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FLY ASH AS A CEMENT SUBSTITUTE: EVALUATING EARLY-STAGE CORROSION POTENTIAL IN REINFORCED FOAMED CONCRETE

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Abstract

Corrosion in reinforced foamed concrete is primarily initiated by chloride ions, which increase the likelihood of corrosion. The fine particle size of fly ash was considered as good as the filler to reduce the capillary of the concrete. This study investigated the effect of cement replacement with fly ash on the potential corrosion of reinforced foamed concrete in the initial stage by using the half-cell potential technique. The beam of 15cm × 20cm × 80cm was investigated by reinforced foamed concrete and 10% fly ash reinforced foamed concrete. Conventional reinforced concrete was used as a control in this study. All types of samples were designed for compressive concrete strength of f'c 25MPa. Furthermore, this study was prepared with a water-cement ratio of 0.4, the longitudinal bar used of 4Ø10mm, and the shear reinforcement of Ø6 – 10cm. The specimen was immersed in 3.5% sodium chloride solution. The result showed that the potential corrosion was -600mV for reinforced normal concrete, -300mV for reinforced foamed concrete and -500mV for fly ash reinforced foamed concrete. It means that the risk of corrosion in reinforced foamed concrete is less than in reinforced normal concrete. Moreover, the addition of fly ash in the reinforced foamed concrete increased the corrosion risk of reinforcement in the initial stage. This is caused by the slow hydration time of the fly ash material, thus requiring a longer concrete curing time. The utilization of fly ash also reduces the pore in the concrete, thereby increasing its density, and an higher concrete density reduces the infiltration of water. Judging from the corrosion behavior of the reinforcement, foam concrete and foam concrete with fly ash are suitable to be employed as a structural element of the building constructed near the coast.

Keywords: Foam Concrete, Fly Ash, Corrosion, Lightweight Concrete, Half Cell Potential.

1. INTRODUCTION

The territory of Indonesia in general and the region of Aceh in particular is located in the earth's plate region. Such conditions make the region prone to earthquakes, both small and large [1]. In addition, most of the Aceh region is surrounded by beaches, which are the environmental causes of corrosion in buildings [2]. Therefore, any construction plan in this area must consider the resistance of the building to earthquakes and corrosion attacks. One way to reduce the earthquake load on buildings is to reduce the weight of the building, so that the earthquake force that works on the building is weaker [3]. If the building structure is made of reinforced concrete construction, the use of lightweight concrete building elements is an alternative, especially for residential buildings or simple structures [4]. According to Abdullah, lightweight concrete is concrete containing light aggregate and has a unit weight of no more than 1900kg/m^3. Fundamentally, lightweight concrete is made by incorporating appropriate number and size of air bubbles air pores into the concrete [5]. As one of the lightweight concretes, foam concrete is relatively easy to produce suggesting the needs for a more advances development

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for wider usages [6]. Various building elements utilize foam concrete, previous foam concrete research have been focused on the effect of changes in cement water factors and the addition of fillers, fibers, cement substitutes, such as coconut belt fibers, fibers fibers, sawdust, pumice, palm shells, fly ash and pozzolan [5], [7], [8]. The inclusion of additives to foam concrete is intended to enhance its mechanical properties. One of the results of research shows that lightweight concrete can be produced with structural quality, ie f'c> 17MPa [9].

In addition to its use as an excellent construction material for floor, the low thermal conductivity and higher fire resistant than ordinary concrete making foam concrete is suitable for used as insulation against heat. Structurally, foam concrete can be used as construction material for floors [10]. Another advantage, foam concrete can be sawed or cut to the desired size, can be nailed, and is more durable [11]. The study of reinforced foam concrete beams and the concrete blocks are suitable for use as structural elements. Research on columns of foam concrete also shows that foam concrete is fit for use as a structural element [12]. However, the behavior of these structural elements, especially their corrosion behavior of the reinforcement when exposed to a corrosive or harsh environment has yet to be studied. Foam concrete that continues to be developed for use as a structural element needs to be studied more in its resistance to corrosion, making it feasible to use as a structural element, especially for areas that are prone to corrosion, such as the seashore, swamps, and others. Fly ash which has been known to reduce the absorption of water in the concrete is expected to reduce the risk of corrosion in concrete. In this study, the effect of cement substitution portion with fly ash on reinforced foam concrete on reinforcing corrosion behavior in the initial stage (initial stage) was investigated. Furthermore, a comparison with normal reinforced foam concrete was also performed.

2. LITERATURE REVIEW

Fly ash is a powdery solid waste generated from coal combustion in power generation plants, which has smooth, round, and pozzolanic characteristics. Fly ash particle size varies from smaller than 1 µm (micrometer) to greater than 100 µm (some literature mentions sizes 0.5 µm - 300 µm), with most particles measuring less than 20 µm [13]. Generally, only about 10% to 30% of fly ash particle size is greater than 50 µm. The surface area of fly ash generally ranges from 300m^2/kg - 500m^2/kg, with a lower limit of 200m^2/kg and an upper limit of 700m^2/kg. The specific gravity (G_s) of fly ash varies between 1.9 - 2.55. The density of fly ash in loose conditions ranges from 540 - 860kg/m^3, and in conditions compacted by vibration in the packaging generally it has a density of 1,120 - 1,500 kg/m^3 [14]. Zhang, W. et. al (2020) stated that the substitution of cement with fly ash in concrete immersed in seawater can reduce the diffusion coefficient of chloride ions, which sequentially slow down the corrosion rate [15].

The composition of Portland cement used for concrete mixes contains tricalcium silicate (C_3S) 45 - 60% by weight, dicalcium silicate (C_2S) 5-30% by weight, tricalcium aluminate (C_3A) 6-15%, tetra calcium iron aluminate (C_4AF) 8% and some types of Portland cement also contain alkaline oxides (K_2O and Na_2O) 0.5 - 1.5% [16]. Portlan Cement Composite has surface area of 300 m²/kg, the specific gravity (G_s) of PCC varies between 3.10 – 3.16. The density of PCC

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cement, or Portland Composite Cement, is generally around 2,400 kg/m³ for plain cement concrete. During concrete mixing, C_3S and C_2S react with water to produce calcium silicate gel (CSH) and calcium hydroxide ($Ca(OH)_2$), according to the following reactions [17] :

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3\ Ca(OH)_2 \quad (1)$$

$$2(2CaO.SiO_2)+4\ H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2 \quad (2)$$

Calcium hydroxide produced from the hydration reaction of cement will cause a concrete pore solution to have a pH of 12.5. However, if there is also K_2O and Na_2O in cement, the cement hydration product will also contain NaOH and KOH, causing the pH of the solution to rise to 13.8. In such a high pH environment, reinforcing steel will be passive and a protective passive membrane is formed in the form of iron oxide (γ-Fe_2O_3) or iron hydroxide (γ-FeOOH) compounds [18]. The reaction process is as follows:

$$2\ Fe + 3\ H_2O \rightarrow Fe_2O_3 + 6\ H^+ + 6\ e^- \quad (3)$$

$$Fe + 2\ (OH)^- \rightarrow Fe(OH)_2 + 2\ e^- \quad (4)$$

$$Fe(OH)_2 + O_2 \rightarrow FeOOH + H_2O \quad (5)$$

This passive membrane is evenly distributed and attached to the surface of the steel reinforcement, thus blocking the contact between the steel reinforcement and its environment, which inhibits the dissolution of the steel. Commonly, the thickness of the membrane is 10-1 µm that protects the reinforcement of concrete from corrosion as long as the pore solution of the concrete remains basic and is free from chloride ions contamination [19].

Broomfield (2011) defines corrosion as a damage or deterioration in the quality of a material caused by the reactions between a material and its environment. In general, chloride ions attack and carbonation are the main causes of corrosion. Pores in normal concrete are generally continuous (capillary) with a diameter of 3nm - 2µm. Capillary pore diameter size allows the compound around the concrete to infiltrate into the concrete by diffusing, permeating, or absorbing capillaries which can cause the passive layer to be damaged. The surface of the steel where the passive layer is lost becomes an anode of the corrosion reaction of reinforcing steel [19]. The equations of the anode and cathode reaction are:

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (6)$$

$$O_2 + 2H_2O + 2e^- \rightarrow 4OH^- \quad (7)$$

The two ions formed at the anode and cathode combine to form a corrosion compound. The equation can be written as follows:

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4Oe^- \quad (8)$$

$$2Fe^{2+} + 4OH^- \rightarrow Fe(OH)_2 \quad (9)$$

$Fe(OH)_2$ as the initial form of the corrosion compound will be on the surface of the steel that is corroded. If high O_2 concentration, $Fe(OH)_3$ will be formed.

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With the following equation:

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \quad (10)$$

The corrosion mechanism on reinforcement in concrete is shown in Figure 1.

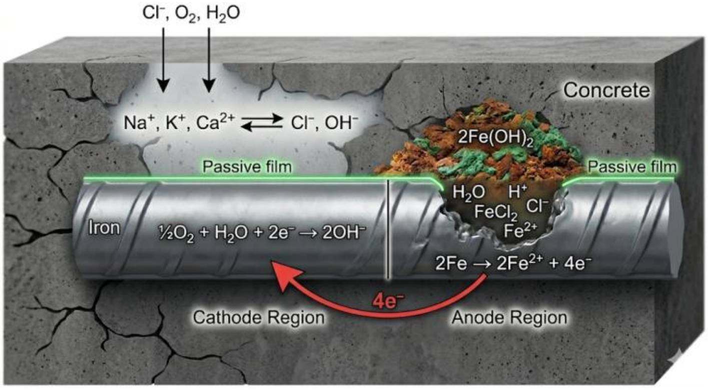

Figure 1: Anode, cathode, oxidation reaction, and hydration of corrosion in reinforced (Broomfield, 2011)

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$ (Ferrous hydroxide ($Fe(OH)_2$)) (11)

$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$ (Ferric hydroxide ($Fe(OH)_3$)) (12)

$2Fe(OH)_2 \rightarrow Fe_2O_3 \cdot H_2O + 2H_2O$ (Hydrated ferric oxide(rust)). (13)

The passive membrane is also contained in foamed concrete, so it can protect the reinforcement from corrosion attack [20].

3. METHODS

The materials used in this study include Portland Cement Composite (PCC) of Andalas, that bought from local market in Banda Aceht, fly ash from Bukit Asam, Tanjung Enim, Sumatera Selatan, the reinforcement used is U32 from local market in Banda Aceh, and aggregate from Krueng Raya, Banda Aceh, Aceh.

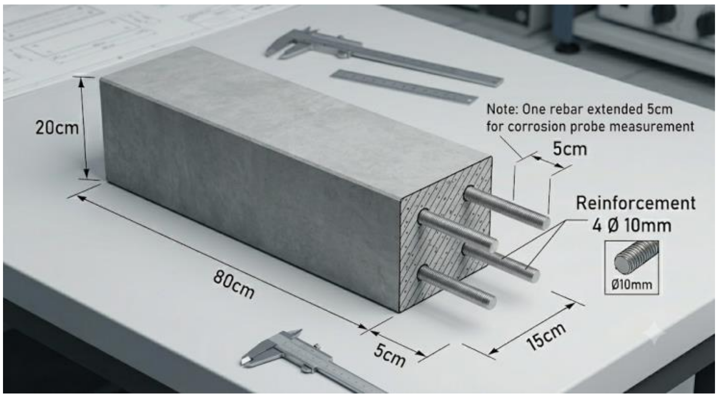

Figure 2: Shape and dimension of specimen for corrosion test

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The specimen is a foam concrete made with compressive strength f'c 25MPa, FAS 0.4 and SG 1.6. The size of the test specimen is made 15cm × 20cm × 80cm and the reinforcement used is 4Ø10mm for the main reinforcement and Ø6-10cm for shear reinforcement. The shape and dimensions of the test specimenis shown in Figure 2. The specimens were made of three variations consisting of normal foam concrete (without additives), fly ash foam concrete, and conventional normal concrete as comparison. Fly ash was added as a substitute for cement by 10% by weight. Each variation use only one test specimen. In addition, each variation of the test specimen is made as a control specimen for testing mechanical properties, in the form of cylinders with 15cm in diameter 30cm length for compressive strength and tensile strength evaluation, each of the three specimens. Schematic diagram of the specimen for mechanical test is displayed in Figure 3.

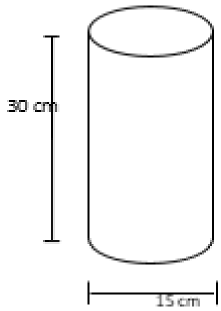

Figure 3: Shape and dimension of specimen for mechanical test

The specimens were cured for 28 days, then immersed in an artificial sea water immersion media (3.5% NaCl solution). The variation of test specimens is shown in Table 1. Data collection is conducted every two weeks for a period of 4 months.

Table 1: The matrix of the preparation and test

Variation of Speciment (15cm × 20cm × 80cm)	Thickness of Concrete Cover (cm)	Code	Treatment	Mechanical Test (dia 15cm × 30cm)	
			NaCl 3,5%	Compressive Test	Tensile Test
Conventional Concrete	2	BNK	1	3	3
Normal Foam Concrete	2	BB	1	3	3
Foam Concrete with *fly ash*	2	BBFa	1	3	3
Amount			3	9	9

To obtain the results as expected in this study needed steps and stages of data collection and analysis of materials. Examination of the chemical properties of PCC and fly ash were carried out at the Banda Aceh Industrial Research and Standardization Testing Laboratory. The PCC and fly ash material test results are shown in Table 2. Well water testing was carried out at the Laboratory of Instruments and Analysis of the Chemical Engineering Department at Syiah Kuala University with the results shown in Table 3. The test results showed that the two wells were not corroded.

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Table 2: Chemical Properties of PCC and Fly Ash

Oxide Component	PCC Analysis (%)	Fly Ash Analysis (%)
SiO_2	14.22	54.93
Al_2O_3	4.11	30.96
Fe_2O_3	2.72	3.76
CaO	73.86	0.85
MgO	0.09	1.6
K_2O	0.85	1.4

Table 3: Chemical Properties of Immersed

No.	Test Parameters	Methode	Unit	Standard Value	Result of Deep Well	Result of Shallow Well
1	Dissolved Oxygen	Probe In-situ	mg/L	-	8.5	8.3
2	Electrical Conductivity	Probe	mg/L	-	1017	661
3	Sulfate (SO_4)	Gravimetric	mg/L	400.00	1.92	3.51
4	Chloride (Cl)	Titrimetric	mg/L	500.00	99.40	49. 98
5	pH	Probe	value	4.5-8.5	7.00	7.03

Step by step of mixing materials is by sequencing water, cement, and cement substitutes, while the stirring was conducted in a concrete mixer. Next, a flow test is carried out on the cement paste, until it reaches a diameter of ≥ 20cm, if not achieved, a superplasticizer was added. Then add foam agent and stir for approximately 3 minutes with a 45° concrete mixer axis tilt. Foam agent is made from synthetic foam mixed with water using a generator.

The main equipment used is equipment for preparing and making test specimens in the form of measuring devices, concrete mixers, foam generators, molds of test specimens, compression testing machines, and steel pulling machines for Ton Industrial brands with UPD numbers. 10-7385 / 1970, with a scale of loading of 10 tons, a hydraulic jack, and a computer device for data processing. Also used profometer 3, half-cell potential mapping, and a meter. The test includes mechanical testing, compressive strength, tensile strength testing, and corrosion potential testing. The method used for corrosion testing is according to ASTM C 876 standard. Before being immersed, a reinforcement mapping using profometer 3 and the location of the reinforcement, as shown in Figure 4. Before the specimens are immersed in immersion media, initial potential measurements (week 0).

Figure 4: Mapping of reinforcement with profometer

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The next measurement was taken every 2 weeks for 4 months. Measurements were made at each meeting point of the main reinforcement and shear reinforcement with a half-cell potential mapping tool. Then the connecting cable from the reference electrode is connected to the iron reinforcement section. Wait a few seconds until the numbers on the stable digital half-cell are usually marked with a number close to zero. After that, insert the connecting foam to the end of the reference electrode after first being moistened with distilled water, and the reference electrode is used by placing the foam part onto the vertically reinforced concrete surface. The setup of the measurement of potential values is shown in Figure 5.

Figure 5: Set up measurement of corrosion with half-cell potential mapping

Corrosion can occur if there is an electrical potential difference between the anode and the cathode. The potential value of a material is obtained by measuring the potential difference of the material with a standard electrode such as SCE (Saturated Calomel Electrode) and SHE (Standard Hydrogen Electrode) and a gel type electrode. The more negative (active) potential of the material the greater the tendency of corrosion to occur [21]. Half-cell potential mapping or also called the half-cell potential technique is a method for the initial survey to detect reinforcement corrosion in concrete, which is measured from the concrete surface without damage [22]. With this technique, a predictable location of high risk and low risk of corrosion can be predicted, but it cannot be used to measure corrosion rates. ASTM C876 is a standard used for measuring half-cell potential mapping. Table 4 present the potential values on the surface of steel reinforcement for several half-cell standards [23].

Table 4: ASTM Criteria of Steel Reinforcement Corrosion for some Half-Cell Standard (Broomfield, 2011)

No. Speciment	Foam Concrete (kg/cm^2)	Foam Concrete *Fly ash* (kg/cm^2)	Conventional Concrete (kg/cm^2)
1	206.086	345.364	203.822
2	305.732	260.439	215.145
3	271.762	317.056	237.792
Average of f'c	261.194	307.620	218.920
Average of f'c (MPa)	26.119	30.762	21.892

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3. RESULT AND DISCUSSION

Concrete compressive strength test results presented in Table 5 indicate that the quality of the concrete (f'c 25MPa) has been achieved. Concrete quality ranges from 21.892MPa to 30.762MPa. Based on SNI 2847:2019, the foam concrete and foam concrete with fly ash are able to be used for structural building, because its compressing strength ≥ 17MPa.

Table 5: Result of Compressing Strength of Concrete

No	Copper copper sulphate	Silver silver chloride	Hydrogen Electrode	Calomel Electrode	Corrosion Condition
1	>-200mV	>-106mV	>+116mV	>-126mV	Low risk (10%)
2	-200 to-350mV	-106 to-256mV	+116 to-34mV	-126 to-276mV	Intermediate risk
3	<-350mV	<-256mV	<- 34mV	<-276mV	High risk (90%)
4	<-500mV	<-406mV	<-184mV	<-426mV	Severe corrosion

Meanwhile, for the concrete splitting tensile strength, the highest value was found in conventional concrete (1.800MPa). SNI 2847:2019 requires that the splitting tensile strength of concrete for structures ranges from 9% to 15% of the compressive strength of the concrete. From Table 5 and Table 6, the percentage of tensile strength of each concrete are 4.34% for foam concrete, 3.79% for foam concrete with fly ash and 8.22% for conventional concrete.This is likely due to the addition of foam, which is lightweight and causes the concrete become more brittle[24] . It reduces the ductility and splitting tensile strength of the concrete, as shown in Table 6.

Table 6: Result of tensile strength of concrete

No. Speciment	Foam Concrete	Foam Concrete *Fly ash*	Conventional Concrete
	(kg/cm^2)	(kg/cm^2)	(kg/cm^2)
1	11.000	10.000	20.000
2	23.000	11.000	19.000
3	0.000	14.000	15.000
Average of f'ct	11.333	11.667	18.000
Average of f'ct (Mpa)	1.133	1.167	1.800
Percentage of tensil strength to compressive strength	4.34%	3.79%	8.22

Testing the value of corrosion potential in the early weeks after the manufacture of test specimens shows the potential value reading was not stable yet. Corrosion potential values are generally stable after week 12. The reading value of the tool may be still influenced by the hydration process of the cement which produces heat. In addition, the level of corrosion on all surfaces of the test specimens tends to be uniform, Figure 6.

When the potential value readings begin to stabilize, it can be seen that compared to conventional normal concrete, foam concrete has a much lower risk of corrosion. This is illustrated by the color contour of the corrosion potential with very different color differences each week. This comparison of corrosion risk is shown in Figure 6(a) and 6(b). At week 16 the color contour potential of conventional concrete specimens was dark with a potential value of

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around -600mV, while the color contour of foam concrete in the same week was bright with a potential value of around -300mV.

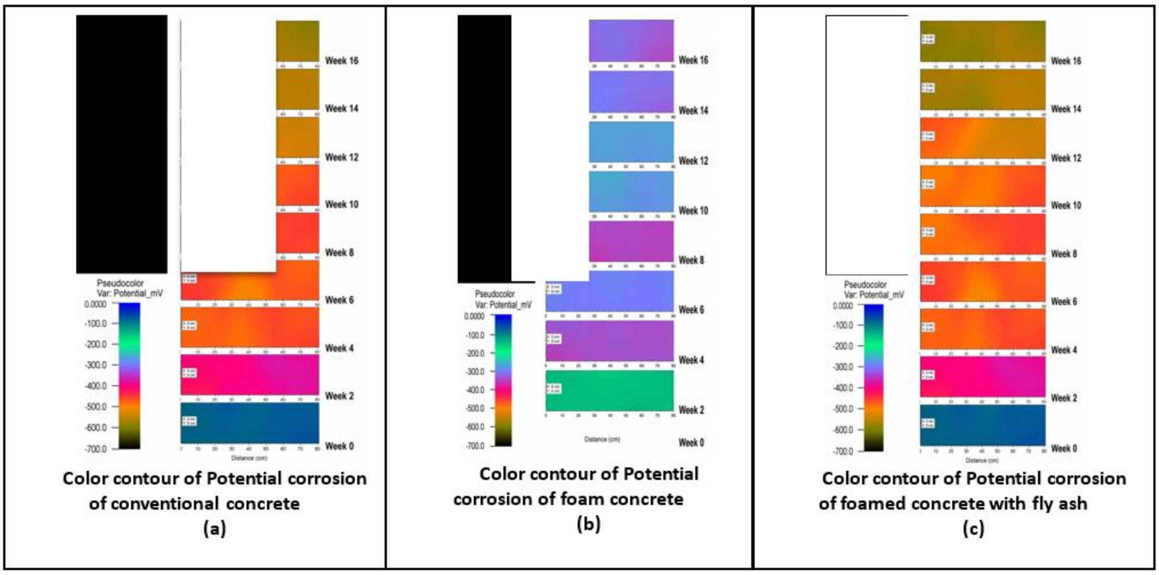

Figure 6: Comparison of potential corrosion conventional concrete (a), foam concrete (b), and foamed concrete with fly ash (c)

From these results, it can be concluded that foam concrete is relatively more resistant to corrosion than conventional concrete. The main cause is that the pores in foam concrete are not interconnected, but rather single, isolated pores that are non-capillary in nature. Non-capillary pores can block water and corrosive ions from infiltrating into the concrete.

Partial replacement of cement with fly ash can increase the risk of corrosion of foam concrete. This is caused by the slow hydration time of the pozzolanic material in fly ash, thus requiring longer concrete treatments. But compared to conventional normal concrete, foam concrete with pozzolanic material still has a lower corrosion risk level. This has also been studied previously by Luo, et. all (2022), who stated that foam concrete with a replacement of cement with pozzolan ash has a lower risk of corrosion compared to conventional normal concrete at the same compressive strength and conditions [25].

Figure 6(b) shows that in the 16th week the color contour of normal foam concrete is still purple, ranging from the potential value -300mV to -400mV, whereas in fly ash foam concrete the same week has dropped to -500mV to -600mV (Figure 6(c)).

In the 16th week, the color of the contour potential of conventional normal concrete test specimens was slightly darker than that of fly ash foam concrete in the same week. From the early weeks, the color contour potential of conventional normal concrete has shown a lighter color compared to foamed concrete with fly ash. A comparison of corrosion potential values is shown in Figure 6.

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4. CONCLUSIONS

From the results of data processing and discussion, the final result of this study are:

Partial replacement of cement with fly ash in foam concrete does not have a significant effect on the risk of reinforcement corrosion resistance if the concrete treatment is carried out in the same 28 days. However, the risk of reinforcement corrosion in this concrete is slightly lower compared to conventional normal concrete.

The risk of reinforcement corrosion in foam concrete if exposed to a corrosive environment is lower than the risk of reinforcement corrosion in conventional normal concrete.

Foamed concrete with fly ash has higher compressive strength than foam concrete without fly as and conventional concrete. On the other side, the splitting tensile strength of foam concrete with fly ash is the lowest compared to foam concrete without fly as and conventional concrete.

Judging from the corrosion behavior of the reinforcement, foam concrete is fit to be used as a structural element of the building in the building in the coastal area.

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