



Electrochemical Characteristics of High-Volume Fly Ash Lightweight Aggregate Concrete Incorporating Hydrated Lime

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High-volume fly ash lightweight concrete, corrosion, Porcelanite, AC resistance, pH test, Rapid chloride penetration

ABSTRACT

Currently, the use of high-volume fly ash lightweight concrete, HVFALWC, has acquired popularity as a durable, resource-efficient, and an option of sustainability for varying concrete applications. Electrochemical characteristics such as half-cell potential, AC resistance, chloride penetration, free chloride, and pH value, up to 180 days were investigated for this type of concrete that uses 50% and 60% of fly ash as a replacement of Portland cement. The effect of using 10% hydrated lime powder as a partial substitute for the weight of cementitious materials for HVFALWC on electrochemical properties was also studied. The results in this study showed the possibility of producing friendly environmental structural lightweight concrete by using high volume fly ash (50% and 60%) as partial replacement by weight of cement. Furthermore, using 10% hydrated lime as partial replacement by weight of cementitious materials could be considered as a reliable measure to reduce the effect of chloride ions in the corrosion process.

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1. INTRODUCTION

Corrosion of rebar is a major type of degradation in reinforced concrete structures. Corrosion products exhibit expansion of volume which induce tensile stress on the concrete that eventually leads to cracking and spalling of the concrete cover. Due to the loss of steel cross-section and

covered concrete, there can be a significant reduction in load bearing of the structure. It is known that reinforcement in concrete is protected from corrosion by a passive thin layer formed as a result of concrete alkalinity. A passive layer of aqueous iron oxide is created with a thickness of a few atomic films on the solid surface. Chloride ions have an important effect on reinforcement of concrete as a result of increasing corrosion of reinforcements embedded in concrete. On corrosion process, chlorides ions act as a catalyst, chlorides ions are not consumed in the corrosion process but assist to destroy the passivity layer on the reinforcement and permit the process of corrosion to progress quickly[1]. Corrosion of steel appears, as a result of chloride, in smaller anode area than cathode area and both can be far from each other. Inspection of steel corrosion can be carried out by many different techniques, half- cell potential is one of them. Corrosion can be examined by measuring half- cell potential (HCP) according to ASTM C876[2] through electrochemical process. The voltmeter device is interconnect to the electrical circuit to measure the reference electrode potential as illustrated in Figure 1. The voltmeter typically indicates a negative reading through measurement. The potential value is used as an indication for potential corrosion activity as demonstrated in Table 1, for copper/copper sulfate reference electrode.

One of the mechanisms that control the rate of corrosion is the resistance control[3]. Resistance control, which depends on the void ratio and moisture content of concrete, mostly governs the corrosion rate of steel reinforcement when the anode and cathode corrosion areas are located at a distance from each other. Therefore, by understanding the state of the electrolytes involved in the corrosion reaction and by obtaining information that enables us to indirectly assess the corrosion environment surrounding the reinforcement, it can gain insight into the concrete resistance [4]. Concrete resistance is determined according to Wenner's method, involving the preparation of two current and Potential electrodes on the surface of concrete[5].

The aim of this study is to determine the relationship between the chloride penetration and AC resistance as well as the effect of using high fly ash ratio in lightweight concrete on free chloride which is responsible for the corrosion of steel and alkalinity environment in structural HVFALWC.

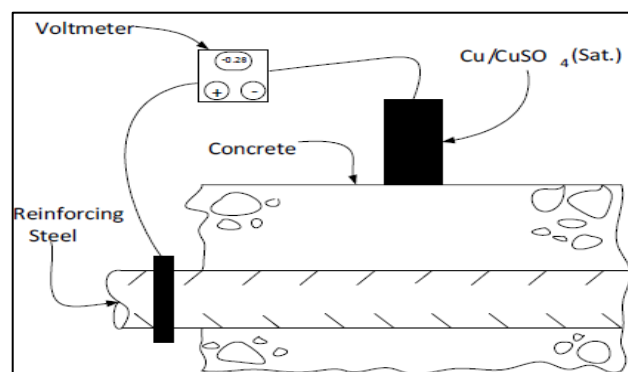


Figure 1: Schematic diagram for half- cell potential measurement[6].

TABLE I: Interpretation of half-cell potential reading according to ASTM C876[2].

Reading half- cell potential (mV.)*	Interpretation of corrosion
More than -200	Low probability of corrosion
From -200 to -350	Uncertain Activity of corrosion
Lower than -350	High probability of corrosion

*measurement by using copper/copper sulfate reference electrode.

The value of concrete electrical resistivity vary over a wide-ranging, between 10 and 1000000 Ω m. It is mainly influenced by the composition and content of moisture in the concrete[7].

Recently, a completely non-destructive technique for determining concrete resistance has been developed using the apparent resistance measurement above the reinforcement rod. This technique has been revised for application in assessing concrete durability [8-10].

In concrete, the current passes through pore water. The value of resistivity is adversely proportional with water cementitious ratio while linear proportional with longer curing-hydration.

Also, the use of reactive minerals materials such as fly ash increases resistivity of concrete. When the concrete is dried, the resistivity increase because of the transporting of current is only by the ions of the pore water in the paste of cement. The important of resistivity comes from the fact that the rate of corrosion of depassivation of steel increases with decreasing concrete resistivity.

There are many standard tests that assess the ability of concrete to resist penetration of chloride ion such as: ASTM C1202 [21]. Generally, it is known as a rapid chloride penetration test, RCPT. This test is used as an indirect evaluation for permeability of concrete mixtures [11].

2. EXPERIMENT OF WORK

I. Materials

A. Portland cement

A cement Type I fulfills the requirements of IQ S 5/1984 [12] produced by Bazain cement factory, which was used in this study. Its chemical analysis and physical properties are shown in Tables 2 and 3 respectively.

B. Fly ash

Fly ash fulfills the requirements of ASTM C618 (class F) [13] was used in this study. Its fineness, specific gravity, and activity index at 7 and 28 days are 3800 cm²/g, 2.59, 87%, and 93.5% respectively, and the chemical properties are illustrated in Table(2).

C. Hydrated lime powder

Local hydrated lime powder [Ca(OH)₂] used with 92.52% purity. The particles residue on 90μ sieve are 2.1%. It fulfills the requirements of IQS 807/2004[14]. The chemical properties of this product are illustrated in Table (2).

TABLE II: Chemical analysis of the used materials*

Chemical configuration	Content %			
	Cement	Fly ash	Porcelanite	Hydrated lime
SiO ₂	19.98	61.4	52.36	2.29
CaO	62.47	2.24	10.19	70.01
MgO	2.26	2.2	5.77	0.44
Fe ₂ O ₃	3.23	4.65	2.64	0.22
Al ₂ O ₃	4.98	25.78	12.34	1.07
SO ₃	2.54	0.3	0.39	0.2
Na ₂ O	0.3	----	----	---
K ₂ O	0.7	----	----	----
L. O. I	3.02	3.29	16.30	22.66
I. R	1.22	----	----	----
L. S. F.	0.977	----	----	----

TABLE III: Physical Properties of cement*

Property	Results
Specific Surface area (Blaine method, cm ² /gm)	3770
Soundness (auto clave method)	0.01
Initial time of setting, hrs: min	2 : 40
Final time of setting, hrs: min	4 : 00
Compressive Strength	
3-days N/mm ²	32
7-days N/mm ²	38

* The tests were done in the National Center of Construction Laboratories and Researches - Karbala laboratory

D. Fine aggregate

Local normal weight sand used throughout this investigation, with grading adequate with the requirements of IQS 45/ 1984 zone 3[15]. Its fineness modulus, specific gravity, and absorption are 2.67, 2.54, and 1.42% respectively.

E. Coarse aggregate

Local Porcelanite stone was used as lightweight coarse aggregate. It was crushed and sieved to a maximum size of 19 mm to satisfy the requirements of grading of IQS 45/1984 [15] . Its specific gravity, and absorption are 1.65, and 29.5% respectively as well as its SO₃ percent composition is 0.39, as shown in Table (2).

II. Mix proportions and test methods

A total of 4 mixes were prepared. The mix proportions of lightweight concrete were selected according to the recommendations presented in Ref. 16. The target compressive strength was 25 MPa at 28 days. Mixes contain cement Type 1, Type F fly ash with 50% and 60 % as partial replacement by weight of cement to produce FA50 and FA60. A 10% hydrated lime as a partial replacement by weight of cementitious materials was used to produce FA50HL10 and FA60HL10. Water to cementitious ratio has varied from 24.5 to 25.75 % by weight of cementitious materials for keeping slump at 120mm. Slump test was carried out according to ASTM C143 [17]. Table 4 shows mix proportions for HVFALWC.

TABLE IV:proportion of mixes for studied HVFALWC

Material	FA50	FA50HL10	FA60	FA60HL10
Water /cementitious ratio, %	25.5	25.75	24.5	24.9
Total cementitious materials, kg/m ³			654	
Cement, kg/m ³	327	294.3	261.6	235.44
Fly ash. kg/m ³	327	294.3	392.4	353.16
Hydrated lime. kg/m ³	0	65.4	0	65.4
Sand, kg/m ³			475	
Porcelanite, kg/m ³			475	
HRWRA, L/100kg cementitious			1.48	
Slump, mm			120± 5	

A 100×100×100 mm cube molds were used for casting compressive strength [18] and water absorption test [19] specimens. Meanwhile, cylinders with dimensions of 100×200 mm were employed for dry density test [20] and for preparing discs with dimensions of 100×50 mm to conduct RCP test [21].

After casting and demolding of concrete, the specimens were cured in lime-saturated water until the age of the test [22].

The strength test at 28 days age were carried out in Building Research Directory by using 2000 kN capacity compression machine. The samples for RCP test were tested at 56 days and 120 days of water curing. The results of compressive strength which is reported in this study represent an average of three samples, while the other properties results are the averages of two samples. Free chloride ions test was achieved for water cured samples after 3 days of air drying and then partially submerged in 5% NaCl solution for 28, 56, 90 , 120, and 180 days. Free chloride test was achieved according to ASTM C 1218 [23]. A pH of concrete test was achieved according to ASTM C25 [25] and ASTM F710 [26] for water cured samples after 3 days of air drying and then partially submerged in 5% NaCl solution for 28, 56, 90 ,120, and 180 days. Figure 2 and 3 show the apparatus of RCP and pH tests respectively.



Figure 2: RCP test

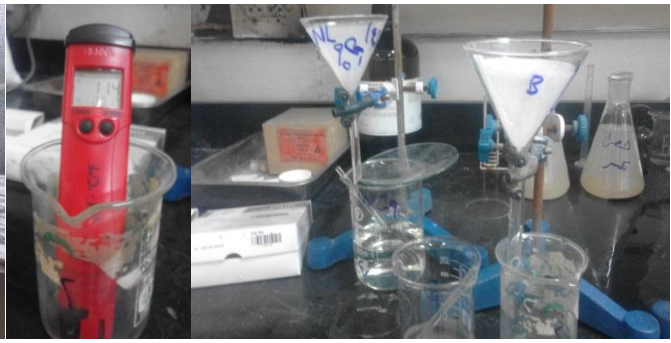


Figure 3: pH test

A 100×100×300 mm specimens, reinforced by 4 bars Ø12, were used for half –cell potential and AC resistance tests. Plastic strips were used to avoid any disturbance during electrical test, each bar connected with wire by welding.

After casting the specimens and covered by nylon sheets, they were demolded after 24 hours, cured in lime-saturated water with for 28 days then dried for 3 days before partially submerged in 5% sodium chloride solution. Half- cell test was accomplished according to ASTM C876 [2], while AC resistance was achieved based on procedure recommended in references 8, 9 and 10. The AC resistance test was achieved after 28, 56,90, 120, and 180 days of partially being submerged in solution, while half-cell potential test was periodically accomplished each three days for first month and then for each ten days up to 180 days. Figures 4 and 5 illustrate AC resistance test and half-cell potential test respectively.



Fig. 3 AC resistance test



Fig. 5 Half-cell potential test

3-RESULTS AND DISCUSSION

I. Physical properties

Table 5 illustrates the dry density, compressive strength, and absorption of water results for all mixes at the age of 28 days.

Results of dry density show that the density of all mixes is within the limit of density of structural lightweight concrete [27]. Also, Table (5) shows that the density of concrete decreased when replacing cement by fly ash and hydrated lime. This reduction is attributed to the lower specific gravity of both fly ash and hydrated lime compared to cement. The results of compressive strength of FA50, FA50LH10, FA60, and FA60LH10 showed that there is a little reduction in strength with the increasing of fly ash at 28 days age. This behavior could be attributed to negative effect of increasing fly ash content on the rate of hydration. While when using 10% hydrated lime as a partial replacement by weight of cementitious materials there was an increase in compressive strength of about 9.2%. This increase could be attributed to the role of hydrated lime in the reaction with fly ash. The results of absorption showed that the absorption of all mixes were lower than 10%, therefore, the concrete can be classified as good concrete [28].

TABLE V: Physical properties of different mix at 28 days water cured conditions.

Mix	density at 28days kg/m ³	Compressive strength MPa	Absorption %
FA50	1816	22.0	7.13
FA50LH10	1783	24.0	7.97
FA60	1807	21.5	7.37
FA60LH10	1769	23.5	8.30

II. Half- cell potential

Half –cell potential measurement is a widespread test that is used in the field. However, there are many limitations that affect half-cell values according to ASTM C876 [2].

Figure 6 shows the results of half-cell potential (HCP) test for all mixes up to 180 days of exposure. From Figure 6, it can be observe that the HCP for all studied HVFALW concrete mixes is ranged between -571 mV and -210mV. All samples results of studied concrete are higher than the threshold line except FA60. The HCP values of FA50 is higher than HCP values of FA60 and this may be attributed to adversely effect of increasing fly ash ratio on hydration process and, then produce denser matrix system. Moreover, using 10% of hydrate lime in both mixes (FA50 andFA60) was more benefit in improving HCP values and it is very significant in mix FA60. This improvement could be attributed to the enhancement of pozzolanic reaction and then with progress of age reducing mobility of charge in concrete pores in addition to increasing its alkalinity.

III. AC resistance and rapid chloride penetration (RCP)

Concrete resistance have an important effect on the rate of corrosion for embedded reinforcement in concrete as the electrical current must move from the anode toward the cathode for the corrosion phenomenon to occur. AC resistance technique can be used to determine ionic movement within the concrete pore solution. Also, it can be used for measuring the resistance of concrete to the chloride penetration as same as the rapid chloride penetration (RCP) test. RCP test was developed to measure the permeability of chloride-bearing solution depending on the mobility of electrical charge (Q) through concrete during a specific time (t). From the definition of the electrical current (I), the current is electrical charge (Q) flow through specific time (t):

$$I = \frac{Q}{t} \quad (1)$$

$$Q = I * t \quad (2)$$

$$I = \frac{V}{R} \quad (3)$$

$$Q = V * \frac{t}{R} \quad (4)$$

Where R is resistance.

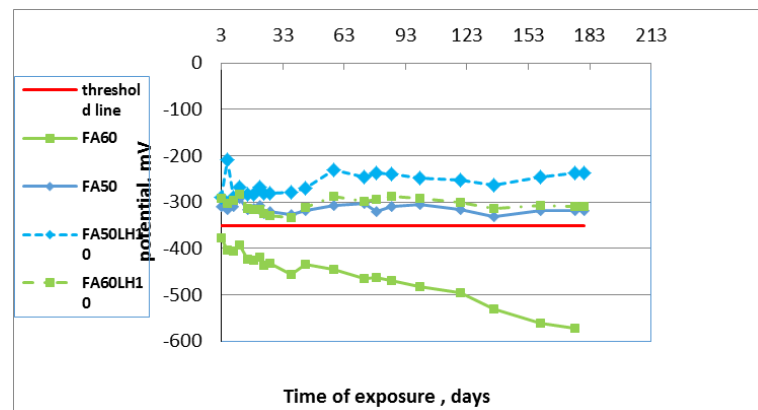


Figure 6: Half- cell potentials for studied HVFALWC mixes exposed to 5% NaCl solution for 180 days

Based on equation 3, one can observe that an inversely relationship between resistance (R) and charge (Q). That means that there is a linear relationship between charge and conductivity.

The results of RCP test which are illustrated in Table 6 shows that all concrete mixes can be classified as low penetrability for ion chloride according to ASTM C1202 [21].

TABLE VI: Results RCP and AC resistance for studied HVFALW concrete up to 180 days of water curing condition*.

Mix	Chloride penetration resistance, coulombs, for water cured concrete at:			AC Resistance Ω , for partially submerged concrete in Cl ⁻ solution at:			
	56 days	120days	180days	28 days	56 days	90 days	180days
	FA50	1081	859	657	186	205	253
FA50LH10	1070	866	674	184	200	254	386
FA60	1310	977	689	177	182	230	233
FA60LH10	1429	1134	871	174	212	267	330

* Tests were carried out in Building Research Directory

From Fig. 7, it can be seen that the reduction of chloride penetration increases with progress of curing age as a result of pozzolanic reaction development. Moreover, for reference mixes, FA50 and FA60, increasing fly ash content caused a higher reduction in chloride penetration and that may be attributed to the more efficient combining chloride as a result of more active alumina often found in fly ash and converted it to Friedel’s salt [29, 30]. On the other hand, using 10% lime hydrated powder leads to lower reduction in chloride ions penetrability due the pozzolanic reaction.

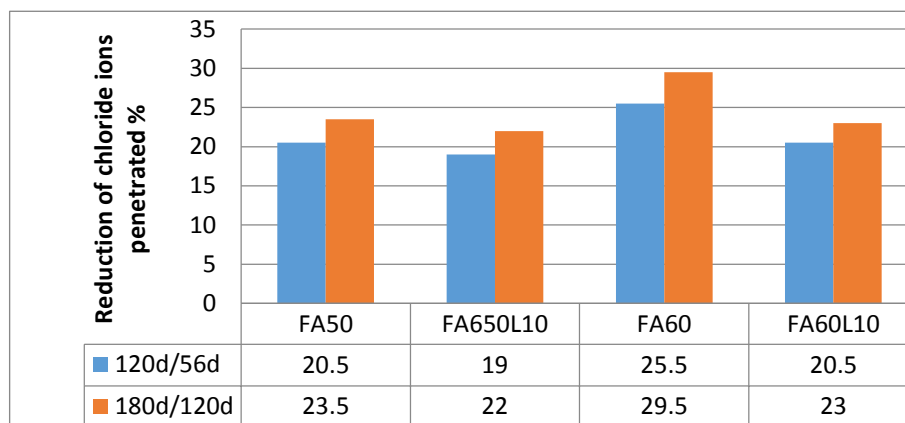


Fig.7 Effect of fly ash and hydrated lime incorporation on the percentage reduction of Cl⁻ ions penetration.

Table 6 shows that the values of AC resistance have varied from 174 to 386 Ω , and they were positively proportional to the progress of exposure time. Mix FA60 showed the lowest values of AC resistance and this is due to the lowest cement content and higher porosity. Additionally, the effect of increasing fly ash ratio showed an inversely proportioned relationship between AC resistance and penetrability of chloride ions for both reference mixes and that is in agreement with equation 4.

Figure 8 shows the AC resistance development with exposure time. The dotted lines in this figure refer to the mixes that include hydrated lime. Adopting the use of hydrated lime was useful in improving the pozzolanic reaction and then in improving the AC resistance. The gain after 180 days of exposure was 3% and 41% for mixes FA50LH10 and FA60LH10, respectively. This significant enhancement in FA60HL10 mixes over FA50 HL10 may be related to the increase in fly ash content in the former mix which leads to the increase in pozzolanic reaction rate due to incorporating hydrated lime.

IV. Free chloride and pH

Table 7 shows the test results of pH value and free chloride for studied HVFALW concrete partially submerged in 5% NaCl solution up to 180 days. From Figure 9 it can be observed that increasing fly ash ratio will reduce free chloride value because of restraining chloride ions by alumina which is available in fly ash to produce chloroaluminate. Also, using 10% of hydrated lime

will reduce free chloride due to increasing alkalinity of concrete which keeps chloroaluminate component from break down[1]. Furthermore free chloride values decrease after 120 days for all mixes as result of increasing Friedel’s salt which filled pores of concrete and reducing mobility of chlorides ions[31]

Figure 10 illustrates the pH values for the studied HVFALW concrete up to 180 days of exposure to Cl⁻ solution. The results pointed out that the pH value decrease with the increase of fly ash content along the period of exposure, and this is in agreement with the results of many researchers [32, 33]. On the other hand, using hydrated lime will lead to a clear increase in pH values which is useful for keeping chloroaluminate component from break down. Berkely et al. as reported by Kumar et al. [34] stated that the corrosion initiated when pH lower than 9.5 and passive layer distorted when pH value is lower than 8.

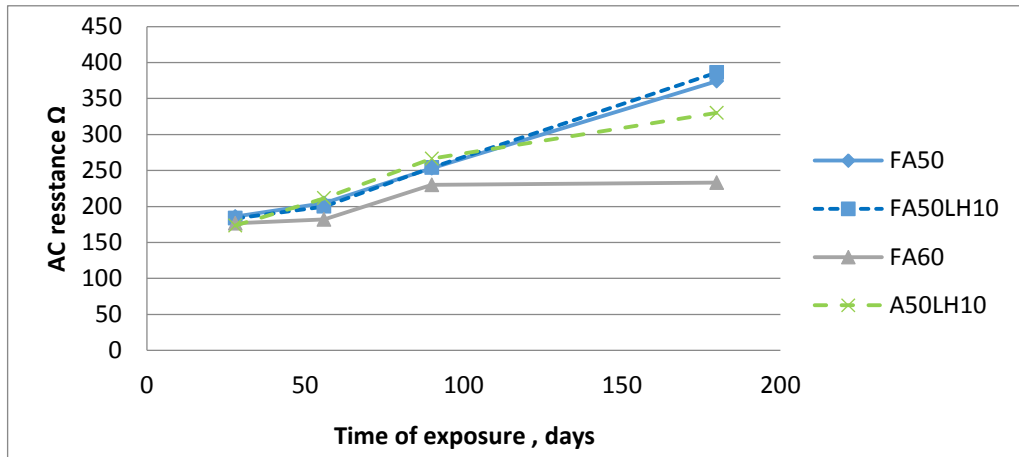


Fig. 8 AC resistance for studied HVFALW concrete up to 180 days of exposure to Cl⁻ solution

TABLE VII: Free chloride and pH values for partially submerged in 5% NaCl solution concrete*

Mix	Free chloride ions , % by weight of cement					pH values at				
	28d	56d	90d	120d	180d	28d	56d	90d	120d	180d
FA50	0.41	0.90	1.08	1.26	0.99	11.6	9.3	10.2	9.2	9.5
FA50LH10	0.35	0.76	0.73	0.71	0.60	11.8	11.5	10.2	10.8	11.1
FA60	0.34	0.87	0.85	0.82	0.79	11.3	8.9	9.6	9.1	9.2
FA60LH10	0.25	0.79	0.71	0.6	0.79	11.8	11.0	11.3	9.6	11

* Tests were carried out in building research directory.

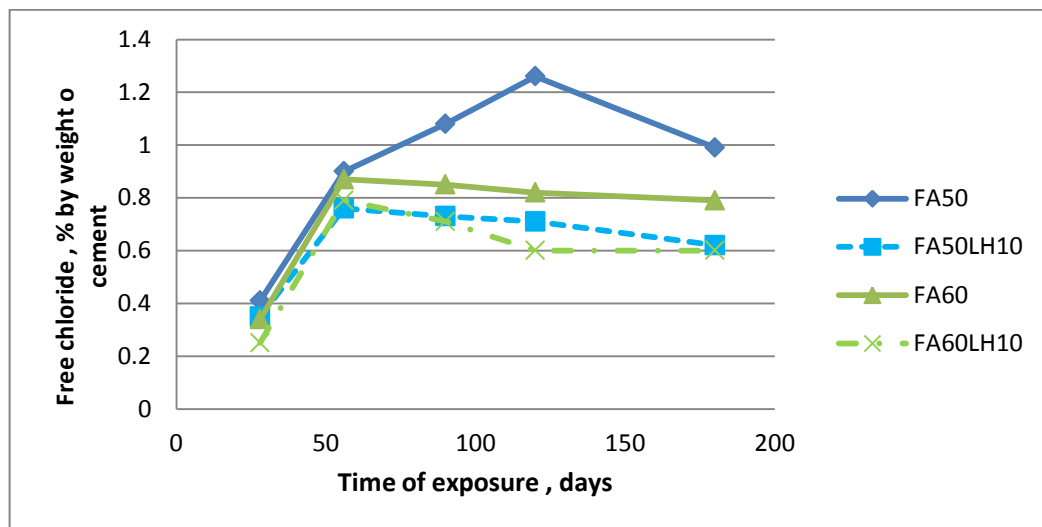


Figure 9: % of free chloride by weight of cement for studied HVFALW concrete up to 180 days of Exposure to Cl⁻ solution

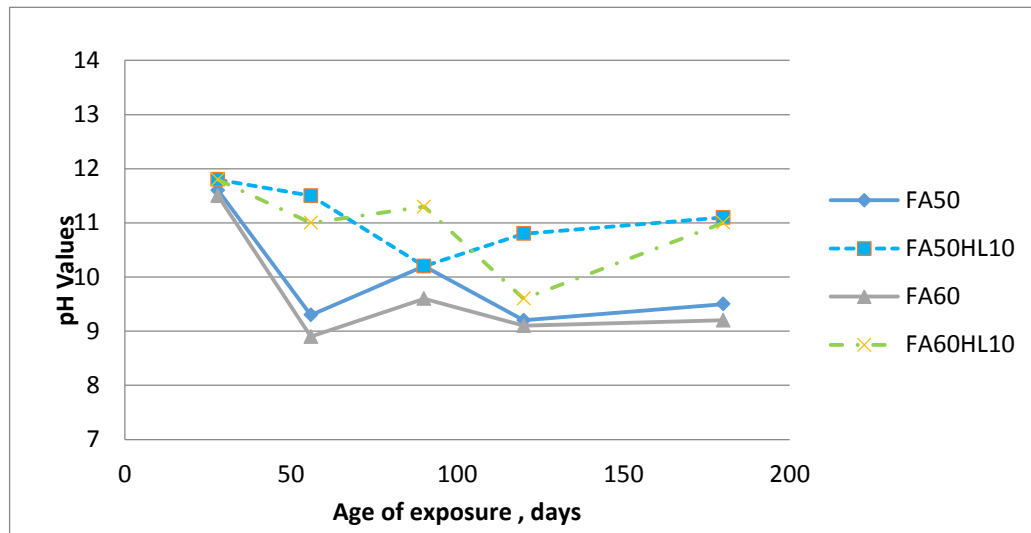


Figure. 10 pH values for studied HVFALW concrete up to 180 days of exposure to Cl⁻ solution

4. CONCLUSIONS:

Depending on the results of this study, the following conclusions can be drawn:

- 1) It is possible to produce high volume fly ash structural lightweight concrete, using 50% and 60% fly ash and Porcelanite as a lightweight aggregate. Also, its compressive strength can be improved when using 10 % of hydrated lime powder as a partial replacement by weight of cementitious materials. As well as, this concrete can be considered friendly to environment due to reducing cement consuming.
- 2) It is commonly known that the fly ash concrete demonstrates better resistance against environment of chloride. However in this investigation, 60% fly ash mix showed earlier de-passivation compared to 50% fly ash mixes.
- 3) Using 10% hydrated lime as a partial replacement by weight of cementitious materials was useful for reducing values of HCP and then enhancement resistance against chloride solution attack. This can be verified by the results of pH value which are higher in mixes of FA50LH10 and FA60LH10 compared to FA50 and FA60 mixes.
- 4) There is an inverse relationship between AC Resistance and penetrability of ion chloride for both mixes, FA50 and FA60, in each age, and that is adequate with Ohms law.
- 5) Using fly ash will reduce free chloride in concrete due to its reaction with alumina that is available in fly ash and produce chloroaluminate, and then reduce the effect of chloride ions in the corrosion process.
- 6) Free chloride percentage inversely proportion with fly ash ratio up to 60%, as well as using 10% hydrated lime powder as partial replacement by weight of cementitious material will reduce free chloride content in spite of increasing RCP. This behavior is a result of increasing alkalinity of concrete which keeps chloride ions
- 7) Restrained as chloroaluminate forms.
- 8) The values of pH inversely proportional with fly ash ratio as a result of pozzolanic reaction, while adding 10 % lime hydrated powder as a partial replacement by weight of cementitious materials lead to increasing pH values and then increasing alkalinity environment of this concrete, which improve resistance against environment of chloride.

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