

Chloride ingress and macro-cell corrosion of steel in concrete made with recycled brick aggregate

Tarek Uddin MOHAMMED^a, Mahfuzur RAHMAN^{b*}, Ahmed SABBIR^a, Mohammad Mehedi HASAN^a, Abdullah Al MAMUN^c

^a Department of Civil and Environmental Engineering, Islamic University of Technology, Board Bazar, Gazipur 1704, Bangladesh

^b Department of Civil Engineering, University of Information Technology and Sciences, Baridhara, Dhaka 1202, Bangladesh

^c Bangladesh Road Research Laboratory, Roads and Highways Department, Mirpur, Dhaka 1216, Bangladesh

*Corresponding author. E-mail: mahfuzurrahman@iut-dhaka.edu

© Higher Education Press 2021

ABSTRACT An investigation on chloride ingress and macro-cell corrosion of steel bars in concrete made with recycled brick aggregate (RBA) was carried out. As control cases, virgin brick aggregate (BA) and stone aggregate (SA) were also investigated. Both cylindrical and cracked prism specimens were studied for 16 different cases. The prism specimens were made with a segmented steel bar providing electrical connection from outside of the specimens to measure macro-cell corrosion current continuously under seawater splash exposure for a period of 30 d using a data logger. Cylindrical specimens were submerged in 3% NaCl solution at a temperature of 40°C to investigate chloride ingress in concrete made with RBA, BA, and SA after 120 and 180 d. Half-cell potential, corrosion area, and depths of corrosion were also investigated. The chloride ingress as well as corrosion of steel bars in concrete made with the different types of aggregate is ordered as RBA > BA > SA.

KEYWORDS brick aggregate, chloride ingress, macro-cell corrosion, recycled brick aggregate

1 Introduction

Due to lack availability of stone aggregate, many buildings in Bangladesh were constructed using brick aggregate. To investigate sustainability of construction materials, several studies have been conducted on recycling of demolished concrete made with brick aggregate. It was found that RBA can be used for making structural concrete of strength 21 to 31 MPa [1]. However, it is necessary to understand the performance of RBA against chloride ingress and corrosion of steel bar in concrete.

Chloride induced corrosion of reinforced concrete structures is found to be one of the main causes of deterioration of concrete structures subjected to marine exposure in Bangladesh and other countries [2]. In 2015 Bangladesh was ranked the 6th among the top 10 countries of the world with the highest risk of natural disaster, such as cyclones [3]. Several thousand cyclone

shelters were constructed for utilization as shelters for people and domestic animals near the Bay of Bengal in 2009 [4]. Unfortunately, many of the cyclone shelters deteriorated very shortly after construction due to the chloride induced corrosion of steel bars in concrete, resulting in a huge loss to national financial resources. Currently, more than 4000 cyclone shelters are planned for new construction [5]. Not only cyclone shelters, but also several mega projects, such as large power plant, deep seaport, tunnels, etc. are also under construction in the coastal area of Bangladesh. To safeguard the investment in this coastal region, it is necessary to construct reinforced concrete structures with high durability.

Concrete is a highly alkaline material with pH level more than 13 [6]. The alkaline environment of concrete creates a passivation film over the steel bars to protect steel bars from corrosion [7]. However, this protection film can be broken due to the ingress of chloride from seawater. It was found that if the chloride level surrounding the steel bars in concrete exceeds 0.4% of

cement mass or 1.2 kg/m^3 of concrete, the passivation film over the steel bars is ruptured and corrosion cells are formed in the presence of oxygen and water [8]. A large number of investigations have been conducted on corrosion of steel in concrete considering W/C [9], different types of cement [10], different exposure conditions (such as submerged, tidal, and splash environment) [11,12], temperature and humidity of environment [13], crack widths [14], interfacial transition zone around steel bars [15], orientation of steel bars in concrete [16], different surface condition of steel bars [7], autogenous healing of cracks [17], corrosion inhibitors of concrete [18], epoxy coated bars [19], cement paste coated bars [20], water reducing chemical admixtures [21], self-compacting concrete [22], variation of cover depth [23], mechanical properties of concrete [24], etc. Few investigations have been made considering the effects of recycled concrete as coarse aggregate in the corrosion process of reinforcements inside concrete. Investigations such as addition of fly ash, silica fume with recycled aggregate [25,26], nano silica suspension modification on recycled aggregate [27], etc. have been conducted to enhance the corrosion resistance property of recycled concrete aggregate.

Detailed investigations on corrosion of steel bars in concrete made with brick aggregate and recycled brick aggregate are rarely found in the literature. Also, for sustainability of construction materials in Bangladesh, several studies have been conducted on possible utilization of RBA in new construction works, considering mechanical properties [28], flexural behavior, [29] and shear behavior [30]. High durability of concrete made with RBA is also a general concern to engineers. With this background, a detailed study on chloride ingress and macro-cell corrosion of steel bars in concrete made with brick aggregate (BA), recycled brick aggregate (RBA), and stone aggregate (SA) was planned. To investigate chloride ingress in concrete, cylindrical specimens were made and submerged in 3% NaCl solution at 40°C for 180 d. Reinforced concrete prism specimens with segmented steel bar were made for investigation of macro-cell corrosion. Some specimens were also made with epoxy coated steel bars. These specimens were pre-cracked and exposed to a seawater splash environment for 30 d. Macro-cell corrosion current was measured at appropriate intervals. Physical evaluation of corrosion of steel bars, such as corroded area and pit depths were also investigated after the specimens were broken open.

2 Research significance

From the viewpoint of sustainability of construction materials, recycling of demolished concrete in new construction works is indispensable. Brick chips are commonly used in Bangladesh as coarse aggregate due to lack of availability of stone aggregate. Several research

works have been carried out to explore the possibility of recycling of concrete made with brick aggregate, investigating mechanical properties, flexural behavior, shear behavior, and drying shrinkage of concrete. The results of those investigations have revealed that the recycled brick aggregate concrete can be utilized for making structural grade concrete. However, durability performance of such concrete in different exposure zones, such as normal atmospheric environment, seawater exposure environment, etc., is still unknown. Therefore, further research was necessary to verify the performance of recycled brick aggregate concrete against carbonation, chloride ingress, and corrosion of steel in concrete. This study therefore aimed to verify the performance of recycled brick aggregate concrete against chloride ingress and macro-cell corrosion in cracked concrete in marine exposure. The results of this study will be useful in understanding durability performance of recycled brick aggregate concrete against chloride ingress and macro-cell corrosion of steel bars in cracked concrete in marine exposure conditions.

3 Experimental investigations

3.1 Material properties

The types of coarse aggregate that were used for this investigation were fresh brick aggregate (BA), recycled brick aggregate (RBA) and stone aggregate (SA). For making RBA, demolished concrete blocks were collected from a 15-year old demolished building located at Tongi, Dhaka. Later the blocks were crushed manually to produce RBA. In RBA, a part of the old mortar was adhered to previously used brick aggregate. Compared to the virgin aggregate, the RBA was angular in shape with relatively blunt edges due to the presence of this adhered mortar. As fine aggregate, natural river sand was used for this investigation. Concrete samples were also made with recycled brick fine aggregate (RBFA). The fineness modulus (FM) of natural river sand and RBFA were 2.7 and 3.15, respectively. The fineness modulus of coarse aggregates was 6.6 in all cases. As binding material CEM Type –1 cement as per BDS EN-197 (95% clinker plus 5% other minor constituents) was used. Coarse aggregates size distribution was maintained as per ASTM C33. Aggregates were used in SSD condition having angular shape and rough texture. The properties of coarse (SA, BA, and RBA) and fine aggregates (natural sand (NS) and RBFA) are summarized in Tables 1 and 2 accordingly. 10 mm diameter Grade 500W (produced as per ASTM A706, minimum yield strength = 500 MPa) steel bars were used for the investigation. The chemical compositions of steel bars are summarized in Table 3. Some specimens were also made with fusion bonded epoxy coated steel bars (epoxy thickness = 175–300 μm ; epoxy coating material consists of inert organic polymer coating with resin, hardener, fillers, and color pigments)

Table 1 Properties of coarse aggregates

item	coarse aggregate			specification / guideline followed
	SA	BA	RBA	
specific gravity	2.65	2.20	2.14	ASTM C127
absorption capacity (%)	2.9	21.1	12.4	ASTM C127
abrasion value (%)	25.0	47.0	43.0	ASTM C131
unit weight (kN/m ³)	15.2	13.0	12.0	ASTM C29

Table 2 Properties of fine aggregates

item	fine aggregate		specification / guideline followed
	NS	RBFA	
specific gravity	2.60	2.10	ASTM C128
absorption capacity (%)	3.9	10.7	ASTM C128
fineness modulus	2.70	3.15	ASTM C136
unit weight (kN/m ³)	15.4	13.9	ASTM C29

Table 3 Chemical composition of steel bars other than Fe

component	C	Mn	Si	S	P
percentage (%)	0.21	0.67	0.17	0.028	0.035

to determine their effectiveness against corrosion. Potable tap water was used as mixing water of the concrete.

3.2 Details of specimens, cases investigated, and exposure conditions

Sixteen different cases were investigated in total. For each case, four 100 mm × 200 mm sized cylindrical specimens and two 100 mm × 100 mm × 400 mm sized prism specimens were made. In total, 64 cylindrical specimens and 32 prism specimens were made. Mixture proportions of concrete for the investigated cases are summarized in Table 4. *W/C* ratios were 0.45 and 0.55. Sand to aggregate absolute volume ratio was 0.44. Cement contents were 340 and 400 kg/m³. Maximum size of coarse aggregate was maintained at 20 mm. The layout of the prism specimens is shown on Fig. 1. In each prism specimen, two steel bars were placed, one as continuous steel bar to avoid collapse of the beams during cracking and one as segmented steel bar to measure macro-cell corrosion current among the steel elements at cracked and un-cracked regions. The length of the continuous steel bar was 340 mm. The segmented steel bars were made by connecting three different segments with epoxy. The length of the end segments was 135 mm and the length of the middle segment was 50 mm. All the segmented steel bars were pre-jointed with electric cables before casting of concrete. This allowed a 100 Ω resistor to be used at each gap between segments, and in series with the segments, to measure voltage drop. The voltage drops were recorded at predetermined intervals by using a data logger. The depth of the cover concrete was 20 mm. After 24 h of curing in the molds, the specimens were de-

molded and cured under wet jute bags for 28 d. To fix the location of crack at the middle of prism specimen, a notch (3 mm wide and 5 mm depth) was made at the center of the bottom face of the specimens. The specimens were cracked by applying load at mid-span using a Universal Testing Machine (UTM). Then the specimens were anchored in pairs by back-to-back support with a roller at the middle as shown in the Fig. 1. The crack width was controlled at 0.6 mm for all specimens. Relatively larger crack width was made to avoid healing of cracks due to seawater splashing as observed by other researchers [14]. After anchoring, the specimens were kept in a seawater spray chamber where natural seawater was sprayed on the specimens once a day for five minutes. The chemical compositions of seawater collected from Bay of Bengal are summarized in Table 5. The cylindrical specimens were submerged in 3% NaCl solution at a temperature of 40°C.

3.3 Method of evaluations

3.3.1 Compressive strength

Cylindrical specimens (diameter 100 mm and height 200 mm) were made to measure compressive strength after 28 d. The compressive strength of the concrete cylinder specimens was measured as per ASTM C39 [31].

3.3.2 Chloride ingress in concrete

Chloride content is one of the most vital influencing factors for generating macro-cell corrosion [12]. After 28 d of curing under wet jute cloths, some cylindrical specimens were submerged in 3% NaCl solution at a temperature of 40°C for 180 d for measuring chloride profiles in concrete at different ages of exposure in warm salt water. For water-soluble chloride measurements in concrete, a disc of height 100 mm was cut from the middle of each specimen. The discs were cut again to collect concrete samples from the different depths of specimens, such as 0–10, 10–20, 20–30, 30–40, and 40–50 mm from the surface to the center region of the specimens. Chloride profiles were measured after 120 and 180 d of exposure in salt water. The concrete samples were crushed into powder (passing through #50 sieve) for the measurement of water-soluble chloride content in concrete. Then the water-soluble chloride concentration in the powder samples was determined as per JCI SC4.

Chloride concentration around steel bars at cracked and un-cracked regions were measured after electrochemical investigation. For this, concrete samples were collected around the steel bars both for cracked region and un-cracked regions. Then chloride concentrations were measured as per JCI SC4.

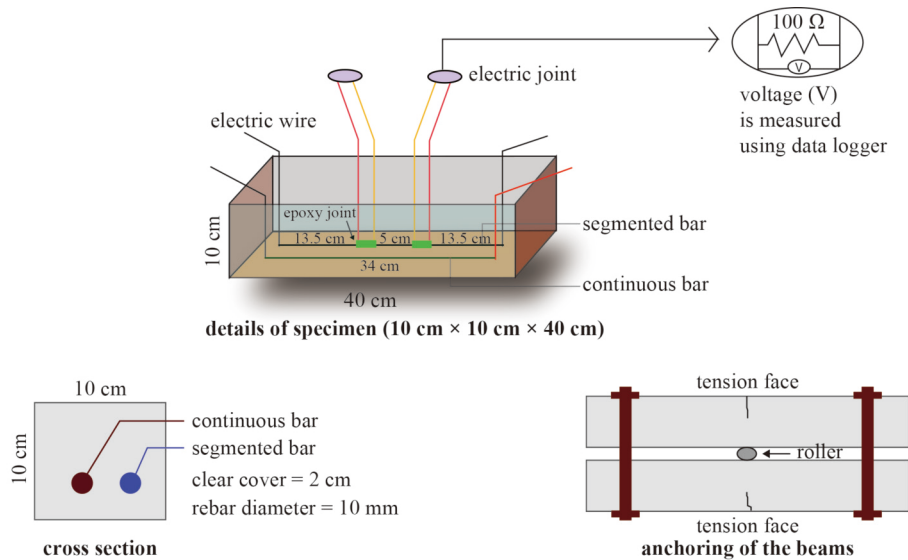
3.3.3 Macro-cell corrosion

Measurement of macro-cell corrosion current flow is an

Table 4 Cases investigated and mixture proportions

case	designation	W/C	cement (kg/m ³)	water (kg/m ³)	fine aggregate (kg/m ³)	coarse aggregate (kg/m ³)
C1	RBA-NS-0.45-340	0.45	340	153	780	836
C2	RBA-NS-0.45-400	0.45	400	180	729	782
C3	RBA-NS-0.55-340	0.55	340	187	743	797
C4	RBA-NS-0.55-400	0.55	400	220	686	736
C5	SA-NS-0.45-340	0.45	340	153	780	1141
C6	SA-NS-0.45-400	0.45	400	180	729	1067
C7	SA-NS-0.55-340	0.55	340	187	743	1087
C8	SA-NS-0.55-400	0.55	400	220	686	1003
C9	BA-NS-0.45-340	0.45	340	153	780	872
C10	BA-NS-0.45-400	0.45	400	180	729	816
C11	BA-NS-0.55-340	0.55	340	187	743	831
C12	BA-NS-0.55-400	0.55	400	220	686	767
C13	RBA-RBFA-0.45-340	0.45	340	153	594	836
C14	RBA-RBFA-0.45-400	0.45	400	180	556	782
C15	RBA-RBFA-0.55-340-E	0.55	340	187	566	797
C16	SA-NS-0.55-400-E	0.55	400	220	686	1003

Note: RBA, SA, BA, and NS represent recycled brick aggregate, stone aggregate, brick aggregate, and natural river sand, respectively. 'E' represents fusion bonded epoxy coated bar. RBFA represents recycled brick fine aggregate.

**Fig. 1** Layout of the specimens.**Table 5** Physical properties and chemical composition of seawater

component	pH	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	SO ₄ (ppm)	CO ₃ (ppm)
seawater	7.9	10752	390	416	1295	19345	2701	145

electrochemical technique for investigating the mechanisms of chloride-induced corrosion of steel in concrete [12]. To measure macro-cell corrosion, a data logger was used. External to the samples but in series with the steel segments a 100 Ω resistance was placed to measure voltage drop due to the current between anode (cracked segment) and cathode (un-cracked segment). As

a crack was made at the middle of the specimens, this middle segment of steel will act as anode and the other two segments (end segments located at the regions of un-cracked concrete) will act as cathodes. The voltage drops were recorded for 30 d using a data logger at pre-fixed intervals of time as summarized in Table 6. A photograph showing the setup of data logger is presented in Fig. 2.

The following equation was used to calculate the current flow from the measured voltage drop through a fixed resistance of 100 Ω :

$$I = \frac{V}{R}, \quad (1)$$

where R is resistance (100 Ω), and V is the voltage drop (in Volt) and I is current (in Ampere).

The following equation was used to calculate macro-cell corrosion current density:

$$I_{\text{mac}} = \frac{I}{A} \times 10^6, \quad (2)$$

where A is the surface area of the steel segment in cm^2 , I is the current, and I_{mac} is the macro-cell corrosion current density in $\mu\text{A}/\text{cm}^2$. It is worth noting that to calibrate the voltage measurement system, known currents of 1, 2 and 3 μA were passed through 100 Ω resistance and the measured voltage drops against these currents were 99, 198 and 298 mV, respectively. The results indicate that the experimental setup can measure current flow between the steel bars accurately.

The depth of corrosion over the steel bars was calculated by using the following equation [32]:

$$D = 0.0116 \times I_{\text{mac}} \times t, \quad (3)$$

where D is the depth of corrosion in mm, I_{mac} is the macro-cell corrosion current density in $\mu\text{A}/\text{cm}^2$, and t is time in years.

3.3.4 Half-cell potential

Half-cell potential was measured by a Cu/CuSO₄ half-cell. The half-cell potentials over the segmented steel bars were measured after completing continuous measurement of macro-cell corrosion current for 30 d. It was done to

avoid interference in the flow of macro-cell corrosion current. During measurement of potential of a particular segment of steel, the segment was isolated electrically from others. Corrosion probability for different half-cell potential (Cu/CuSO₄) values were determined as per ASTM C876 as explained in Table 7.

3.3.5 Visual observation, corroded area and pit depths

After completing macro-cell corrosion current measurement, the prism specimens were broken open and steel bars located at both cracked and un-cracked regions of the specimens were taken out for visual observation and measurement of corrosion area, and the depth of corrosion pits. To measure corroded area over steel bars, the corroded area on the steel bars was traced on a transparent paper. The depths of corrosion were measured by inserting nails into the pits.

4 Experimental results and discussions

4.1 Compressive strength

The results of 28-d compressive strengths are shown in Figs. 3(a), 3(b), and 3(c), where standard deviations are plotted as error bars. For the same mix design parameters, it is found that RBA shows the lowest compressive strength compared to virgin brick (BA) and stone aggregate (SA). It can be observed from Figs. 3(a) and 3(b) that with the increase of cement content and decrease of W/C , compressive strength is increased irrespective of type of coarse aggregate. By increasing the cement content to 400 kg/m^3 and reducing W/C to 0.45; it is possible to increase strength of recycled brick aggregate concrete to 32 MPa. RBFA has higher absorption capacity compared to natural sand. RBFA is softer than natural sand. It results in reduction of strength of concrete made with RBFA by about 16% compared to the cases made with natural sand, as can be observed in Fig. 3(c). Considering the viewpoint of sustainability of construction materials, the provision for possible utilization of recycled aggregate has been included in ACI 318-19 with the condition of satisfaction of strength requirement [33]. As the minimum strength requirement for structural grade concrete is specified at 17 MPa in ACI 318-19 [33], it is clear from the results that RBA can be utilized for making structural grade concrete.

Table 6 Time schedule of voltage drop measurement by data logger

total period	interval of measurement
30 d	Measure immediately before spray, after spray first 5 min at every 1 s interval, next 30 min at every 5 min, next 1 h at every 10 min, next 4 h at every 30 min and then at every 1 h or immediately before spray.

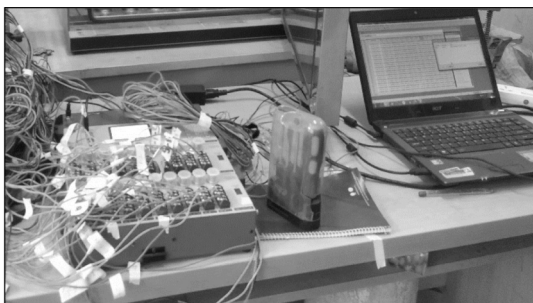


Fig. 2 Voltage measurement using data logger.

Table 7 Cu/CuSO₄ half-cell potential and probability of corrosion (ASTM C876)

half-cell potential reading (mV)	corrosion probability (%)
greater than -200 mV	90% probability of no corrosion
between -200 mV to -350 mV	intermediate corrosion risk (uncertain)
less than -350 mV	90% probability of corrosion

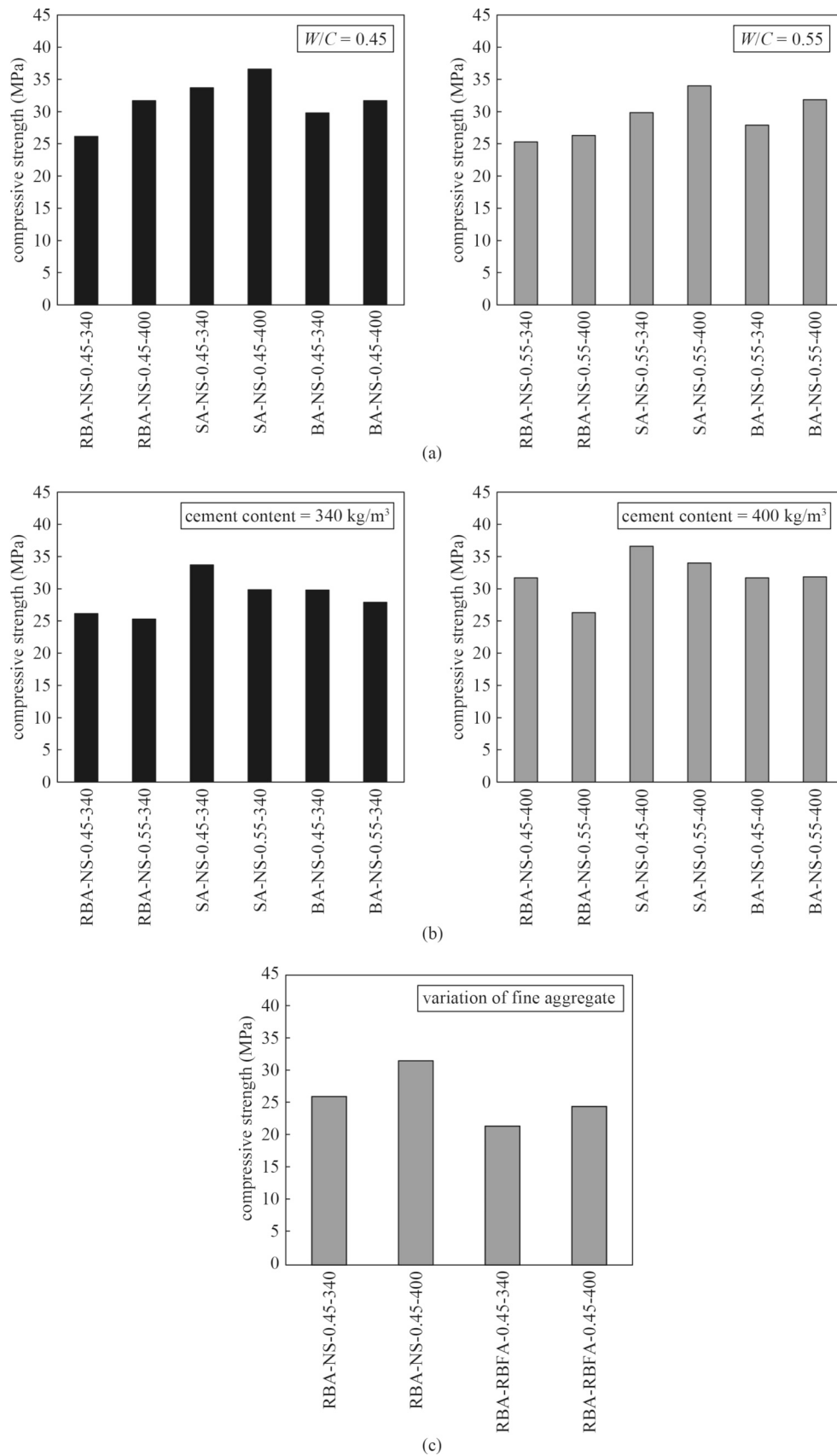


Fig. 3 (a) Compressive strength: variation of cement content; (b) compressive strength: variation of W/C ; (c) compressive strength: variation of fine aggregate.

4.2 Chloride profiles

Chloride profiles in concrete cylinders after 120 d of saltwater exposure at 40°C are shown in Figs. 4 and 5, respectively. As expected, it is clear from Figs. 4 and 5 that chloride concentration level increases with increase of exposure period in salt water. More chloride is generally found at the outer surface of the specimens and the level of chloride decreases with increase of depth from the surface. Due to the short exposure period in seawater at a larger depth from surface (15–50 mm), the chloride concentration is relatively low and varies slightly at the larger depth irrespective of the cases. It is expected that more variation in chloride level at a larger depth can be found after further exposure. In the inner region of the specimens, more chloride is found for RBA irrespective of the exposure periods. By comparing the chloride profiles, the chloride ingress into concrete with respect to the types of aggregate is ordered as $RBA > BA > SA$. The absorption capacities of RBA, BA, and SA were 12.4%, 21.1%, and 2.9%, respectively. The absorption capacity of BA is higher than that of RBA because of the greater connectivity of the capillary pore channels in BA. However, it does not lead to more chloride ingress in concrete made with BA compared to that in RBA. The old interfaces, impermeable voids, and micro-crack in RBA may create easier paths for chloride to move faster

into the concrete made with RBA than into BA. Similar trend of results have also been reported in other studies [20]. For a higher amount of cement content, more resistance against chloride ingress is found. Higher amount of chloride ingress is also found for the cases made with high W/C . It is understood that if RBA or BA is used in new construction works, it is necessary to increase cement content and keep W/C at a lower level. A previous study was carried out with application of cement paste coating and polymer coating on recycled brick aggregate and it was found that both absorption capacity as well as wear value of aggregate were reduced with application of coating [34]. Therefore, there is a possibility for reduction of chloride ingress in concrete made with BA and RBA if coating over the aggregate is applied. Extended study on this topic is still necessary.

Chloride concentrations around the steel bars in concrete at the cracked and un-cracked regions of the prism specimens are shown in Fig. 6. Higher amount of chloride are found over the steel bar at the cracked region compared to the steel bar at the un-cracked region. For the un-cracked regions chloride concentrations were less than the threshold limit of chloride against corrosion of steel in concrete (0.4% mass of cement mass) [35]. On the other hand, at the cracked region, the chloride level around the steel bars exceeds that chloride threshold

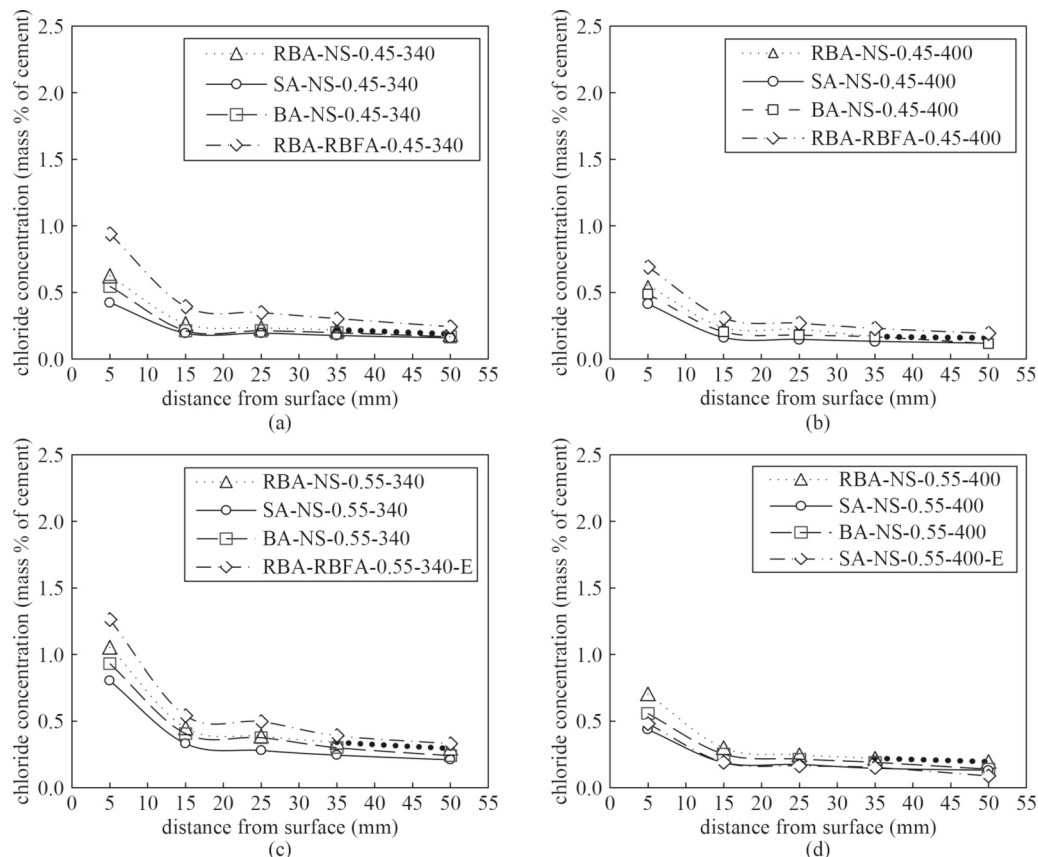


Fig. 4 Chloride profiles after 120 d of exposure in salt water. (a) For cement content 340 kg/m³, $W/C = 0.45$; (b) for cement content 400 kg/m³, $W/C = 0.45$; (c) for cement content 340 kg/m³, $W/C = 0.55$; (d) for cement content 400 kg/m³, $W/C = 0.55$.

limit. Due to the difference in chloride levels, it is understood that macro-cell corrosion cell over the steel bar is formed with anode at the cracked region and cathode at the un-cracked region. More chloride is found around the steel bars for the cases made with RBA and BA compared to SA. Therefore, macro-cell corrosion activities over the steel bars for concrete made with RBA

and BA are higher than the concrete made with SA.

4.3 Macro-cell corrosion

The variations of macro-cell corrosion current density over the steel bars at the cracked region with time for the 16 cases of cracked prism specimens made with

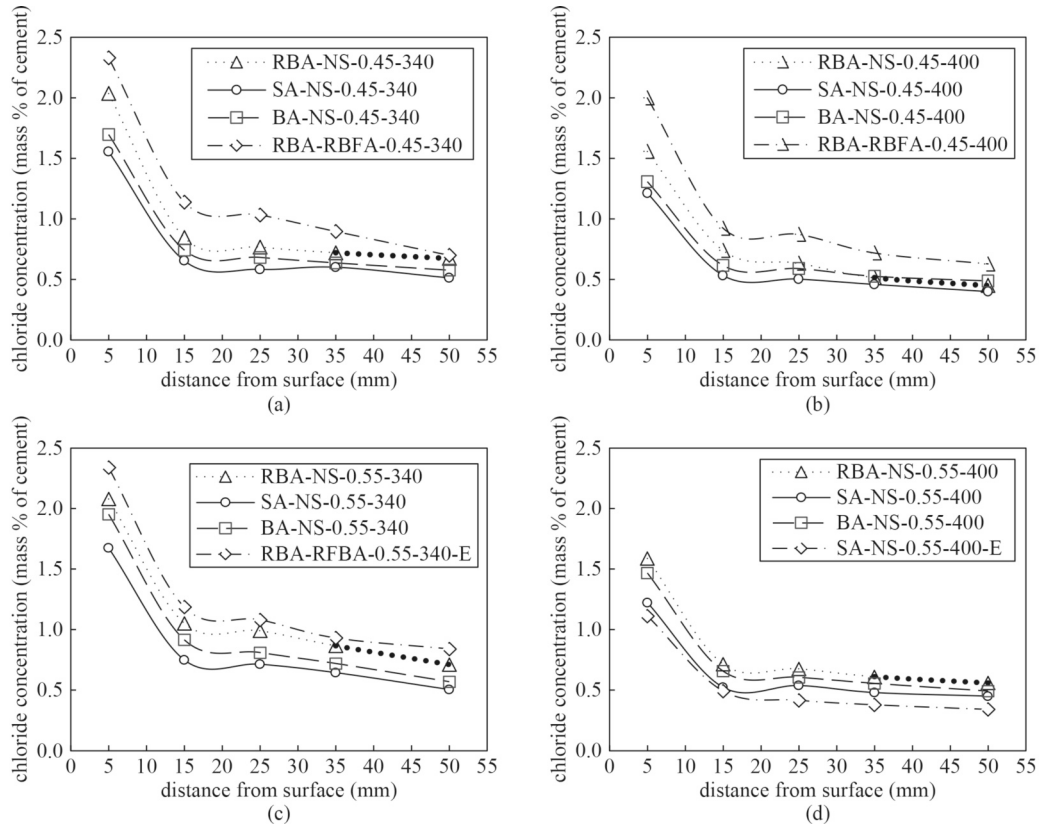


Fig. 5 Chloride profiles after 180 d of exposure in salt water. (a) For cement content 340 kg/m³, W/C = 0.45; (b) for cement content 400 kg/m³, W/C = 0.45; (c) for cement content 340 kg/m³, W/C = 0.55; (d) for cement content 400 kg/m³, W/C = 0.55.

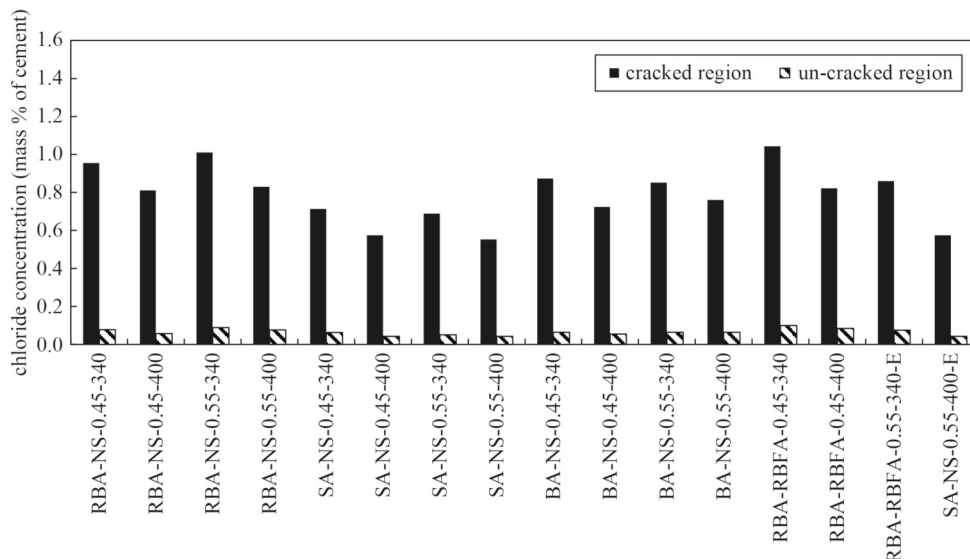


Fig. 6 Chloride concentrations around steel bars at cracked and un-cracked regions.

segmented steel bars are shown in Figs. 7(a)–7(c) for the cases made with RBA, SA, and BA, respectively. The results related to RBFA and fusion bonded epoxy coated steel bars are listed in Fig. 7(d). At the beginning of seawater splash exposure, it is seen that due to the splash

of seawater over the specimens, the rate of macro-cell corrosion is increased but reduced over time until the next instance of seawater spray. However, the overall macro-cell corrosion current density is reduced with time. The reduction of macro-cell corrosion current density over

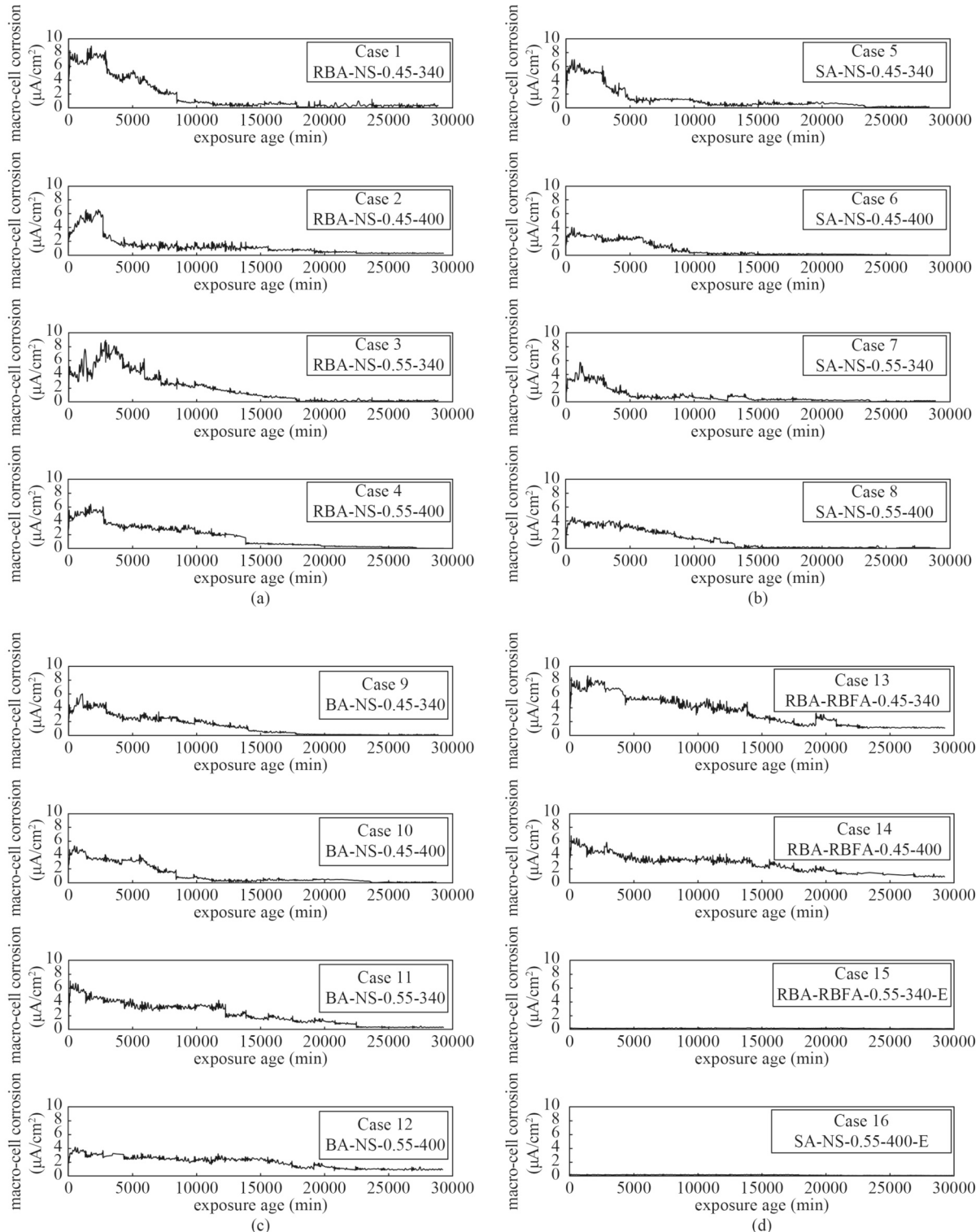


Fig. 7 (a) Macro-cell corrosion current density for RBA as coarse aggregate; (b) macro-cell corrosion current density for SA as coarse aggregate; (c) macro-cell corrosion current density for BA as coarse aggregate; (d) macro-cell corrosion current density for RBA as coarse aggregate, RBFA as fine aggregate and for epoxy coated bars.

steel bars at the cracked regions of concrete is explained in a previous investigation on macro-cell corrosion [36]. In this investigation, deposits of ettringite, CaCO_3 , and $\text{Mg}(\text{OH})_2$ were found at the cracked openings as well as over the de-bonded steel at the cracked regions. It was also found that the rusted areas on the steel bars at the cracked regions were covered by these deposits due to the splashing of seawater [36]. The reduction values of macro-cell corrosion of this study are well matched with a previous investigation. A higher level of macro-cell corrosion current density is observed for concrete made with RBA compared to that for BA and SA. The amount of macro-cell corrosion current density above the steel bars with respect to the types of aggregate can be ordered as $\text{RBA} > \text{BA} > \text{SA}$. The porous nature of RBA and BA are responsible for higher level of macro-cell corrosion current density of the embedded steel bars. It is also understood that for utilization of RBA and BA for construction works, it is necessary to enhance the microstructure of the mortar portion of concrete by reducing W/C and increasing cement content, which will eventually reduce the permeability of the concrete. Alternatively, suitable coatings over the RBA and BA can be applied to reduce water absorption as well as blocking of the pathways of chloride movement through the aggregate. A very low macro-cell corrosion current density is found for fusion bonded epoxy coated steel bars compared to the bared steel irrespective of types of RBA and SA. Similar effectiveness of epoxy coated bar has been previously reported in several studies [37–39]. It is also understood that RBA and BA can be utilized in concrete if epoxy coated steel bars are used.

For further comparison of corrosion at the cracked region of the specimens, the areas under the macro-cell corrosion current graphs of Fig. 7 are calculated. The data can be used to compare macro-cell corrosion activity of steel bars in concrete made with different aggregates. The results are summarized in Table 8. The depths of corrosion over steel bars are also calculated using Eq. (3) and posted in Table 9. It can be noted that the actual depth of corrosion can be four to eight times higher than the depth of corrosion over the steel bars calculated from the corrosion current data [32]. The rankings based on the corrosion activity of the steel bars (more corrosion to least corrosion) are evaluated and the results are summarized in Table 8. More corrosion activity is found over the steel bars in concrete made with RBA (both as coarse aggregate and fine aggregate). The porous nature of BA and RBA causes enhancement of corrosion activity over the steel bars in concrete. The results matches well with the data related to chloride ingress in concrete as discussed earlier. W/C is also found to be an influencing factor related to corrosion of steel in concrete. The samples made with higher W/C and lower cement content show higher level of corrosion due to the porous microstructure of concrete. Similar results have also been reported in other studies [40]. Utilization of epoxy coated bars is found to be an effective way to reduce macro-cell corrosion of steel bars in concrete irrespective of the types of aggregate investigated.

The total corrosion rate is the summation of macro-cell and micro-cell corrosion of the steel bar in concrete. This study focuses on macro-cell corrosion of concrete made with RBA. However, based on other studies, it is found

Table 8 -Area under corrosion-time curve, depth of corrosion, and ranking of the cases

case	case identification	area under corrosion-time graphs ($\frac{\mu\text{A}}{\text{cm}^2} \cdot \text{year}$)	depth of corrosion (mm)	ranking*
C13	RBA-RBFA-0.45-340	0.184	0.00214	1
C14	RBA-RBFA-0.45-400	0.143	0.00166	2
C11	BA-NS-0.55-340	0.133	0.00155	3
C12	BA-NS-0.55-400	0.120	0.00140	4
C3	RBA-NS-0.55-340	0.105	0.00123	5
C1	RBA-NS-0.45-340	0.095	0.00111	6
C4	RBA-NS-0.55-400	0.093	0.00108	7
C9	BA-NS-0.45-340	0.074	0.00087	8
C2	RBA-NS-0.45-400	0.071	0.00083	9
C5	SA-NS-0.45-340	0.068	0.00079	10
C8	SA-NS-0.55-400	0.066	0.00077	11
C10	BA-NS-0.45-400	0.062	0.00073	12
C6	SA-NS-0.45-400	0.046	0.00054	13
C7	SA-NS-0.55-340	0.044	0.00051	14
C15	RBA-RBFA-0.55-340-E	0.008	0.00010	15
C16	SA-NS-0.55-400-E	0.007	0.00008	16

*Note: descending order of corrosion activity.

Table 9 corroded area and pit depth at cracked and un-cracked region

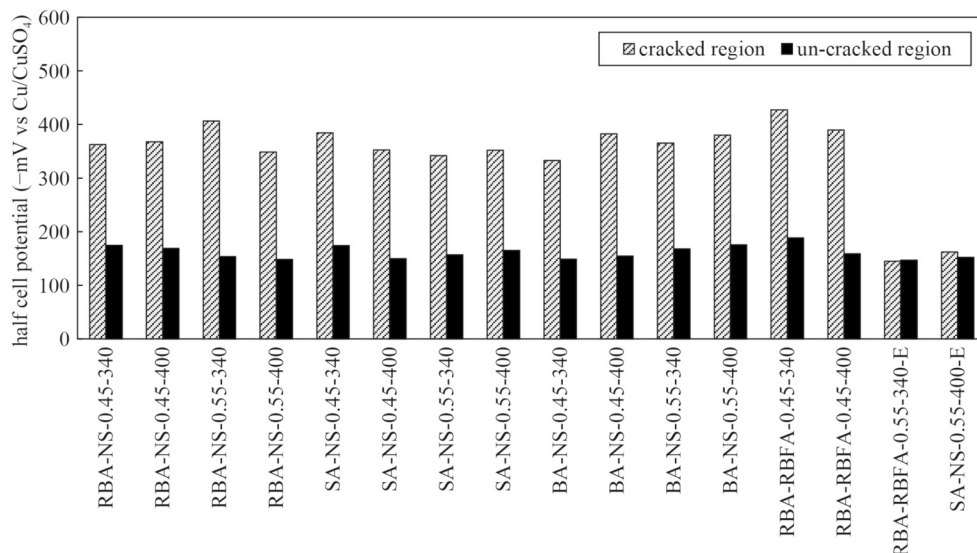
case	short description	cracked region			un-cracked region		
		corroded area (cm ²)	corroded area (%)	max. pit depth (mm)	corroded area (cm ²)	corroded area (%)	max. pit depth (mm)
1	RBA-NS-0.45-340	9.4	54.4	2.0	0.95	2.3	0.5
2	RBA-NS-0.45-400	8.7	50.3	1.5	1.12	2.7	0.5
3	RBA-NS-0.55-340	9.8	56.7	2.0	0.65	1.6	–
4	RBA-NS-0.55-400	9.25	53.5	2.0	0.8	2.0	–
5	SA-NS-0.45-340	6.5	37.6	1.0	0.0	0.0	–
6	SA-NS-0.45-400	5.4	31.3	–	0.15	0.4	1.0
7	SA-NS-0.55-340	5.9	34.1	1.0	0.0	0.0	–
8	SA-NS-0.55-400	5.55	32.1	–	0.25	0.6	–
9	BA-NS-0.45-340	6.6	38.2	1.0	0.2	0.5	–
10	BA-NS-0.45-400	6.2	35.9	–	0.5	1.2	–
11	BA-NS-0.55-340	6.85	39.6	1.5	0.0	0.0	–
12	BA-NS-0.55-400	6.4	37.0	1.0	0.0	0.0	–
13	RBA-RBFA-0.45-340	10.5	60.8	2.0	1.35	3.3	1.0
14	RBA-RBFA-0.45-400	9.9	57.3	1.5	0.15	0.4	0.5
15	RBA-RBFA-0.55-340-E	0	0	–	0.0	0.0	–
16	SA-NS-0.55-400-E	0	0	–	0.0	0.0	–

that the macro-cell corrosion is reduced with exposure period and on the other hand micro-cell corrosion is increased with exposure period [9,10]. It is expected that the relative judgment of total corrosion in RBA in comparison to other aggregates as investigated in this study will be similar to the macro-cell corrosion of this study. It can also be noted that in addition to the chloride concentration, the macro-cell corrosion will also be influenced by the oxygen permeability as well as resistivity of concrete between anode and cathode. These parameters are not evaluated in this study. However, a

higher level of oxygen permeability as well as less concrete resistance are expected for concrete made with RBA.

4.4 Half-cell potential

Half-cell potentials over the steel bars at cracked and un-cracked regions after 30 d of seawater exposure are shown in Fig. 8. It is observed that half-cell potential over the steel bars at the cracked regions are more negative than -350 mV which indicates 90% probability of active

**Fig. 8** Half-cell potential values at cracked and un-cracked region.

corrosion as per ASTM C876 as summarized in Table 7. On the contrary, half-cell potentials at the un-cracked regions of the specimens are found to be more positive than -200 mV which indicated only 10% probability of corrosion. The half-cell potentials at the cracked and un-cracked regions of steel bars indicate that macro corrosion cells will form at the anode on the surface of the steel segment at cracked region and at the cathodes over the steel segments at the un-cracked regions. The results match well with the macro-cell corrosion current density data as explained earlier. Similar observations

have also been found in a previous investigation [36]. The half-cell potential over the epoxy coated bars indicates no corrosion irrespective of cracked and un-cracked regions.

4.5 Corroded area and pit depth observation

The specimens were autopsied after electrochemical investigations for 30 d. The surface conditions of the segmented steel bars at the cracked region are shown in Fig. 9. Corroded areas and pit depths on the surface of the steel bars were measured. The results are recorded in

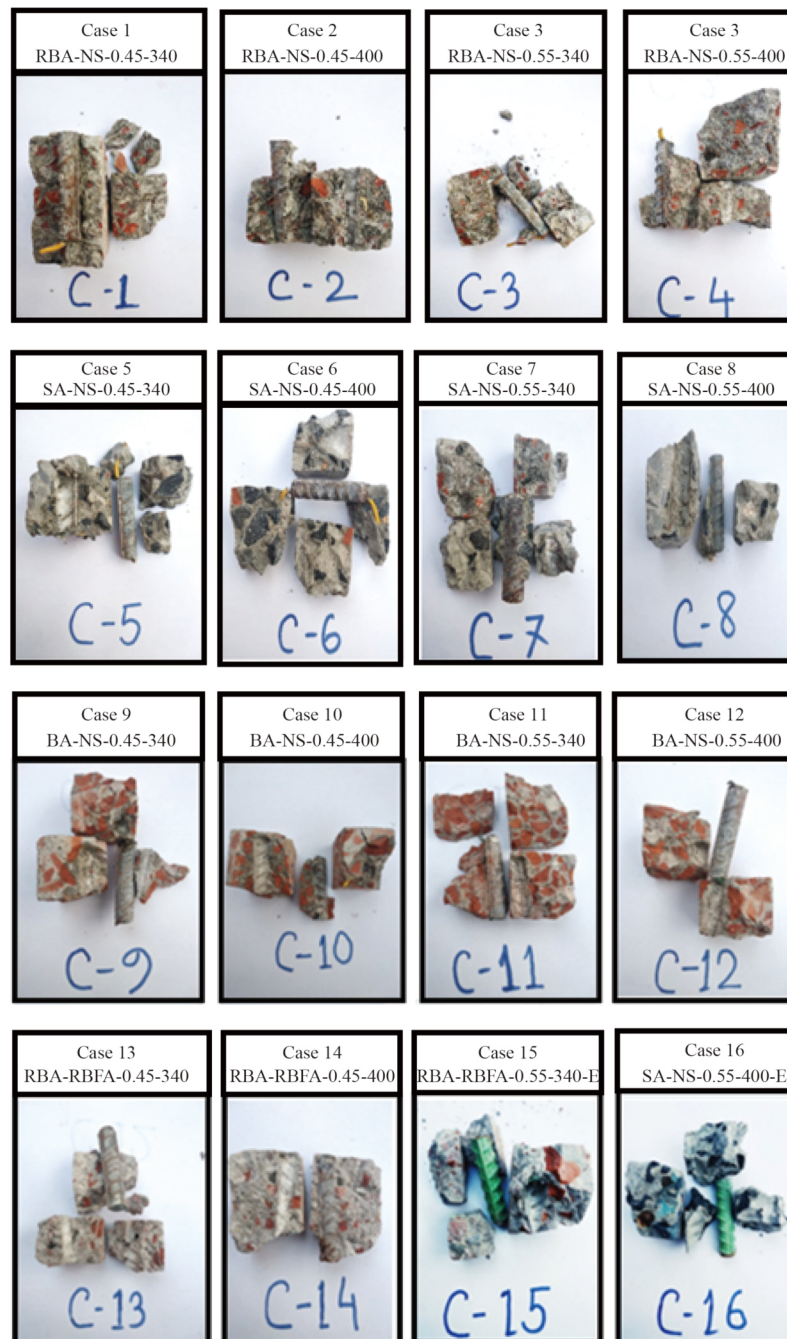


Fig. 9 Visual observation: segmented steel bar at cracked region.

Table 9. Higher percentages of corroded area are observed for the segmented steel bars at the cracked region compared to the un-cracked regions as expected from the electro-chemical data. Light corrosion over the steel bars at the un-cracked region can be explained due to the voids at the steel concrete interface as well as continuation of de-bonding with concrete around the steel bar from the cracked region to the un-cracked region [14].

Higher pit depths are also observed for the cases made with RBA and BA. Based on the corroded area and corrosion pits; the corrosion activity over the steel bars in concrete with the variation of aggregates can be ordered as $RBA > BA > SA$. Physical observation data are well matched with data related to chloride ingress and macro-cell corrosion over steel bars.

5 Conclusions

Based on the experimental results related to chloride ingress as well macro-cell corrosion of steel bar in concrete made with recycled brick aggregate (RBA), brick aggregate (BA), and stone aggregate (SA), the following conclusions are drawn.

- 1) Recycled brick aggregate can be utilized for producing structural grade concrete.
- 2) Chloride ingress as well as macro-cell corrosion of steel in concrete with respect to types of coarse aggregate is ordered as $RBA > BA > SA$.
- 3) More chloride ingress and corrosion activity on the surface of the steel bars in concrete is found for the cases with RBA and recycled brick fine aggregate (RBFA).
- 4) The macro-cell corrosion current density is reduced with the age of exposure period irrespective of the types of aggregates.
- 5) Fusion bonded epoxy coated steel bars exhibit least macro-cell corrosion compared to the bare steel bar irrespective of RBA and SA.
- 6) For improving durability performance of concrete made RBA and BA, it is necessary to increase cement content and keep W/C at a lower level.

Acknowledgements The authors wish to express their sincere appreciation to Bangladesh Road Research Laboratory (BRRL) for their financial support to conduct this study. The authors also acknowledge the support of laboratory facilities of Islamic University of Technology (IUT) provided for conducting this study.

References

1. Mohammed T U, Hasnat A, Awal M A, Bosunia S Z. Recycling of brick aggregate concrete as coarse aggregate. *Journal of Materials in Civil Engineering*, 2014, 27(7): B4014005
2. Mohammed T U, Mahmood A H, Chowdhury I M, Humayun A M, Ahmed T. Sustainability of construction materials in Bangladesh.

In: 4th International Conference on Sustainability of Construction Materials and Technologies. Nevada: CreateSpace Independent Publishing Platform, 2016

3. Kreft S, Eckstein D, Junghans L, Kerestan C, Hagen U. Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2013 and 1994 to 2013. *Global Climate Risk Index 2015*
4. Ministry of Food and Disaster Management, Bangladesh. Report on Cyclone Shelter Information for Management of Tsunami and Cyclone Preparedness, Comprehensive Disaster Management Programme. Center for Environment and Geographic Information Services (CEGIS), 2009
5. Miyaji M, Okazaki K, Ochiai C. A study on the use of cyclone shelters in Bangladesh. *Journal of Architecture and Planning*, 2017, 82(737): 1871–1880 (Transactions of AIJ)
6. Behnood A, Van Tittelboom K, De Belie N. Methods for measuring pH in concrete: A Review. *Construction & Building Materials*, 2016, 105: 176–188
7. Mohammed T U, Hamada H. Corrosion of steel bars in concrete with various steel surface condition. *ACI Materials Journal*, 2006, 103(4): 233–242
8. Rilem, Corrosion of Steel in Concrete. State of the Art Report, Committee 60-CSC. 1988
9. Otsuki N, Miyazato S, Diola N B, Suzuki H. Influences of bending crack and water-cement ratio on chloride-induced corrosion of main reinforcing bars and stirrups. *ACI Materials Journal*, 2000, 97(4): 454–464
10. Mohammed T U, Hamada H, Yokota H. Macro-cell and micro-cell corrosion of steel bars in cracked concrete made with various cements. *ACI Special Publication*, 2004, 221(2): 51–72
11. Islam M S, Mondal B C, Islam M M. Effect of sea salts on structural concrete in a tidal environment. *Australian Journal of Structural Engineering*, 2010, 10(3): 237–252
12. Sandra N. Corrosion current density of macrocell of horizontal steel bars in reinforced concrete column specimen. *International Journal of GEOMATE*, 2019, 16(54): 123–128
13. Lu C, Wang W, Jiang J, Hao M. Micro-environment temperature and relative humidity response of fly ash concrete under natural climatic conditions. *Advances in Cement Research*, 2017, 19(6): 1–10
14. Mohammed T U, Otsuki N, Hisada M, Shibata T. Effect of crack width and bar types on corrosion of steel in concrete. *Journal of Materials in Civil Engineering*, 2001, 13(3): 194–201
15. Kenny A, Katz A. Influence of the interfacial transition zone properties on chloride corrosion in reinforced concrete-characterization of ITZ. *Advanced Materials Research*, 2010, 95: 69–72
16. Mohammed T U, Otsuki N, Hisada M. Corrosion of steel bars with respect to orientation in concrete. *ACI Materials Journal*, 1999, 96(2): 154–159
17. Kang C, Kunieda M. Evaluation and observation of autogenous healing ability of bond cracks along rebar. *Materials (Basel)*, 2014, 7(4): 3136–3146
18. Rivetti M L S, Neto J D S A, Júnior N A, Ribeiro D V. Corrosion inhibitors for reinforced concrete. *Corrosion Inhibitors, Principles and Recent Applications*, 2018: 35–58

19. McDonald D B. Use and performance of epoxy-coated reinforcing steel over 37 years. In: 27th Annual International Bridge Conference. Pittsburgh: Engineers Society of Western Pennsylvania, 2010
20. Mohammed T U, Hamada H, Mamun M A A, Hasnat A. Corrosion of cement paste coated steel bars in marine environment. In: 3rd International Conference on Sustainable Construction Materials and Technologies (SCMT3). Kyoto: International Speech Communication Association, 2013
21. Khatib J M, Mohammed T U, Zhang J S, Hamada H. New generation water reducing admixture for concrete. In: 2nd International Conference on Sustainable Construction Materials and Technologies. Ancona: Milwaukee, 2010
22. Wasim M, Hussain R R. Comparative study on induced macro-cell corrosion phenomenon in repaired ordinary reinforced and self-compacting concrete structures. *International Journal of Corrosion Processes and Corrosion Control*, 2013, 48(5): 370–379
23. Otieno M, Beushausen H, Alexander M. Chloride-induced corrosion of steel in cracked concrete—Part I: Experimental studies under accelerated and natural marine. *Cement and Concrete Research*, 2016, 79: 373–385
24. Apostolopoulos C A, Demis S, Papadakis V G. Chloride-induced corrosion of steel reinforcement—Mechanical performance and pit depth analysis. *Construction & Building Materials*, 2013, 38: 139–146
25. Corral Higuera R, Arredondo Rea S P, Almaral Sánchez J L, Castorena González J H, Neri Flores M, Martínez Villafañe A, Almeraya Calderón F. Corrosion of steel in concrete with recycled aggregate and pozzolanic materials. *ECS Transactions*, 2009, 20(1): 477–487
26. Gurdíán H, García-Alcocel E, Baeza-Brotons F, Garcés P, Zornoza E. Corrosion behavior of steel reinforcement in concrete with recycled aggregates, fly ash and spent cracking catalyst. *Materials (Basel)*, 2014, 7(4): 3176–3197
27. Zeng W, Zhao Y, Zheng H, Poon C. Improvement in corrosion resistance of recycled aggregate concrete by nano silica suspension modification on recycled aggregates. *Cement and Concrete Composites*, 2020, 106: 103476
28. Mohammed T U, Khan A Z, Mahmood A H. Recycling of demolished brick aggregate concrete as coarse and fine aggregates. In: International Conference on the Regeneration and Conservation of Concrete Structures (RCCS). Nagasaki: Japan Concrete Institute, 2015: 1–12
29. Mohammed T U, Das H K, Mahmood A H, Rahman M N, Awal M A. Flexural performance of RC beams made with recycled brick aggregate. *Construction & Building Materials*, 2017, 134: 67–74
30. Mohammed T U, Shikdar M K H, Awal M A. Shear strength of RC beam made with recycled brick aggregate. *Journal of Engineering Structures*, 2019, 189: 497–508
31. ASTM C 39/ C39M–16. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen. West Conshohocken: ASTM International, 2016
32. González J A, Andrade C, Alonso C, Feliu S. Comparison of rates of general corrosion and maximum pitting penetration on concrete embedded steel reinforcement. *Cement and Concrete Research*, 1995, 25(2): 257–264
33. ACI 318R–19. Building Code Requirements for Structural Concrete. Farmington Hills: American Concrete Institute, 2019
34. Mohammed T U, Hasnat A, Awal M A, Bosunia S Z. Recycling of demolished concrete as brick aggregate: An extended study on some key issues. In: 3rd International Conference on Sustainable Construction Materials and Technologies (SCMT3). Kyoto: International Speech Communication Association, 2013
35. Alonso C, Andrade C, Gonzalez J A. Relation between resistivity and corrosion rate of reinforcements in carbonated mortar made with several cement types. *Cement and Concrete Research*, 1988, 18(5): 687–698
36. Mohammed T U, Otsuki N, Hamada H, Yamaji T. Macro-cell and micro-cell corrosions of steel bars in cracked concrete exposed to marine environment. In: 5th CANMET/ACI International Conference on Recent Advances in Concrete Technology. Farmington Hills, MI: ACI International, 2011: 55–169
37. López-Calvo H Z, Montes-García P, Kondratova I, Bremner T W, Thomas M D A. Epoxy-coated bars as corrosion control in cracked reinforced concrete. *Materials and Corrosion*, 2012, 64(7): 599–608
38. Kobayashi K, Takewaka K. Experimental studies on epoxy coated reinforcing steel for corrosion protection. *International Journal of Cement Composites and Lightweight Concrete*, 1984, 6(2): 99–116
39. Pour-Ali S, Dehghanian C, Kosari A. Corrosion protection of the reinforcing steels in chloride-laden concrete environment through epoxy/polyaniline–camphorsulfonate nanocomposite coating. *Corrosion Science*, 2015, 90: 239–247
40. Nanayakkara O, Kato Y. Macro-cell corrosion in reinforcement of concrete under non-homogeneous chloride environment. *Journal of Advanced Concrete Technology*, 2009, 7(1): 31–40