generally lower on the steel bars embedded. In contrast to the results, the rate of oxygen permeability of OPC and CUS60 in the lower part of those specimens was (2.5 to 5) × 10-11 mol/cm²/sec, which is relatively higher than those of FA mixtures. In the specimens taken from the height of 1250 mm in the CUS60 specimen showed 1.5 × 10-11 (mol/cm²/sec) or less. This was much lower than those observed in the OPC specimens. Therefore, compared to the OPC and the CUS60 mixtures, the rate of oxygen permeability of FA mixtures is very low (less than 1.0 × 10-11mol/cm²/sec). This could be attributed to the fact that FA mixture reduces the influence of material segregation due to bleeding, and pore refinement could take place due to pozzolanic reactions in the presence of moisture around the horizontal steel bars.

Figure 7 shows the relationship between the microcell corrosion current density and the rate of oxygen permeability bar. As can be seen, the corrosion current density was increased with the higher rate of oxygen permeability regardless of the mixtures. The rate of oxygen permeability which indicates the loss of integrity owing to segregation including bleeding water affected the microcell corrosion current density. Particular in the FA mixtures showed smaller microcell current density which could be caused by the lower rate of oxygen permeability. The formation of initial defects of the concrete around the steel bars is less affected by the bleeding water, thus the
penetration of chloride ions is reduced which subsequently discussed in Section 3.6. Besides that, the replacement of FA made it possible to reduce the rate of oxygen permeability by densifying the pore structure by the pozzolan reaction around steel bars.

![Figure 6. Rate of oxygen permeability](image)

![Figure 7. Microcell corrosion current density and the rate of oxygen permeability](image)

3.6. Oxygen permeability (Cathodic Polarization)

Figures 8 showed the content of chloride ion measured with depth for the specimens up to the depth of 70 mm from the exposed surface. The results showed that the content of chloride ions was generally larger for the OPC cases exceeding the threshold value 1.2 kg/m3 for all the specimens tested. The content of chloride ion was relatively larger with higher locations of the OPC specimen tested. In contrast to the result, the content of chloride ions in the CUS60 specimens taken from the height of 1250 mm showed the smallest amount of chloride ions. This highlights a distinction between the OPC and the CUS60 specimens in that the resistance against the ingress of chloride ions could be varied with the presence of CUS. Although it was not clear that the presence of CUS could enhance the resistance against diffusion of chloride ions, the effect of CUS replacement on the diffusion of chloride ions will be further investigated for future research. On the other hand, the content of chloride ions measured in the FA specimens is generally smaller especially in the deeper zones of the specimens. In addition, the content of chloride ions was slightly higher in the case of the specimens located in the height of 1250 mm; however, the content was comparatively comparable among the specimens taken from the three locations in the case of FACUS30 mixture. Based on the results obtained, it seems that the FA replacement is effective in facilitating more uniform quality formed in the column specimens especially in the case of FACUS30. On the other hand, the effect of bleeding on the corrosion processes is prominent even for the OPC specimens. This could be attributed to the modified
resistance against the ingress of corrosive substances including chloride ions, water and dissolved oxygen especially in the upper parts of the specimens.

![Graphs showing chloride ion concentration](image)

**Figure 8.** Chloride ion concentration (a): OPC; (b): CUS60; (c): FACUS60; & (d): FACUS30

4. Conclusions

This study aimed to investigate the effects of bleeding on the corrosion of horizontal steel bars placed in reinforced concrete column specimens cast with CUS and FA. This was examined through electro-chemical tests including the half-cell potential, polarization resistance, and corrosion current density carried out using specimens in which corrosion was induced via dry and wet (NaCl 10%) cycles. The results suggested that the corrosion of horizontal steel bars in the upper part of the column concrete specimen was adversely affected by bleeding water even for the OPC specimens with relatively lower bleeding rate. This was attributed to less resistance against the ingress of corrosive substances including chloride ions, water and dissolved oxygen especially in those locations. In the case of FA mixtures, more uniform pore structure in the column specimens could be formed, which led to higher corrosion resistance. This was subsequently improved through the pozzolanic reactions leading to lower rate of oxygen permeability.

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