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\textendash;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.
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 SiO₂, Al₂O₃, and Fe₂O₃ 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 is 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).

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 0.50. 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.

| Mix    | Mixture proportions of concretes (kg/m$^3$) | Coarse aggregate | Water | SP | W/B ratio |
|--------|--------------------------------------------|------------------|-------|----|-----------|
|        | Cement Fly ash Fine aggregate 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 64 767                                 | – 979 190        | 0.4   | 0.45 |
| I45FR15| 360 106 767                                | – 957 190        | 0.4   | 0.45 |
| I45FR25| 318 148 767                                | – 938 190        | 0.4   | 0.45 |
| I45FR35| 276 212 767                                | – 925 190        | 0.4   | 0.45 |
| I45FR50| 237 58 767                                 | – 912 190        | 0.3   | 0.50 |
| I50FR00| 385 0 767                                  | – 925 190        | 0.4   | 0.45 |
| I50FR15| 327 58 767                                 | – 903 190        | 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 |

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 found to be 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.
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.

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 in marine site (%) |
|-----|---------------------------|---------------------------------------------------------------------|
|     | 28 days  | 7-year exposure |                                                                 |
| 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                                                                  |

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
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...
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.

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 content of NA and RCA concretes at the depth of 45 mm after 7-year exposure in a marine site.
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$_2$O$_3$, and Fe$_2$O$_3$ 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; Rattanasotinunt 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:

$$\frac{\partial c}{\partial t} = D_c \frac{\partial^2 c}{\partial x^2},$$  

(1)

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

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

(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 =$\text{error}$ 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 $4.5 \times 10^{-6}$, $2.6 \times 10^{-6}$, $2.4 \times 10^{-6}$, $1.5 \times 10^{-6}$, and $1.0 \times 10^{-6}$ mm$^2$/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.](image)

### Table 5

| Mix  | Chloride diffusion coefficient, $D_c \times 10^{-6}$ mm$^2$/s |
|------|-------------------------------------------------------------|
| I40  | 3.5                                                          |
| I45  | 5.5                                                          |
| ISO  | 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                                                          |
| ISOFR00 | 6.3                                                          |
| ISOFR15 | 3.5                                                          |
| ISOFR25 | 3.1                                                          |
| ISOFR35 | 2.2                                                          |
| ISOFR50 | 1.7                                                          |
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 $D_c$ 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 super-plasticizer 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:

$$ RA = \frac{RS}{SS} \times 100. $$  \hspace{1cm} (3)

Figure 8 shows the corrosion of steel bar embedded in concrete specimens after being exposed to marine condition for 7 years. It 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% 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 ingestion 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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References
ACI 201.2R-16. (2016). Guide to durable concrete. ACI Committee 201, American Concrete Institute, Farmington Hills, ISBN: 9781945487392.

ASTM C1152 / C1152M-04. (2012). Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete; ASTM International, West Conshohocken, PA, www.astm.org.

ASTM C618–19 (2019). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, www.astm.org.

Cheewaket, T., Jaturapitakkul, C., & Chalee, W. (2014). Concrete durability presented by acceptable chloride level and chloride diffusion coefficient in concrete: 10-year results in marine site. Materials and Structures, 47, 1501–1511.

Choi, H., Choi, H., Lim, M., Inoue, M., Kitagaki, R., & Noguchi, T. (2016). Evaluation on the mechanical performance of low-quality recycled aggregate through interface enhancement between cement matrix and coarse aggregate by surface modification technology. International Journal of Concrete Structures and Materials, 10(1), 87–97.

Gbozee, M., Zheng, K., He, F., & Zeng, X. (2018). The influence of aluminum from metakaolin on chemical binding of chloride ions in hydrated cement pastes. Applied Clay Science, 158, 186–194.

Githachuri, K., Alexander, M., & Moyo, P. (2012). Durability performance of a range of marine concretes and the applicability of the South African Service Life Prediction Model. Materials and Structures, 45, 185–198.

Gopalakrishnan, R., & Chinnaraju, K. (2019). Durability of ambient cured alumina silicate concrete based on slag/fly ash blends against sulfate environment. Construction and Building Materials, 204, 70–83.

Jiang, P., Jiang, L., Zha, J., & Song, Z. (2017). Influence of temperature history on chloride diffusion in high volume fly ash concrete. Construction and Building Materials, 144, 677–685.
Lei, B., Li, W., Tang, Z., Li, Z., & Tam, V. W. Y. (2020). Effects of environmental actions, recycled aggregate quality and modification treatments on durability performance of recycled concrete. *Journal of Materials Research and Technology*, 9(6), 13375–13389.

Lei, B., Li, W., Luo, Z., Li, X., Tam, V. W. Y., & Tang, Z. (2021). Performance deterioration of sustainable recycled aggregate concrete under combined cyclic loading and environmental actions. *Journal of Sustainable Cement-Based Materials*, 10(1), 23–45.

Liu, J., Ou, G., Qiu, Q., Chen, X., Hong, J., & Xing, F. (2017). Chloride transport and microstructure of concrete with/without fly ash under atmospheric chloride condition. *Construction and Building Materials*, 146, 493–501.

Lopez-Calvo, H. Z., Montes-Garcia, P., Jiménez-Quero, V. G., Gómez-Barranco, H., Bremner, T. W., & Thomas, M. D. A. (2018). Influence of crack width, cover depth and concrete quality on corrosion of steel in HPC containing corrosion inhibiting admixtures and fly ash. *Cement and Concrete Composites*, 88, 200–210.

McCarthy, M. J., Tittle, P. A. J., & Dhir, R. K. (2019). Corrosion of reinforcement in concrete containing wet-stored fly ash. *Cement and Concrete Composites*, 102, 71–83.

Medeiros, M. H. F., Gobbi, A., Reus, G. C., & Helene, P. (2013). Reinforced concrete in marine environment: Effect of wetting and drying cycles, height and positioning in relation to the sea shore. *Construction and Building Materials*, 44, 452–457.

Moffatt, E. G., Thomas, M. D. A., & Fahim, A. (2018). Performance of high-volume fly ash concrete in marine environment. *Cement and Concrete Research*, 113, 65–73.

Osilovic, I. S., Bjevecic, D., & Mikulic, D. (2010). Evaluation of service life design models on concrete structures exposed to marine environment. *Materials and Structures*, 43, 1397–1412.

Qu, F., Li, W., Dong, W., Tang, V. W. Y., & Yu, T. (2021). Durability deterioration of concrete under marine environment from material to structure: A critical review. *Journal of Building Engineering*, 35, 102074.

Rattanashotinunt, C., Tangchirapat, W., Jaturapitakkul, C., Cheewaket, T., & Chindaprasirt, P. (2018). Investigation on the strength, chloride migration, and water permeability of eco-friendly concretes from industrial by-product materials. *Journal of Cleaner Production*, 172, 1691–1698.

Rulkon, S., & Chindaprasirt, P. (2009). Pore structure changes of blended cement pastes containing fly ash, rice husk ash, and palm oil fuel ash caused by carbonation. *Journal of Materials in Civil Engineering*, 16, 666–671.

Shen, X., Liu, O., Hu, Z., Jiang, W., Lin, X., & Hao, D. (2019). Combine ingress of chloride and carbonation in marine-exposed concrete under unsaturated environment: A numerical study. *Ocean Engineering*, 189, 106350.

Somna, S., & Jaturapitakkul, C. (2012). Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete. *Cement and Concrete Composites*, 34, 848–854.

Somna, R., Jaturapitakkul, C., Rattanachu, P., & Chalee, W. (2012a). Effect of ground bagasse ash on mechanical and durability properties of recycled aggregate concrete. *Materials & Design*, 36, 597–603.

Somna, R., Jaturapitakkul, C., Chalee, W., & Rattanachu, P. (2012b). Effect of W/B ratio and ground fly ash on properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 24, 16–22.

Tang, Z., Li, W., Ke, G., Zhou, J. L., & Tam, V. W. Y. (2017). Sulfate attack resistance of sustainable concrete incorporating various industrial solid wastes. *Journal of Cleaner Production*, 218, 810–822.

Tangchirapat, W., Khamklai, S., & Jaturapitakkul, C. (2012). Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates. *Materials & Design*, 41, 150–157.

Wang, Y., Shui, Z., Gao, X., Yu, R., Huang, Y., & Cheng, S. (2019). Understanding the chloride binding and diffusion behaviours of marine concrete based on Portland limestone cement-alumina enriched pozzolans. *Construction and Building Materials*, 198, 207–217.

Wang, Y., Tan, Y., Wang, X., & Liu, C. (2020). Mechanical properties and chloride permeability of green concrete mixed with fly ash and coal gangue. *Construction and Building Materials*, 233, 117166.

Yehia, S., Helal, K., Abusharkh, A., Zaher, A., & Istaitiyeh, H. (2015). Strength and durability evaluation of recycled aggregate concrete. *International Journal of Concrete Structures and Materials*, 9(2), 219–239.

Ying, J., Xiao, J., & Meng, Q. (2016). On probability distribution of chloride diffusion coefficient for recycled aggregate concrete. *International Journal of Concrete Structures and Materials*, 10(1), 61–73.

Yu, Y., Yu, J., & Ge, Y. (2016). Water and chloride permeability research on ordinary cement mortar and concrete with compound admixture and fly ash. *Construction and Building Materials*, 127, 556–564.

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