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# Corrosion-induced cracking time in recycled aggregate concrete (RAC)

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## Abstract

The objective of this research was to determine the influence of using recycled concrete aggregates (RCA) on the time for corrosion-induced cracking. Three levels of replacement by recycled aggregates were adopted, i.e., 0%, 50% and 100% by volume. Corrosion of reinforcement was accelerated using DC current. The compressive and tensile strengths were also investigated. The results showed that the reinforcement mass losses of the RCA were 2.5% and 2.4% higher than those of the NAC for 50% and 100% replacement, respectively. The corrosion-induced cracking times of the RAC were 5.6% and 8.6% longer than those of the NAC for 50% and 100% replacement, respectively. Additionally, the Maaddawy's and Modified Maaddawy's models were found to be acceptable for predicting concrete cover cracking time.

**Keywords:** Recycled aggregate concrete, Cracking time, Corrosion current density, Reinforcement corrosion

## 1. Introduction

Coarse aggregates (CA) occupy the major share of concrete with respect to volume. Rapid development and necessity for large scale infrastructure have resulted in indiscriminate exploitation of natural rocks to meet the soaring demand for aggregates [1]. Recycled aggregate is used as coarse aggregate in concrete production to conserve the natural aggregate resources and to reduce waste from demolition [2-3]. Although recycled coarse aggregate (RCA) has been widely used as a wearing course worldwide, it has not been done in Thailand [4]. To use recycled aggregate in structural concrete, not only the mechanical properties, but durability should be considered as well. The RCA replacement percentage has significant influence on concrete durability, such as chloride penetration resistance, water absorption, permeability and abrasion resistance. The study of Xiao J et al. (2013) [5] reported that abrasion resistance decreased with an increasing RCA replacement percentage. It is well established that knowledge of the durability of concrete is an essential as it allows understanding the performance of concrete throughout the service life of reinforced concrete structures [6]. Corrosion of reinforcement is one of the most important aspects of durability. The formation of the corrosion reduces the cross-sectional area of reinforcing bars [7-8]. Various analytical models have been proposed to predict concrete cover cracking time due to corrosion in reinforced concrete structures (e.g., Bazant ZP (1979) [9], Liu T and Weyers RW (1998) [10], Pantazopoulou SJ and Papoulia KD (2001) [11], El Maaddawy T, Soudki K (2007) [12], Lu C et al. (2011) [13] and Reale T and O'Connor A (2012) [14]). Existing models were developed considering a thick-walled uniform cylinder under internal pressure and based on elasticity theory considering concrete as a homogeneous linear elastic material. Corrosion-induced concrete cracking has four significant factors: concrete cover depth, porous zone thickness, concrete quality (tensile strength and modulus of elasticity) and corrosion current density [8, 12-16].

For RCA, corrosion-induced concrete cracking is more complex than that of NAC. In comparison with NAC, RAC is more porous with old cement pasted on the aggregate surfaces. The microstructure of the interfacial transition zone (ITZ) in RAC is different from that in NAC [17]. Xiao et al. (2012) [18] proposed a recycled aggregate model as a five-phase composite material considering the old and new ITZs, new mortar, attached old mortar and original aggregate as continuous phases. Its properties are influencing factors that affect corrosion-induced concrete cracking. Ma Z et al. (2019) [19] stated that adding RCA increased the water permeability of concrete and this is an important indicator of concrete durability. The current research is aimed to determine the influence of the properties of recycled aggregate concrete on corrosion-induced cover cracking time. It also compares the experimental concrete cover cracking time with those predicted by three existing models, (Lu's model [13], Maaddawy's model [12] and Modified Maaddawy's model [14]). Several researchers have reported

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**Figure 1** Coarse aggregate.

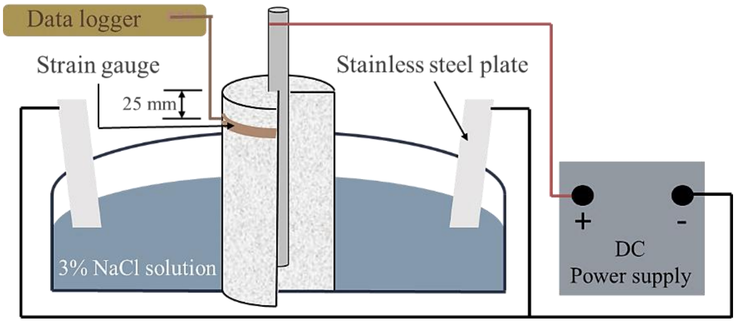


**Figure 2** Accelerated corrosion test set-up.

**Table 1** Concrete mix proportions.

| | Cement ($kg/m^3$) | NCA ($kg/m^3$) | RCA ($kg/m^3$) | FA ($kg/m^3$) | Water ($kg/m^3$) | Slump (mm) |
|---|---|---|---|---|---|---|
| R000[a] | 417 | 1025 | - | 706 | 200 | 105 |
| R050[b] | 417 | 461 | 416 | 706 | 200 | 100 |
| R100[c] | 417 | - | 819 | 706 | 200 | 90 |

[a] R000 = NAC
[b] R050 = 50% replacement of recycled aggregate
[c] R100 = 100% replacement of recycled aggregate

predictions of the time for concrete cover cracking that show that NAC is fully understood. However, the predictions of for concrete cover cracking using RAC should be carefully investigated. The result of this research should be used to plan maintenance suitably for extending service life of reinforced concrete structures, particularly when using RCA.

## 2. Materials and methods

### *2.1 Materials*

Ordinary Portland cement Type I (OPC) was used for all mixes. The natural coarse aggregate (NCA) was crushed limestone. It had a specific gravity of 2.75, unit weight of 1,567 $kg/m^3$ and water absorption of 0.84%. Recycled coarse aggregate (RCA) was crushed concrete pile cut off. It had a specific gravity of 2.20, unit weight of 1,252 $kg/m^3$ and water absorption of 5.28%. It had a maximum size of 19.0 mm. The aggregates were used in an air-dried state. Figure 1 shows photographic images of NCA and the RCA. The fine aggregate (FA) was river sand with a fineness modulus of 2.5, specific gravity of 2.57 and water absorption of 0.80%.

### *2.2 Methods*

#### *2.2.1 Specimens preparation*

Cylindrical concrete specimens with diameters of 75 mm and lengths of 150 mm were prepared with reinforcement installed in the middle. Two duplicate specimens were prepared for each test case. The reinforcement was a 16 mm diameter deformed bar with a yield strength of 400 MPa. For compressive strength and spitting tensile strength tests, cylindrical concrete specimens with diameter of 150 mm and with lengths of 300 mm were prepared and three duplicate specimens were tested. All cylindrical concrete specimens were moist-cured for 28 days before testing. The concrete mix proportions were as shown in Table 1.

#### *2.2.2 Accelerated corrosion test*

After 28 days of curing, a strain gauge was installed along the specimen's circumference at distance 25.0 mm from the top surface. The corrosion of the reinforcing bar was accelerated using an anodic DC current, with the reinforcing bar as an anode and a steel plate as a cathode, as depicted in Figure 2. The specimen was soaked in a 3% sodium chloride solution throughout the test. A corrosion current density ($i_{corr}$) of 55 $mA/cm^2$ were applied for 168 hours. The concrete surface strain was recorded using a data-logger. The time required for the concrete cover to crack was recorded at the time that the first visible crack was observed. At this point, the crack width was around 0.05 mm [13-15, 20-21].

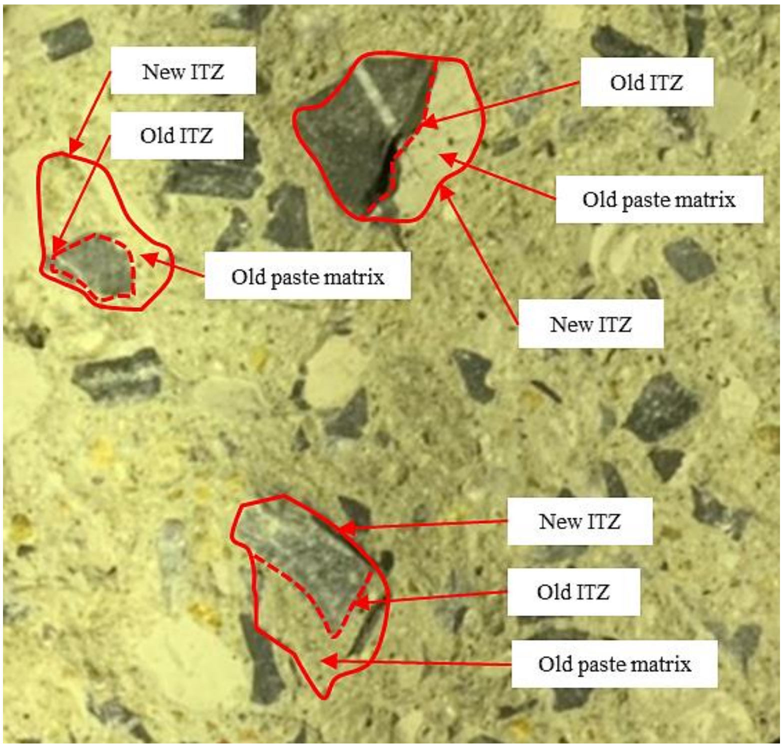


**Figure 3** The interfacial transition zone of the recycled aggregate concrete.

**Table 2** Properties for each specimen.

| | Compressive strength (MPa) | Splitting tensile strength (MPa) | Modulus of elasticity (GPa) |
|---|---|---|---|
| R000 | 30.4 | 3.73 | 31.877 |
| R050 | 34.5 | 3.53 | 27.231 |
| R100 | 34.6 | 3.43 | 25.262 |

*2.2.3 Determining mass loss of reinforcement*

After 168 hours of accelerated corrosion testing, the concrete specimens were broken. The corroded reinforcing bar was removed and immersed in a 12% (by volume) HCl solution for 30 minutes, and then in a 5% NaOH solution for 5 minutes before being cleaned using water [22]. The cross-sectional loss of the corroded reinforcement ($\eta_s$) was calculated using Equation 1.

$$\eta_s = (m_o - m_c)/ m_o \times 100\% \quad (1)$$

where $m_o$ is the mass of a bar before corrosion (g) and $m_c$ is the mass of the bar after corrosion (g).

**3. Results and discussion**

Property test results for concrete are presented in Table 2. The compressive strength of RAC was higher than that of the NAC for both of the replacement percentages. This was due to the condition of the coarse aggregate used in the mix. The slump values of concretes containing RCA in air-dried state were lower than those of concrete containing NCA in an air-dried state. The amounts of absorbed water were approximately 6, 16 and 42 kg/m$^3$ for R000, R050 and R100, respectively, according to moisture content of the aggregates. The RAC used in this study could still absorb water from the mix. Therefore, the water/cement ratio of the mix of RAC was lower than that of the NAC mix. Sri Ravindrarajah R and Tam CT (1985) [23] reported that the compressive strength of recycled-aggregate concrete was governed by the water/cement ratio of the new mortar. However, the splitting tensile strength of concrete was found to decrease with increased replacement of recycled aggregate. When the percentages replacement of RCA in the mixes were 50% and 100%, the reduction in the splitting tensile strength was found to be 5.4% and 8.0%, respectively. This could have been since the interfacial transition zone (ITZ) of the recycled aggregate concrete included multiple interfacial zones. With decreased bonding performance due to multiple ITZ zones, the splitting tensile strength of the RAC was lower than that of the NAC [1, 24-25]. Figure 3 shows multiple ITZ zones in the RAC. The modulus of elasticity of the RAC was 14.6% and 20.6% lower than that of the NAC for R050 and R100, respectively. Previous studies reported that the use of RCA in place of NCA decreased the modulus of elasticity of concrete [23, 26]. The study of Thomas et al. (2018) [1] also explained that the presence of inherent micro cracks in the ITZ was responsible for variations in the modulus of elasticity of concrete. The micro-cracks formed within the RCA during the crushing process and also at the interface between the aggregate and the old mortar led to a reduction of the stiffness of the composite system.

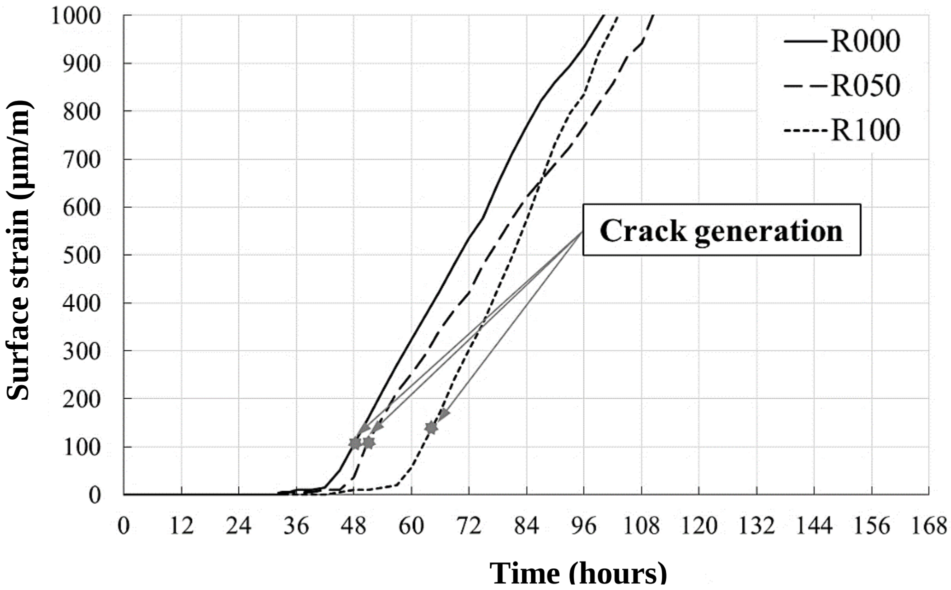


**Figure 4** The relationships between the concrete surface strain and corrosion acceleration time.

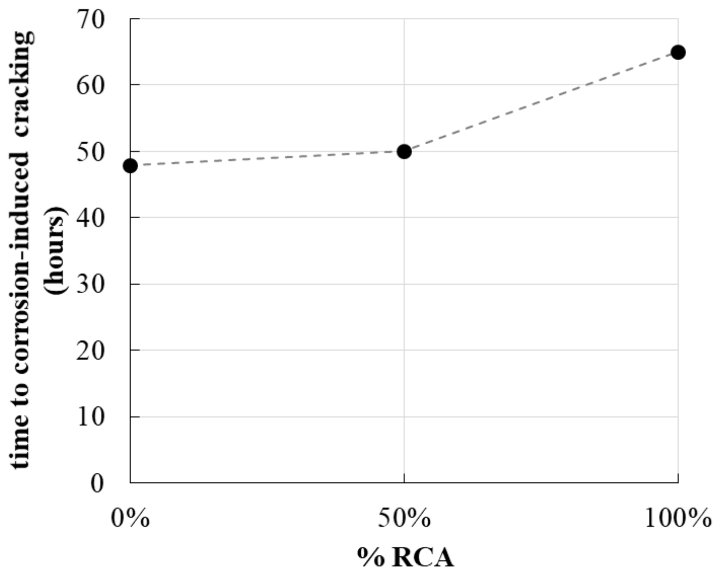


**Figure 5** The relationships between time for corrosion-induced cracking and percentage replacement of RCA.

*3.1 The time to corrosion-induced cracking*

The concrete surface strain was monitored using strain gauges. As shown in Figure 4**,** the surface strain of specimens increased with time. The times for corrosion-induced cracking of R000, R050 and R100 were 48, 50 and 65 hours, respectively.

The effect of percentage replacement of RCA on the time for corrosion-induced cracking is shown in Figure 5. This time increased with the percentage replacement of RCA. The corrosion-induced cracking time of the RAC was 5.6% and 8.6% longer than that of the NAC for 50% and 100% replacement, respectively. This could have been because the ITZ of the RAC included multiple interfacial zones and high porosity of the porous zone around the coarse aggregate. With more porous zones, the free expansion period was longer due to increased space to accommodate corrosion products. This agreed with the studies of Alonso C et al. (1998) [15], Zhao Y et al. (2014) [27], Zhao Y et al. (2015) [28] and Fernandez I et al. (2016) [29], who reported that the higher porosity of RAC could delay the formation of cracks on the surface of concrete cover.

Figure 6 shows the percentage of corroded reinforcement mass loss of RCA compared with that of the NAC. As shown, the percentage mass loss of RAC was higher than that of NAC. The percentage mass loss of the RAC was 2.5% and 2.4% higher than that of the NAC for 50% and 100% replacement, respectively. This could have been because the increase of replacement of RAC diminished the concrete quality. Also, the corrosion rate of reinforcement in the low quality concrete was more rapid than in high quality concrete. Therefore, a higher replacement increased the corroded reinforcement mass loss. This agreed with the study of Liang et al. (2019) [30] who indicated that the addition of RCA increased the steel corrosion of reinforced concrete.

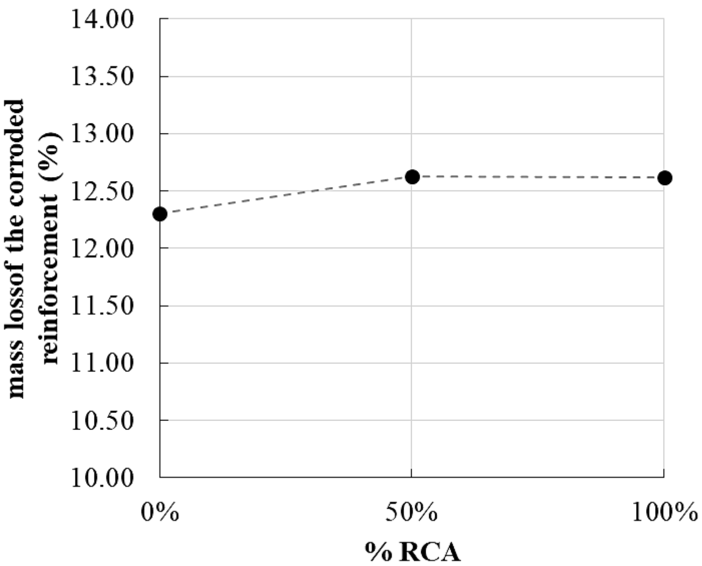


**Figure 6** The relationships between percentage mass loss of the corroded reinforcement and replacement percentage of RCA.

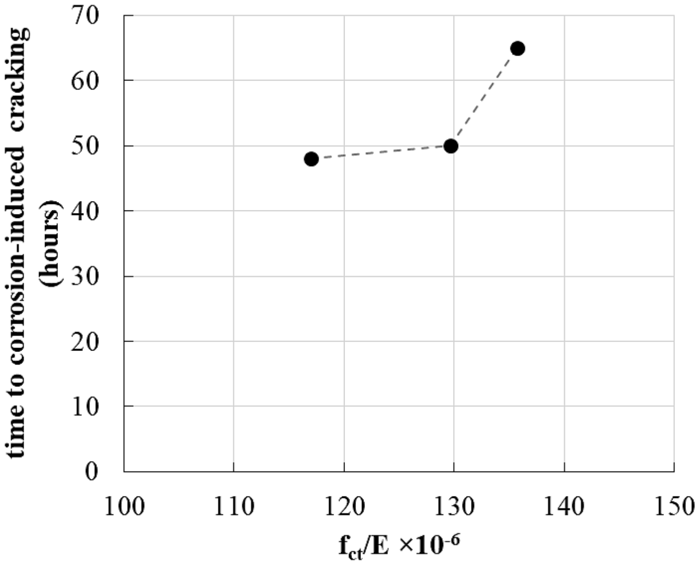


**Figure 7** The relationship between time for corrosion-induced cracking and $f_{ct}/E$ ratio.

Various studies reported that the penetration resistance of RAC, resulting from its pore structure, permitted more rapid ingress of harmful substances [31-33]. Therefore, a higher corrosion degree was needed to achieve the same external cracking for RAC [29]. Zhao Y et al. (2014) [27] suggested the rate of steel corrosion increased nonlinearly with the percentage of replacement with RCA. Therefore, caution was advised when the replacement percentage was large (more than 67%).

Figure 7 shows the relationship between time for corrosion-induced cracking and the $f_{ct}/E$ ratio. As shown, the tensile strength and the modulus of elasticity affected the time for corrosion-induced cracking. The $f_{ct}/E$ ratios were $117.0\times10^{-6}$, $129.6\times10^{-6}$ and $135.8\times10^{-6}$ for R000, R050 and R100, respectively. The time to corrosion-induced cracking increased with increase of the $f_{ct}/E$ ratio. This could have been due to increased tensile strength that resulted in a greater cracking strain limit for cover concrete. Therefore, this ultimately resulted in a delay of corrosion-induced cracking [34]. Lu C et al. (2011) [13] stated that the increase of the tensile strength of concrete would simultaneously increase its elastic modulus, so the ratio $f_{ct}/E$ should be taken into account.

*3.2 Comparison of experimental results with predictions using existing models*

Test parameters of the experiments used as input data in the existing models and observed times for corrosion-induced cracking are shown in Table 3. The existing models consider four important factors, i.e., concrete cover depth, porous zone thickness, concrete quality (tensile strength and modulus of elasticity) and corrosion current density ($i_{corr}$). The thickness of porous zone was about 7.5 μm [8].

The predicted times for corrosion-induced cracking comparing the Lu [13], Maaddawy [12] and Modified Maaddawy models [14], are shown in Figure 8. Accordingly, the existing models were developed to predict concrete cover cracking time in NAC.

**Table 3** Parameters of the experiments for the predicted times.

| Reference | Type of concrete | %RCA | d (mm) | C (mm) | $f_{cm}$ (MPa) | $f_{ct}$ (MPa) | E (GPa) | $i_{corr}$ ($\mu$A/cm$^2$) | Observed time (hours) |
|---|---|---|---|---|---|---|---|---|---|
| | R000 | 0 | 16 | 29.5 | 30.4 | 3.73 | 31.877 | 55,000 | 48 |
| | R050 | 50 | 16 | 29.5 | 34.5 | 3.53 | 27.231 | 55,000 | 50 |
| | R100 | 100 | 16 | 29.5 | 34.6 | 3.43 | 25.262 | 55,000 | 65 |
| Fernandez I et al. [29] | CC | 0 | 12 | 44.0 | 51.2 | 3.94[a] | 33.630[a] | 7,023[c] | 114 |
| | RCA-20 | 20 | 12 | 44.0 | 48.3 | 3.82[a] | 32.171[b] | 6,319[c] | 148 |
| | RCA-50 | 50 | 12 | 44.0 | 47.8 | 3.80[a] | 32.011[b] | 6,894[c] | 184 |
| | RCA-100 | 100 | 12 | 44.0 | 49.9 | 3.89[a] | 32.723[b] | 6,800[c] | 157 |

[a] Calculated value based on ACI318-11 [35] ($E = 4.70f_{cm}^{0.5}$, GPa).
[b] Calculated value based on Eq. (1) from [23] ($E = 4.63f_{cm}^{0.5}$, GPa).
[c] Estimated value using reported steel mass loss based on Faraday's law.

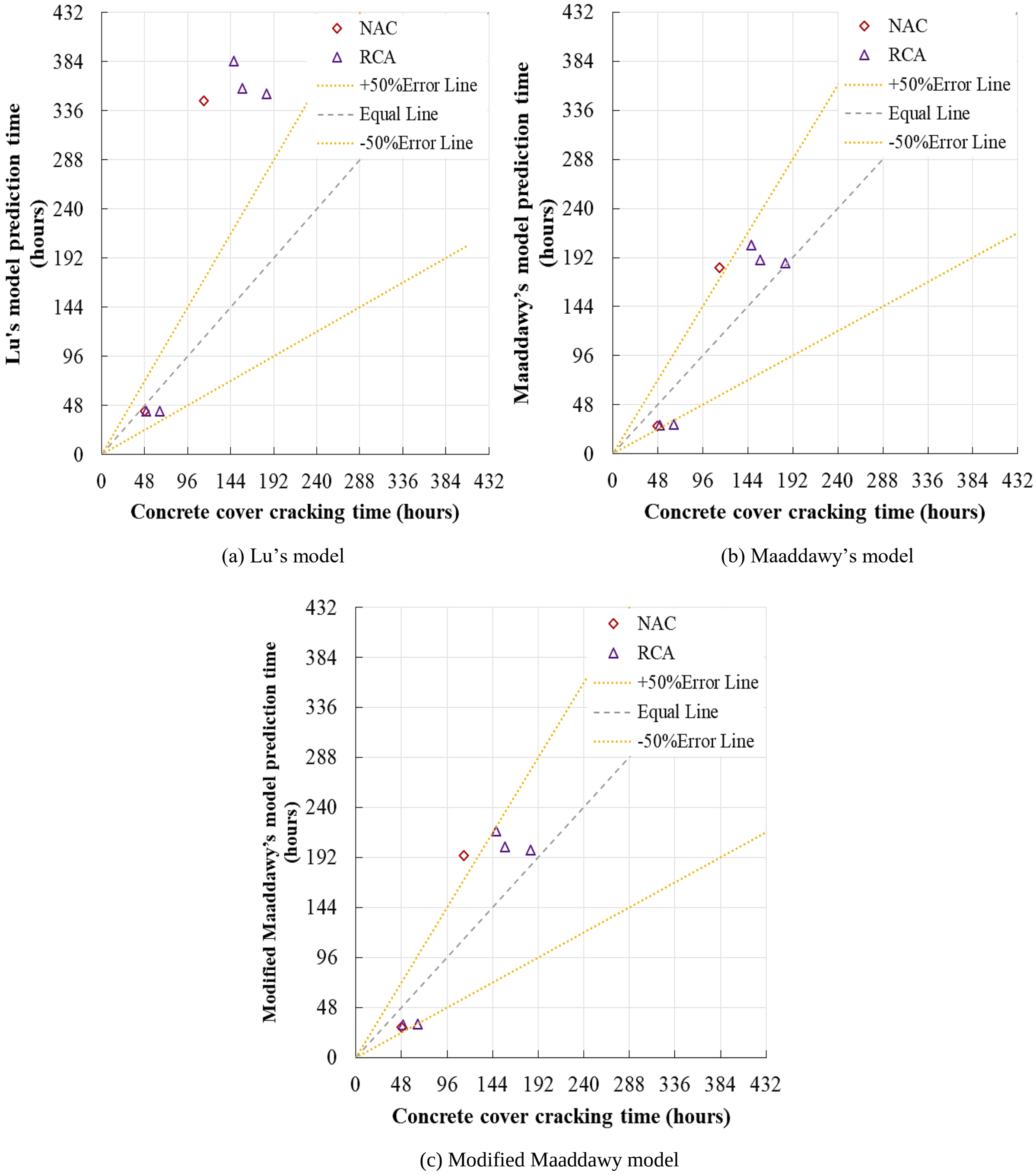


**Figure 8** Comparison between the predicted time by the existing models and observed times for concrete cover cracking.

For the predicted corrosion-induced cracking time of the NAC, the error varied from -12.5 to 203.5% for Lu's model, from -43.8 to 59.6 % for Maaddawy's model and from -39.6 to 70.1 % for the Modified Maaddawy's model. For the predicted corrosion-induced cracking time of the RCA, the error varied from -16.0 to 160.8 % for Lu's model, from -55.4 to 38.2 % for Maaddawy's model and from -38.0 to 47.0 % for the Modified Maaddawy's model. The predicted time of the RCA was not much different from that of the NCA. However, the observed time of the RCA was longer than that of the NCA. This was due to the higher porosity of RAC. It was reported that the corrosion current density was the most important factor affecting the time for concrete cover cracking [8, 36-37]. The corrosion current density is governed by environmental conditions, i.e., relative humidity, temperature, and concrete quality. Decreased concrete quality increased corrosion current density [10, 20, 38-39]. Higher corrosion current density induced more corrosion products around the reinforcement, resulting in higher radial pressure caused by corrosion [20, 40]. The study of Cui Z and Alipour A (2018) [41] reported that high corrosion current density could affect the accuracy of the predictive model and that the models predicted that initiation of cracking time decreased significantly with increased corrosion current density. In this study, the Maaddawy's model and Modified Maaddawy's model gave more acceptable predictions for RCA than Lu's model. This was probably since the influences of concrete quality had no effect in Lu's model [8, 37]. However, the quality of RAC in terms of its mechanical properties was apparently different from those of NAC.

## 4. Conclusions

The following conclusions are made from the experimental results presented in this paper.

(1) The reinforcement mass loss percentage of RAC for both replacement percentages (50% and 100%) were more than that of NAC. The percentage mass loss of the RAC was 2.5% and 2.4% higher than that of the NAC for 50% and 100% replacement, respectively.

(2) The corrosion-induced cracking time of the RAC was 5.6% and 8.6% longer than that of the NAC for 50% and 100% replacement, respectively. Tensile strength and the modulus of elasticity affected the initial corrosion-induced cracking time. Also, the corrosion-induced cracking time increased with the percentage replacement of RCA. This was due to the increased the tensile strength to modulus of elasticity ratio with an increasing percentage replacement of RCA.

(3) Maaddawy's model and the Modified Maaddawy's model were better than Lu's model for predicting the corrosion-induced cracking time. For the NAC, the error of prediction by the Maaddawy's model and Modified Maaddwy's model varied from -43.8 to 59.6% and from -39.6 to 70.1%, respectively. For the RCA, the error of prediction by the Maaddawy's model and Modified Maaddwy's model varied from -55.4 to 38.2% and from -38.0 to 47.0%, respectively.

## 5. Acknowledgements

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