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Utilization of Recycled Aggregate Concrete for Marine Site Based on 7-Year Field Monitoring

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Abstract

This research aimed to create value of construction and demolition waste to be able used as a recycled coarse aggregate (RCA) in durable concrete, based on 7-year field investigation in marine site. Fly ash was used to substitute Portland cement type I in RCA concrete varied from 0 to 50% by weight of binder with three W/B ratios and comparing to natural aggregate (NA) concrete. Cubical concrete specimens were cast having round steel bars embedded with various concrete coverings to evaluate the durability performances. After 28-day curing, the specimens were placed at a tidal zone in the gulf of Thailand and investigated both mechanical and durability performances at 7-year exposed period. Based on site monitoring, 15–25% fly ash RCA concrete with W/B ratio of 0.40 would be advantaged to resist destruction due to the marine attack when compared with NA concrete with the same water-to-binder ratio.

Keywords: recycled coarse aggregates, fly ash, chloride penetration, marine site, steel corrosion, compressive strength

1 Introduction

Recycled coarse aggregates were derived from demolished concrete structures and were crushed into smaller particles to obtain specified sizes. Recycled aggregates were usually used in a concrete mixture to conserve natural aggregates as well as to reduce waste of concrete debris in landfills. The properties such as compressive strength, modulus of elasticity, water impermeability, abrasive resistance, durability, and etc. of recycled aggregate concretes, however, are generally lower than those of natural aggregate concretes (Choi et al., 2016; Lei et al., 2020; Yehia et al., 2015; Ying et al., 2016). However, some pozzolanic materials have been incorporated with Portland cement type I in the concrete mixtures to improve those properties of recycled aggregate concretes.

Previous publications (Somna et al., 2012a, 2012b; Tangchirapat et al., 2012) based on laboratory studies reported that the use of bagasse ash, palm oil fuel ash, or fly ash could increase compressive strength, lower water permeability, increase sulfate and chloride resistances of recycled aggregate concrete at the later age. Somna et al. (2012a, 2012b) found that higher in the replacement rate of ground bagasse ash could lower both water permeability and chloride penetration of recycled coarse aggregate concrete. The study also suggested that use of ground bagasse ash as high as 20% by weight could improve either mechanical or durability properties of recycled coarse aggregate concrete. In addition, Tangchirapat et al. (2012) reported that use of ground palm oil fuel ash as high as 20% by weight to replace OPC in recycled coarse aggregate concrete yielded only 7% lesser in compressive strength comparing to the control concrete, however, performed significant decrease in chloride penetration comparing to the control one. Besides, ground fly ash could increase compressive strength of recycled coarse aggregate concrete comparing to that of natural aggregate concrete at all W/B ratios and could be used as high as 35% by weight of binder with W/B ratio of 0.45. Moreover, Lei et al. (2021) reported that the stress level and strength grade is significant factor affecting the durability of recycled aggregate concretes.

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In addition, using fly ash in natural aggregate concretes subjected to long-term exposure in marine environment were efficiently improved durability performance of concrete (Cheewaket et al., 2014; Githachuri et al., 2012). It was found that use of fly ash to replace natural aggregate concrete ranging from 30 to 40% by weight of binder with W/B ratio as low as 0.40 would have less concrete destruction and prolong reinforced concrete structure subjected to marine environment. Previous studies (Somna et al., 2012a, 2012b; Tangchirapat et al., 2012) especially in recycled aggregate concrete have been conducted in laboratory; however, field data obtaining from a long-term study in actual marine site should have been investigated to provide more reliability of database. This research, therefore, studied the effects of fly ash content and water to binder ratio particularly on compressive strength, chloride penetration, chloride diffusion coefficient, and steel corrosion of recycled coarse aggregate concretes subjected to marine environment up to 7 years. The findings would provide a long-term database and benefit to improve the durability of recycled aggregate concretes to be as efficient as those of natural aggregate concretes which are exposed in a severe condition especially in marine environment.

2 Methodology

2.1 Materials

Portland cement type I and fly ash had been used as binders in RCA concrete mixtures. Fly ash was a by-product of burning lignite in a pulverized system resulted in spherical solid particles. The specific gravity of fly ash was 2.23 and its amount retained on a No. 325 sieve was 32% by weight which was less than 34% as specified in ASTM C618. Accordingly, the fly ash does not need to be improved its physical properties before using as a co-binder. The major chemical compositions of fly ash include SiO_2, Al_2O_3, and Fe_2O_3 which were summed up to be 72.51% by weight and its LOI was 0.07% by weight. This could be classified as class C fly ash, since CaO is higher than 18% by weight in accordance with ASTM C618. The chemical compositions of Portland cement type I and fly ash are summarized in Table 1.

River sand with fineness modulus of 2.74 and specific gravity of 2.63 was used as a fine aggregate in the NA and RCA concrete mixtures. A coarse aggregate from demolished concrete having compressive strengths ranging from 24 to 32 MPa was crushed, and sieved and was used as a recycled coarse aggregate in the concrete mixture. The fineness modulus and specific gravity of the recycled coarse aggregate were 6.42 and 2.44, respectively. Water absorption of recycled coarse aggregate was as high as 4.92% by weight, about 5 folds of that in the limestone, due to some old mortars adhered around the particles (Somna et al., 2012a, 2012b).

Table 1 Chemical compositions of Portland cement type I and fly ash.

Chemical composition (%)	Sample	
	Portland cement type I	Fly ash
Silicon Dioxide, SiO_2	21.52	36.02
Aluminum Oxide, Al_2O_3	3.56	20.58
Iron Oxide, Fe_2O_3	4.51	15.91
Calcium Oxide, CaO	66.70	18.75
Magnesium Oxide, MgO	1.06	-
Sodium Oxide, Na_2O	0.12	0.69
Potassium oxide, K_2O	0.24	1.69
Sulfur trioxide, SO_3	2.11	2.24
Loss On Ignition, LOI	1.74	0.07

Table 2 Physical properties of aggregates.

Physical properties	Fine aggregate	Coarse aggregate	
		Recycled (RCA)	Crushed limestone (NA)
Fineness modulus	2.74	6.42	6.66
Bulk specific gravity	2.63	2.44	2.80
Water absorption (%)	0.91	4.92	0.64
Density (kg/m^3)	1725	1475	1615

Natural coarse aggregate was crushed limestone and had nominal maximum size of 20 mm. Fineness modulus of the coarse aggregate is 6.66. Bulk specific gravity at saturated surface dry condition of the coarse aggregate is 2.80. The physical properties of aggregates are also shown in Table 2.

3 Specimens Preparation

Fly ash was used to replace Portland cement type I at the rates of 0, 15, 25, 35, and 50% by weight of binder in RCA concrete. Water to binder ratios (W/B) were varied as 0.40, 0.45, and 0.50. The slump of fresh recycled coarse aggregate concrete was controlled within the ranges of 50 to 100 mm using sulfonated melamine–formaldehyde condensates (superplasticizer). The mix proportions of natural aggregate concrete (NA concrete) uses Portland cement type I as a cementitious material with W/B ratio of 0.40, 0.45 and 0.55. For natural aggregate, limestone with a 19-mm (3/4 inch) nominal maximum size and a fineness modulus (FM) of 6.69 was used as a coarse aggregates and river sand having an FM of 2.61 was utilized as a fine aggregate.

The specific gravities (under saturated surface dry conditions) of the coarse and fine aggregates are 2.75 and 2.55, respectively. The mix proportions of NA and RCA concrete mixtures are summarized in Table 3.

Cylindrical concrete specimens of 100 mm in diameter and 200 mm in height were cast to perform compressive strength tests of all concrete mixtures. Cubical concrete specimens of $200 \times 200 \times 200$ mm^3 having 12-mm diameter round steel bars (grade SR24) embedded at its corners with coverings of 50, and 75 mm had been cast. All specimens were cured in fresh water for 28 days before they were placed at a tidal zone in the Gulf of Thailand. The seawater in this region has temperature ranged from 25 to 35 °C and has pH between 7.9 and 8.2. Sulfate and chloride ions in the seawater were recorded to be 16,000–19,000 mg/l and 2200–2700 mg/l, respectively. After being exposed to marine environment for 7 years, the cubical specimens were cored out to obtain cylindrical concretes of 100 mm in diameter and sliced into several 10-mm thick discs to test for acid soluble chloride ion penetration in concrete which were performed corresponding to ASTM C1152. Percentage of surface rusted area of embedded steels were determined by comparing the rusted area appeared on transparent graph paper to the surface area of embedded steels. Both specimen preparations and testings are presented in Fig. 1.

4 Results and Discussion

4.1 Compressive Strength of Concrete

Compressive strengths of ***NA*** and RCA concretes at 28 days are shown in Table 4. Refer to the table, the compressive strengths of NA concrete were obviously higher than those of RCA concretes. However, Concrete I40FR25 gained a higher 28-day compressive strength than concrete I50 and yielded almost the same 28-day compressive strength of I45 concrete. As a result, the use of fly ash in suitable amount could increase the compressive strength of RCA concrete to be as high as that of NA concrete. Moreover, the compressive strengths of RCA concretes containing fly ash as high as 25% by weight of binder were found to be higher than those of RCA concretes without any fly ash at the same W/B ratio. This similar result has been shown by previous researches that the compressive strengths at 28 days of RCA concretes incorporating of fine particle pozzolans such as ground fly ash, ground palm oil fuel ash or ground bagasse ash as high as 20% by weight of binder were greater than those of RCA concretes without any pozzolan (Somna et al., 2012a, 2012b; Tangchirapat et al., 2012). However, the higher fly ash content for more than 25% by weight of binder tended to lower the compressive strength of RCA concretes.

Pozzolanic reaction is evidently responsible to the increase of compressive strength of RCA concretes.

Table 3 Mixture proportions of NA and RCA concretes.

Mix	Mixture proportions of concretes (kg/m^3)							W/B ratio
	Cement	Fly ash	Fine aggregate	Coarse aggregate		Water	SP	
				NA	RCA			
I40	480	–	765	935	–	190	–	0.40
I45	425	–	765	980	–	190	–	0.45
I50	385	–	765	1010	–	190	–	0.50
I40FR00	477	0	767	–	935	190	0.5	0.40
I40FR15	405	72	767	–	910	190	0.5	0.40
I40FR25	358	119	767	–	894	190	0.5	0.40
I40FR35	310	167	767	–	875	190	0.5	0.40
I40FR50	239	239	767	–	850	190	0.5	0.40
I45FR00	424	0	767	–	979	190	0.4	0.45
I45FR15	360	64	767	–	957	190	0.4	0.45
I45FR25	318	106	767	–	938	190	0.4	0.45
I45FR35	276	148	767	–	925	190	0.4	0.45
I45FR50	212	212	767	–	903	190	0.4	0.45
I50FR00	385	0	767	–	1012	190	0.3	0.50
I50FR15	327	58	767	–	990	190	0.3	0.50
I50FR25	289	96	767	–	978	190	0.3	0.50
I50FR35	250	135	767	–	964	190	0.3	0.50
I50FR50	193	193	767	–	944	190	0.3	0.50

Fig. 1 Specimens preparation and testing of exposed concrete.

Table 4 Compressive strengths of NA and RCA fly ash concretes after being exposed to marine environment for 7 years.

Mix	Compressive strength (MPa)		Compressive strength at 7 years compared to 28 days (%)
	28 days	7-year exposure in marine site	
I40	48.6	48.2	99
I40FR00	38.3	30.3	79
I40FR15	38.1	35.5	93
I40FR25	41.4	38.1	92
I40FR35	35.7	32.6	91
I40FR50	31.6	27.1	86
I45	42.6	41.9	98
I45FR00	30.4	24.2	80
I45FR15	37.3	30.9	83
I45FR25	31.7	27.1	85
I45FR35	28.5	25.5	89
I45FR50	27.0	23.2	86
I50	39.1	38.4	98
I50FR00	28.5	21.6	76
I50FR15	31.0	23.2	75
I50FR25	30.5	23.7	78
I50FR35	28.2	21.2	75
I50FR50	26.7	21.1	79

As a result, the use of fly ash as high as 25% by weight of binder could improve compressive strength of RCA concrete. Furthermore, this study also found that the compressive strengths of RCA concretes with W/B ratio of 0.40 and containing fly ash ranged from 15 to 35% by weight of binder were greater than 35 MPa which satisfied the suggestion in accordance with ACI 201.2R for marine concrete.

Compressive strengths of NA concretes and RCA fly ash concretes after being exposed to marine environment for 7 years are shown in Table 4. Based on the results, the quality of coarse aggregates has an important effect on the compressive strength of concrete after immersed in seawater for 7 years. It is found that all RCA concretes provided a significantly lower compressive strength than NA concrete, although the W/B ratio in RCA concrete is less than that NA concrete. Figure 2 illustrates the effect of W/B ratios on compressive strength of RCA concrete. The results showed that the variation in fly ash replacement in RCA concrete is more susceptible to compressive strength of concrete with low W/B ratio rather than that high W/B ratio. The fly ash replacement was varied from 0 to 50% by weight of binder, resulting in the variation of compressive strength of RCA concrete with W/B ratio of 0.40 in the range of 27.1–38.1 MPa, while in concrete with

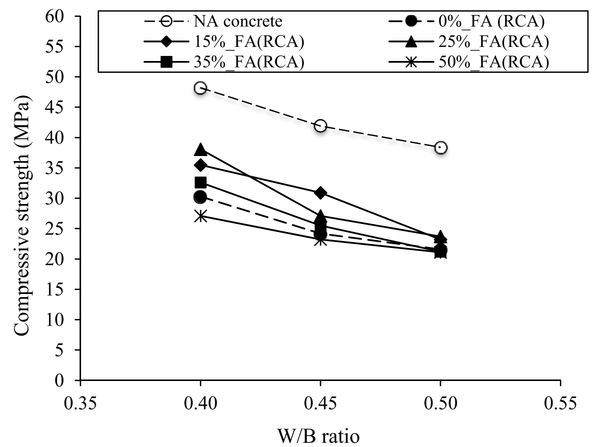

Fig. 2 Effect of W/B ratios on compressive strength of NA and RCA fly ash concretes after 7-year exposure in a marine site.

W/B ratio up to 0.50, the compressive strength of the concrete only varies from 21.2 to 23.7 MPa.

This is due to the high water content in RCA concrete causes the concrete to have high porosity together with low compressive strength, resulting in easily destroyed due to physical and chemical of marine site. Therefore, the use of different amounts of fly ash has no significant effect on the improvement of the mechanical properties of RCA concrete with a high W/B ratio (Cheewaket et al., 2014). However, when reducing the W/B ratio in RCA concrete, it is found that the compressive strength after exposed in seawater significantly changes with the variation of fly ash replacement. It is indicated that the improvement of mechanical properties of RCA concrete with low W/B ratio (high strength grade) using fly ash has more effective against destruction due to the marine environment when compared to low strength grade.

The effective against the destroying due to tidal marine site can be presented in terms of the percentages of 7-year compressive strengths of concretes compared to their corresponding 28 days, as shown in Table 4. These results can be confirmed more clearly that the use of fly ash in RCA concrete with low W/B ratio can resist damage due to the marine environment better than RCA concrete with high W/B ratio. For instance, the RCA concrete with W/B ratio of 0.40 containing fly ash of 0, 15, 25, 35, and 50% by weight of binder gave the percentages of 7-year compressive strengths compared to 28 days of 79, 93, 92, 91, and 86%, respectively, while the same fly ash replacement in RCA concrete with W/B ratio of 0.50 had the percentages of 7-year compressive strengths compared to 28 days of 76, 75, 78, 75, and 79%, respectively.

Loss of compressive strength of concrete exposed to marine environment was possibly due to both chemical and physical destruction from the seawater (Cheewaket et al., 2014; Qu et al., 2021). Chemically, sulfate ions dissolved in seawater would generate major products in concrete such as calcium sulfoaluminate (ettringite) and calcium sulfate (gypsum) which expand and increase crack leading to compressive strength loss (Medeiros et al., 2013; Moffatt et al., 2018; Tang et al., 2017). Moreover, extremely physical attacks from abrasion–erosion, temperature, moisture, etc. in the tidal zone would also help the aggressive chemicals ingress easily that cause even more damage of the concrete structure. Higher quality of aggregate would yield a greater effect to prevent concrete deterioration from physical destruction, whereas fly ash would help prevent concrete deterioration from sulfate attack. For this reason, natural coarse aggregate concretes yielded a lesser degree of compressive strength loss than fly ash RCA concretes.

Effect of fly ash on compressive strength of RCA concrete, the results found that the use of fly ash to replace OPC would reduce loss in compressive strength of RCA concretes exposed to marine environment. For example, RCA concretes with W/B ratios of 0.45 containing fly ash replacement of 0, 15, 25, 35, and 50% by weight of binder had the ratio of 7-year to 28-day compressive strengths of 80, 83, 85, 89, and 86%, respectively. It was due to the pozzolanic reaction that the concrete would develop compressive strength with time, and as the presence of fly ash in the concrete mixtures decrease of $Ca(OH)_2$ which is the reactant in sulfate attack that would reduce loss in compressive strength of concrete (Gopalakrishnan et al., 2019; Tang et al., 2017; Tangchirapat et al., 2012).

4.2 Chloride Penetration

After being exposed in marine environment for 7 years, chloride penetration profiles of RCA concretes and NA concrete are illustrated in Fig. 3. It was found that high variations of chloride contents near the concrete surface were recorded and could not clearly find their trends against the effect of fly ash content. However, chloride penetration in the concretes tended to decrease as fly ash replacement rate increased, especially at a deeper distance from the concrete surface. Similar trends were also found in NA concretes containing fly ash which were exposed to marine environment for 7 years (Chalee et al., 2010). In addition, previous publications reported that use of ground fluidized bed fly ash in the mixtures could lower both water permeability coefficients and chloride diffusion coefficients of RCA concretes (Somna et al., 2012a, 2012b). It was due to the products of either calcium silicate hydrate (C–S–H) or calcium aluminate hydrate (C–A–H) derived from pozzolanic reaction that

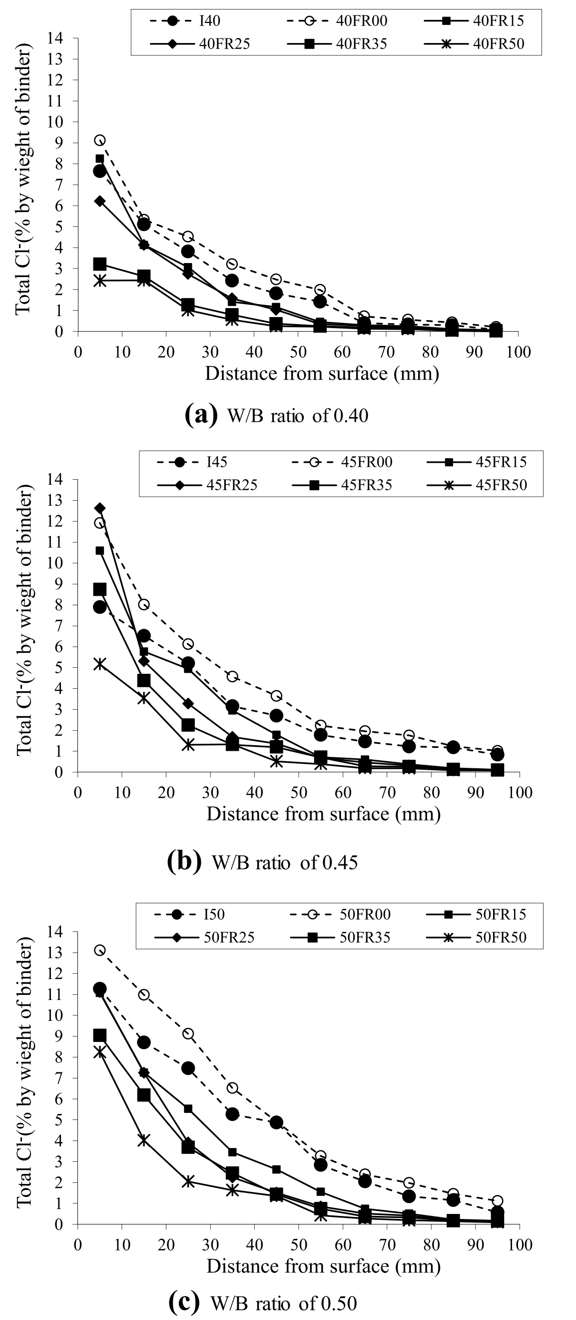

Fig. 3 Total chloride penetration profiles of NA and RCA concretes with a W/B ratio of **a** 0.40, **b** 0.45 and **c** 0.50 after 7-year exposure in a marine site.

filled in the voids or pores of concretes (Chalee et al., 2010; Cheewaket et al., 2014). For these reasons, low chloride penetrations in RCA concretes containing fly ash were detected. Accordingly, fly ash could efficiently improve chloride resistance of RCA concrete in marine environment.

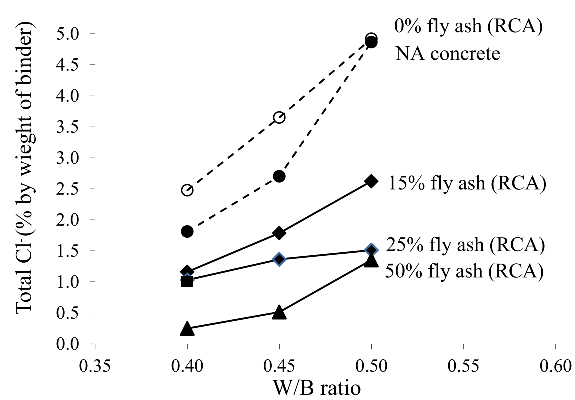

Fig. 4 Effect of W/B ratios on chloride content of NA and RCA concretes at the depth of 45 mm after 7-year exposure in a marine site.

Refer to ACI 201.2R-16 recommendation, W/B ratio of concrete should not exceed 0.45 to minimize any adverse effect on concrete exposed to marine condition. The results from this study indicated that RCA concretes with W/B ratio of 0.40 and 0.45 containing fly ash allowed a lesser amount of chloride penetration into concrete than NA concrete did, accordingly, fly ash could be used to improve durability of RCA concrete especially in marine environment. Concrete structures exposed to marine condition, however, would subject to concrete deterioration from both physical attack (wave impact, erosion, barnacle, lichen, etc.) and chemical attack (mainly from sulfate and chloride). Consequently, concrete to be used in marine condition should satisfy not only durability (have high water tightness, endure sulfate and chloride attacks), but also mechanical property (as high compressive strength). Based on the study, RCA concrete with W/B ratio of 0.40 and containing fly ash to replace OPC in the amount of 15 to 25% by weight of binder satisfied both durability and mechanical property of RCA concrete exposed to marine environment as recommended by ACI 201.2R-16 specification.

Figure 4 illustrates the effect of W/B ratio on chloride penetration of RCA concretes at the penetration depths of 45 mm. Refer to the figure, the decrease of W/B ratio resulted in the decrease of chloride content. A greater effect of W/B ratio on the reduction of chloride content was also observed in RCA concretes without any fly ash. At the penetration depth of 45 mm, for instance, the chloride content in RCA concretes containing no fly ash reduced by 2.44% (from 4.92 to 2.48% corresponding to the W/B ratios of 0.50 and 0.40, respectively). Whereas, chloride contents in RCA concretes containing fly ash of 25% by weight of binder reduced only 0.48%, from 1.51 to 1.03% corresponding to the W/B ratios of 0.50 and 0.40, respectively. Similar trends were also noticed in other various penetration depths.

Chloride ion would hardly ingress into concretes with higher in water impermeability and consequently lower chloride penetration were detected in concretes with a lower W/B ratio. Not only low W/B ratio that increased the water impermeability of concretes, but also SiO_2, Al_2O_3, and Fe_2O_3 in fly ash induced pozzolanic reaction which resulted in higher water impermeability and subsequently reduced chloride penetration of concretes containing fly ash (Liu et al., 2017; Rattanashotinunt et al., 2018; Somna et al., 2012a, 2012b; Wang et al., 2020; Yu et al., 2016). Because the water impermeability of concretes containing no fly ash depend largely on W/B ratio, decrease in W/B ratio would bring about a greater reduction in chloride content of RCA concretes without any fly ash than that of RCA concretes with fly ash.

4.3 Chloride Diffusion Coefficient of Concretes

Determination of chloride diffusion coefficients (D_c) of both RCA and NA concretes subjected to seawater for 7 years based on the similar previous research (Chalee et al., 2010), are followed Fick's second law of diffusion as being shown in the following equation:

$$\frac{\partial c}{\partial t} = Dc\frac{\partial^2 c}{\partial x^2}, \quad (1)$$

where D_c in Eq. (1) is a constant, the general solution of Eq. (1) can be expressed in the following equation:

$$C_{x,t} = C_0\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_C t}}\right)\right], \quad (2)$$

where $C_{x,t}$ = total chloride ion (by weight of binder) at distance x, and exposure time t, x = distance from concrete surface (mm), t = exposure time in seawater (second), C_0 = chloride concentration at concrete surface (x = 0), and exposure time t, D_c = Chloride diffusion coefficient of concrete at exposure time t, erf = error function.

Refer to Eq. (2), both D_c and C_0 were generated from chloride penetration profile of each concrete specimens via the least square method. Figure 5 shows the determination of D_c of RCA concretes with W/B ratio of 0.40 after being exposed to seawater for 7 years, similar procedures were processed to determine D_c of the other concretes as being shown in Table 5.

Figure 6 shows the effect of fly ash on D_c of RCA concretes after being exposed to seawater for 7 years. The results indicated that use of higher amount of fly ash to replace OPC would reduce D_c effectively. Similar trends were found in concretes with other W/B ratios. For example, RCA concretes with W/B ratio of 0.40 and containing fly ash replacements of 0, 15, 25, 35, and 50% by weight of binder provided chloride diffusion coefficients at 7 years of 4.5×10^{-6}, 2.6×10^{-6}, 2.4×10^{-6}, 1.5×10^{-6}, and 1.0×10^{-6} mm²/s, respectively. Comparing to the NA concretes and using of fly ash to replace OPC in RCA concretes could also reduce chloride diffusion coefficients to be less than those in NA concretes having similar W/B ratio. Accordingly, the pozzolanic

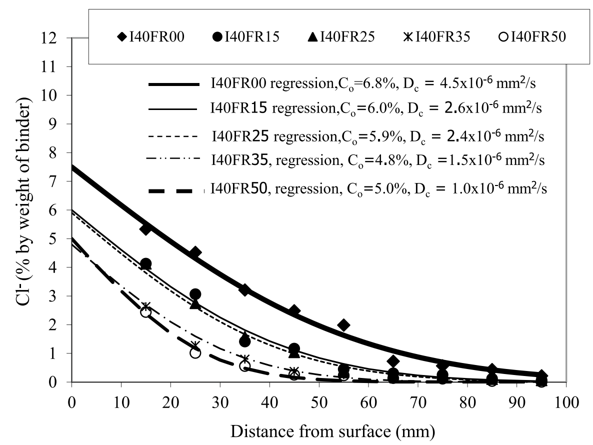

Fig. 5 Determination of D_c of RCA concretes with W/B ratio of 0.40 after being exposed to seawater for 7 years.

Table 5 D_c of NA concrete and RCA fly ash concretes after being exposed to marine site for 7 years.

Mix	Chloride diffusion coefficient, $D_c \times 10^{-6}$ mm²/s
I40	3.5
I45	5.5
I50	6.2
I40FR00	4.5
I40FR15	2.6
I40FR25	2.4
I40FR35	1.5
I40FR50	1.0
I45FR00	5.8
I45FR15	3.3
I45FR25	2.9
I45FR35	1.8
I45FR50	1.3
I50FR00	6.3
I50FR15	3.5
I50FR25	3.1
I50FR35	2.2
I50FR50	1.7

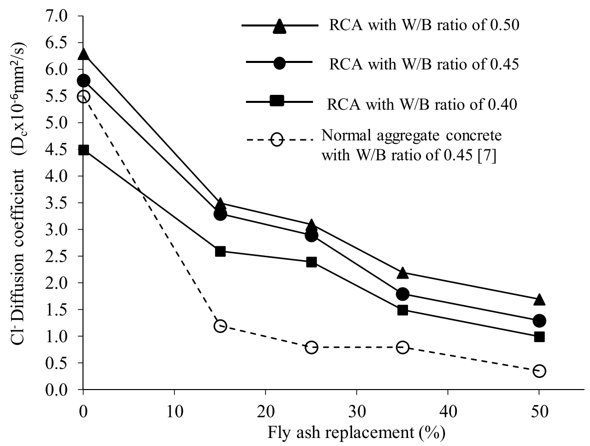

Fig. 6 Effect of fly ash on D_c of RCA concrete after being exposed to seawater for 7 years.

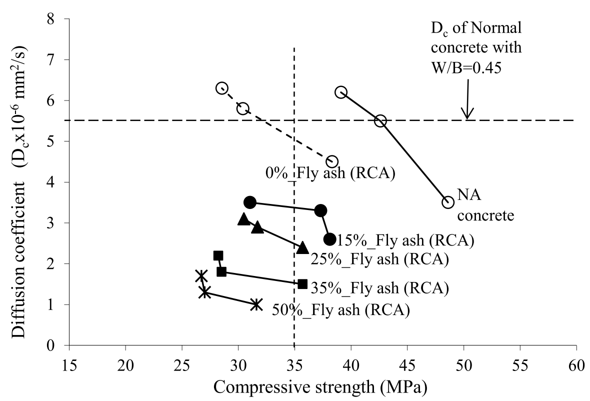

Fig. 7 Relationship between compressive strength at 28 days and D_c of NA and RCA concretes after being exposed to seawater for 7 years.

reaction from fly ash is effectively improved durability of RCA concretes especially against chloride attack from seawater.

Moreover, a lower W/B ratio brought about a lower D_c of concrete and a greater effect was found in concretes containing fly ash conforming to previous research (Jiang et al., 2017). It was due to the water tightness of Portland cement concrete which depended mainly on its W/B ratio and compressive strength. Whereas, the water tightness of concrete containing fly ash depended on both chemical property of fly ash in pozzolanic reaction and physical property of fly ash to fill up concrete's voids leading to reduce D_c effectively, especially in RCA concrete containing solid-round fly ash.

Figure 7 shows relationship between compressive strength at 28 days and D_c of NA and RCA concretes after being exposed to seawater for 7 years. It is interesting that concretes containing RCA and fly ash yielded lower *Dc* than NA concretes with W/B ratio of 0.45. ACI 201.2R, however, recommended that the concretes exposed to marine environment should have compressive strength of no less than 35 MPa with a W/B ratio of no greater than 0.45. Consider the ACI recommendation along with the results (Fig. 7), RCA concretes containing fly ash of no greater than 35% by weight of binder with a W/B ratio of 0.40 and RCA concrete containing fly ash of 15% by weight of binder with a W/B ratio of 0.45 brought about their 28-day compressive strengths greater than 35 MPa as well as their D_c were less than the D_c of natural aggregate concrete with a W/B ratio of 0.45. Due to the quality of RCA is lower than that of natural aggregate, this research, therefore, suggested that RCA concretes containing fly ash ranging from 15 to 25% by weight of binder with a W/B ratio of 0.40 together with a superplasticizer could gain their compressive strengths above 35 MPa as well as significantly lower D_c than that of NA concrete with W/B ratio of 0.45.

5 Embedded Steel Corrosion in Concrete

The percentage of surface rusted area of embedded steels (RA) were determined by comparing the surface rusted area (RS) to the surface area of embedded steels (SS), as shown in the following equation:

$$RA = \frac{RS}{SS} \times 100. \quad (3)$$

Figure 8 shows the corrosion of steel bar embedded in concrete specimens after being exposed to marine condition for 7 years. Ii is clearly seen that the use of fly ash in concrete mixture could reduce corrosion effectively. For instance, the surface rusted area of embedded steel bars at RCA concretes for covering of 50 and 75 mm were 15, 8, 5, 1, 1% and 8, 0, 1, 0, 0% corresponding to RCA concretes with W/B ratio of 0.40 and containing fly ash in the amount of 0, 15, 25, 35, and 50% by weight of binder, respectively. It was indicated that the pozzolanic reaction resulted in higher water tightness of concrete which reduced chloride penetration leading to the reduction of embedded steel corrosion (Lopez-Calvo et al., 2018; McCarthy et al., 2019). Pozzolanic reaction would reduce $Ca(OH)_2$ as well as would produce extra calcium silicate hydrate (C–S–H) or calcium aluminate hydrate (C–A–H) which reduced pore size in concrete matrix resulting in higher water tightness of concrete (Rukzon & Chindaprasirt, 2009). Furthermore, $Ca(OH)_2$, a product from hydration would be found a higher amount in Portland cement concrete, is a reactant in sulfate attack to produce dissolved gypsum which is a weaken product structure leading to concrete deterioration. Moreover, the fly ash in this study contains high amount of Al_2O_3 (20.58%)

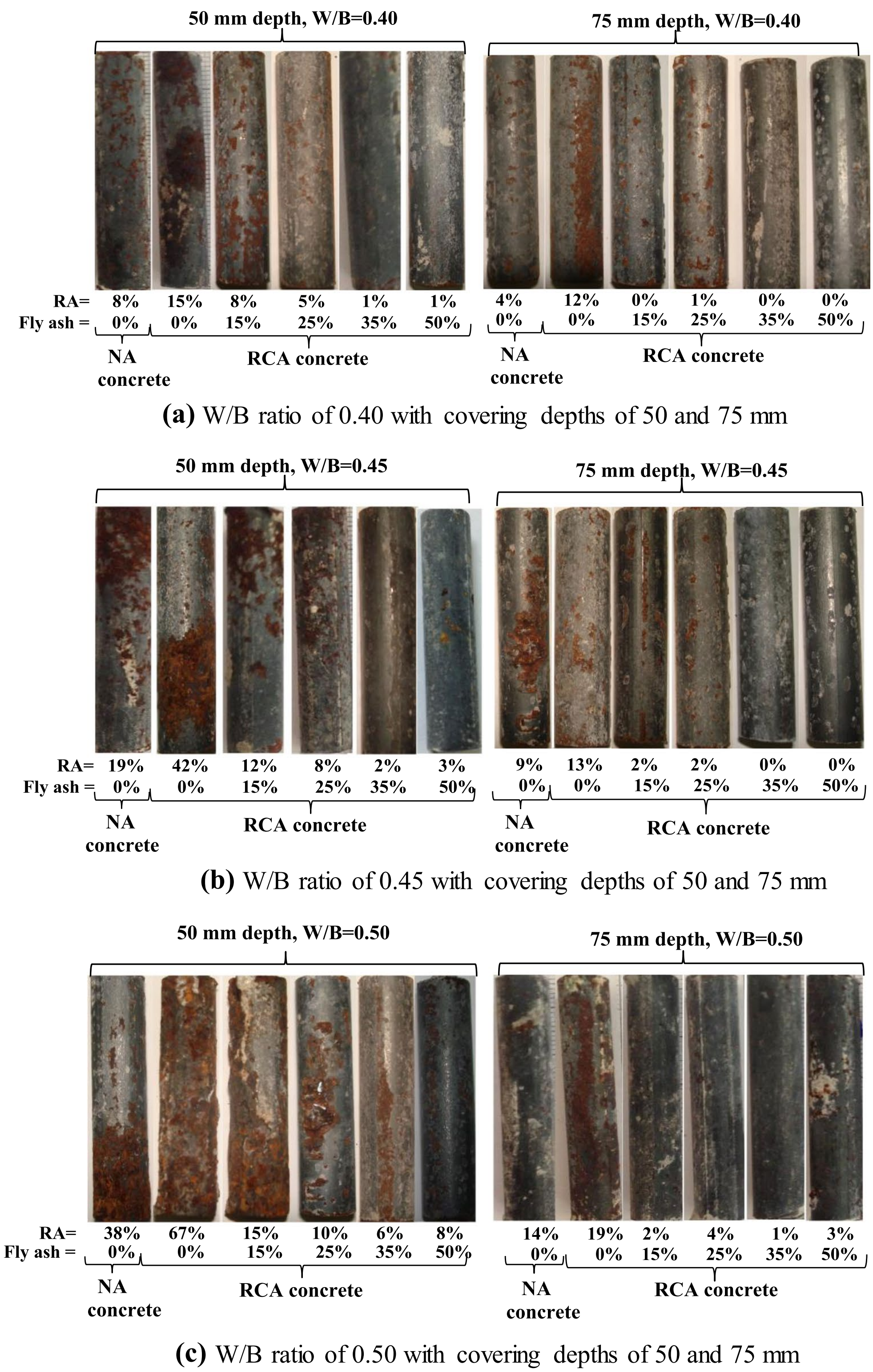

Fig. 8 Rusted area of embedded steel in NA and RCA concretes with a W/B of **a** 0.40, **b** 0.45 and **c** 0.50 after 7-year exposure in a marine site.

which could bind chloride ions chemically decrease free chloride ingression into concrete leading to a lesser degree of deterioration of reinforced steel concrete in marine environment (Gbozee et al., 2018; Oslakovic et al., 2010; Shen et al., 2019; Wang et al., 2019). Interestingly, the use of fly ash to replace OPC in RCA concretes could reduce embedded steel corrosion to be lesser than that of NA concrete with similar W/B ratio. Accordingly, fly ash could be used to improve durability of RCA concrete, even though its mechanical property would be less than NA concrete, especially at a low W/B ratio.

6 Conclusions

(1) The higher in compressive strengths after being exposed to marine environment for 7 years were found in NA concretes than those in RCA concretes. The increasing fly ash content could be reduced the compressive strength loss of RCA concretes due to marine environment.
(2) Use of fly ash at the replacement rates of 15 and 25% by weight of binder in RCA concretes with W/B ratio of 0.40 could improve the 28-day compressive strength of RCA concretes to be higher than NA concrete with W/B ratio of 0.50 and to be closed to NA concrete with W/B ratio of 0.45.
(3) Fly ash could significantly improve durability performances of RCA concretes. Higher in the replacement rate of fly ash in OPC would provide higher the chloride and steel corrosion resistances.
(4) Decrease in the water to binder ratio (W/B) would decrease chloride content of RCA concretes, a greater positive effect was found in the concrete mixtures containing no fly ash.
(5) Incorporation of fly ash in RCA concretes could effectively reduce D_c to be smaller than NA concretes without any presence of fly ash at similar W/B ratio.
(6) Use of fly ash at the replacement rates between 15 and 25% by weight of binder with W/B ratio of 0.40 would be satisfied both compressive strength, chloride and steel corrosion resistance of RCA concretes exposed to marine environment.

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Authors' contributions
The authors contribute to obtain concrete durability data from the marine site. As well as studying the mechanism of concrete destruction due to the marine environment to increase the durability of the RCA concrete. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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