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Seawater curing effects on the permeability of concrete containing fly ash

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Abstract. Due to seawater's physical and chemical deterioration effects on concrete structures, it is crucial to investigate the durability of these structures in marine environments. In some conditions, concrete structures are exposed to seawater from the first days of construction or because of the lack of potable water, part of the concrete curing stage is done with seawater. In this research, the effects of exposure to seawater after 7 days of curing in standard conditions were evaluated. To improve the durability of concrete, fly ash has been used as a substitute for a part of the cement in the mixing design. For this purpose, 5, 15, and 30% of the mixing design cement were replaced with type F fly ash, and the samples were examined after curing in seawater. The resistance of concrete against chloride ion penetration based on the rapid chloride penetration test (RCPT), water permeability based on the depth of water penetration under pressure, and water absorption test was done. The changes in the compressive strength of concrete in different curing conditions were also investigated. The results show that the curing in seawater has slightly reduced concrete resistance to chloride ion permeation. In the long-term, samples containing FA cured in seawater had up to 10% less resistance to chloride ion penetration. The amount of reduction in chloride ion penetration resistance was more for samples without FA. Whiles, for both curing conditions in the long-term up to 15%, FA improved the chloride ion penetration resistance up to 40%. Curing in seawater slightly increased the penetration depth of water under pressure in samples containing FA, while this increase was up to 12% for samples without FA. In the long-term the compressive strength of samples cured in seawater is not much different from the compressive strength of samples cured in plain water, while at the age of 28 days, due to seawater salts' accelerating effects the difference is more noticeable.

Keywords: chloride ion; concrete durability; curing, fly ash; permeability; seawater

1. Introduction

In concrete structures, much water is consumed for mixing and curing concrete. Optimal water allocation and protection of potable water resources are crucial issues in sustainable development. In developing communities where concrete usage is increasing, supplying adequate water soon can become a critical challenge, so finding a way to use non-potable water resources for concrete construction in these communities is inevitable. In coastal areas, in addition to the shortage of fresh water, the use of seawater for construction can have many economic benefits (Alaejos and Bermúdez 2011, Xiao *et al*. 2017).

Concrete curing is one of the most critical steps in concrete construction, which should be considered to ensure cement hydration and achieve the characteristic strength of concrete and achieve sufficient durability to deal with the aggressive environment's effects (Zhao *et al*. 2015). Curing is a condition to control the temperature and humidity of the concrete to reach the desired specifications. A proper curing condition, making concrete more impermeable and resistant to aggressive agents. The cement hydration is rapid at an early age and continues to improve over the concrete lifetime; therefore, adequate ambient conditions of relative humidity and temperature on the first days of casting the concrete are very important (Zeyad *et al*. 2022). Curing is usually done with water and sometimes with steam; therefore, water quality can affect the final concrete properties. The most critical problem that challenges seawater's use for the construction or curing of reinforced concrete is the high concentration of chloride ions, which eventually causes corrosion of the steel reinforcement. In addition to reinforcement corrosion, the presence of sulfate ions, especially magnesium sulfate and potassium sulfate, in seawater can expose the concrete to sulfate attack and crystallization (Wegian 2010). In marine environments, even for concrete made of plain water, corrosion of reinforcement due to the penetration of chloride ions is one of the most important reasons for early deterioration and durability failure of concrete structures (Tadayon *et al*. 2016, Zhang *et al*. 2018).

There are many conflicting opinions about using seawater as mixing or curing water. The researchers have reported the differences in the results to include both the properties of fresh and hardened concrete; for example, some previous results have reported the reduction in workability and setting time of seawater concrete, while others have reported increased workability and setting time (Etxeberria *et al*. 2016b, Younis *et al*. 2018). Chen *et al*. (2021) reported an enhanced effect of seawater on the early strength development of sea sand concrete. Nishida *et al*. (2013) concluded that until 2013, for concretes made of ordinary cement, most of the results indicate the destructive

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effects of seawater on concrete properties. However, by changing the composition of concrete and using materials such as FA, the results favored seawater as mixing water. Design codes and standards also take a different approach to seawater use in the construction of concrete structures. ACI does not recommend the use of seawater for curing (ACI308R-16 2016, Eglinton 2003).

In addition to causing rebar corrosion, the long-term effects of chloride ions on concrete have also been reported in the form of reduced compressive strength (Kaushik and Islam 1995, Mohammed *et al*. 2004). Guo *et al*. (2018) Reported that the strength of concrete specimens made with fresh water and cured with seawater is reduced by around 7% and for samples made and cured with seawater, this reduction has been reported up to 15%. Shayan *et al*. (2010) reported that reducing w/c can reduce the detrimental effects of curing with seawater on the long-term strength of concrete. Wegian (2010) Reported that the type of cement has a significant effect on the compressive strength of concrete made and cured in seawater. They also found that in the early ages of 7 and 14 days, concrete mixed and cured in seawater has higher compressive, flexural and tensile strengths than the control samples which made and cured in plain water. Construction and curing of concrete in marine environments and strength can also affect the permeability of concrete. Alaejos and Bermudez (2011) showed that the permeability of concrete cured in seawater initially high and became similar to the samples cured in plain water over time.

The use of pozzolans such as FA as supplementary cementitious material (SCM) has long been considered as an alternative to cement (Celik *et al*. 2015, Sahmaran and Li 2009, Hosseini and Bagheri 2022). The most important reasons for using these materials are to reduce the environmental impact of cement production and improve some of the concrete properties (Khan and Ali 2019, Teixeira *et al*. 2019). The use of pozzolans can improve concrete permeability, especially against ions (Badogiannis *et al*. 2015, Cheng *et al*. 2018, Duan *et al*. 2013). By improving the permeability of concrete, especially in marine and aggressive environments, concrete properties can be improved to be more resistant to chloride ingress (Chousidis *et al*. 2016). Concrete permeability is directly related to the durability of concrete, so that by finding ways to reduce permeability, the concrete durability can be enhanced. FA usually reduces the corrosion rate of reinforcement in concrete and has high long-term strength; Therefore, by replacing some cement of mixing design with FA, especially in the marine environment, the proper performance of concrete can be expected (Assas 2012, Chousidis *et al*. 2015, Sinsiri *et al*. 2010). The increase in strength and durability of FA-containing concrete is related to its reaction during cement hydration with calcium hydroxide ($CaCO_3$) and the production of calcium aluminate hydrate (CAH) and calcium silicate hydrate (CSH) (Malvar and Lenke 2006, Shaikh and Supit 2014).

Based on the literature mentioned above survey, further research is recommended to investigate the effect of curing with seawater on the concrete containing FA. In this field, especially the effect of the amount of FA on the durability-related properties of concrete need more works and experiments. Construction near the coastal area can be considered as an opportunity to supply part of the project's water needs. As shown in Fig. 1, Iran's entire southern border is connected to the Sea of Oman and the Persian Gulf. According to rainfall statistics, the southern part of Iran, shown on the map, has an average long-term rainfall of less than 100 mm per year, which cannot meet the needs of drinking water, agriculture, and industry. Location of some critical industries and essential ports in the south of Iran and the need to develop construction; Concrete structures have increased the need for water for construction. In this study, to reduce potable water in marine environments, seawater has been used for curing. To consider the possible positive effects of FA to eliminate the detrimental effects of seawater, different percentages of cement have been replaced with FA. In fact, in this study, the possibility of the impact of two environmental issues is examined; the replacing part of the mixed design cement with FA, which can reduce the emission of greenhouse gases, and the possibility of using seawater, which will reduce the consumption of drinking water in concrete construction. Compressive strength, water absorption, and chloride ion permeation tests have been used to evaluate different mixing design scenarios at different ages. In this research, specimens were exposed to the seawater after 7 days of standard curing condition.

Fig. 1 Location of areas with less than 100 mm annual rainfall in southern Iran

2. Materials and methods

2.1 Material properties

The ASTM Type II Portland cement (ASTM C150 2017) and a Class F fly ash (low-calcium) were used as cementitious materials. Some of the main physical and mechanical characteristics and chemical composition of cement and FA are presented in Table 1. based on the laboratory test results, the density of cement and fly ash was 3150 kg/m^3 and 2150 kg/m^3 respectively (ASTM C188-17 2017, ASTM C311/C311M-22 2022). Based on the ASTM C204-18 (2018) the Blaine of cement and fly ash was 310 m^2/kg and 440 m^2/kg respectively. The chemical compositions of cement and fly ash obtained from XRF

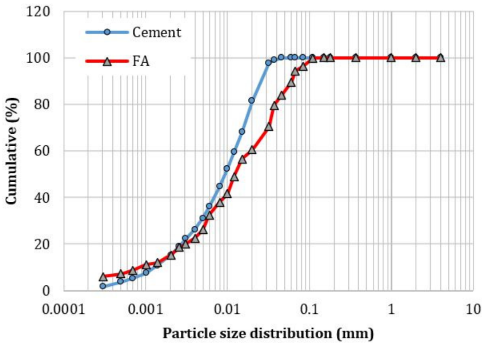


Fig. 2 Particle size distribution of binders

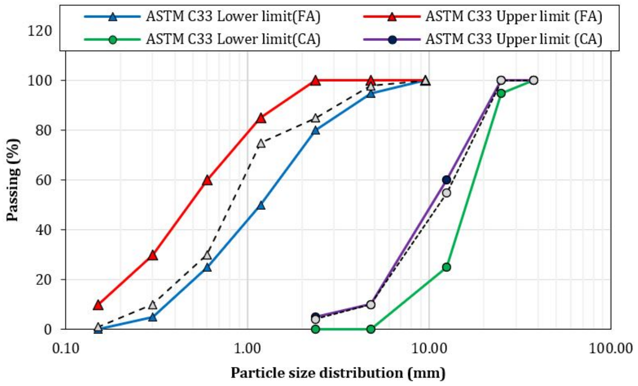


Fig. 3 Particle size distribution of aggregates

analysis and presented in Table 1. From Table 1, it is found that the total sum of Al_2O, SiO_2, and Fe_2O_3 content of fly ash was 90.4% (higher than 70%), and the CaO content was 3.5% (less than 8%). These values revealed that the fly ash is classified as Type F according to the ASTM C618 (2017b).

The particle size distributions of the cementitious materials presented in Fig. 2. Seawater with the chemical composition shown in Table 2 was used for curing some concrete samples. The seawater was taken from Bushehr coastal area in south of Iran. Despite that the pH value of the seawater which was comparable with the potable water (7-8), the salinity and the total dissolved solids (TDS) of this water were relatively high.

The crushed dolomitic limestone with a maximum size of 20 mm was used as coarse aggregate. The specific gravity of coarse aggregates and their water absorption were measured to be 2.73 and 1.23%, respectively. These quantities meet the requirements of the BS EN 1097-6 (2013). The fine aggregate from the local river with a maximum size of 5 mm and fineness modulus of 2.42 was used in mixed designs. The grading and quality of fine and coarse aggregate satisfied ASTM C33/C33M (2018) requirements, and the mixing water quality satisfied ASTM C1602 / C1602M (2018). Fig. 3 shows the particle size distribution of aggregates.

2.2 Preparation of test specimens

The concrete mix design followed the ACI procedure, and a water-binder ratio (w/b) of 0.4 was taken. FA was used to replace cement at 5, 15%, and 30% by weight. Table 3 shows the mixture proportions and replacement levels of FA. Based on the slump test, the workability of all mixes was held within a range of 100 ± 25 mm. For this purpose, the required amount of a Polycarboxylic ether-based superplasticizer which complies with ASTM C494/C494 (2019) was used. 150 mm cube molds were covered soon after casting to retain moisture. The concrete specimens

Table 1 Chemical and physical properties of binders

	Chemical composition (%)								Physical properties	
	CaO	SO_3	Al_2O_3	MgO	SiO_2	Fe_2O_3	Na_2O	K_2O	Density (kg/m^3)	Blaine (m^2/kg)
Cement	63.2	1.5	4.1	2.6	22.6	3.5	0.2	0.5	3050	310
FA	3.5	1.4	27.4	1.8	54.5	8.4	0.2	0.6	2150	440

Table 2 Chemical and physical properties of Persian Gulf water (mg/L)

Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)	Na^+ (mg/L)	Cl^- (mg/L)	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	TDS	pH
420	1490	430	14300	25500	140	2600	44930	8.2

Table 3 Concrete mix design per 1 m^3

Specimens	w/c	w/b	Water (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	FA (%)	Fine aggregates (kg/m^3)	Coarse aggregate (kg/m^3)
FA05	0.42	0.4	140	332.5	17.5	5	610	1180
FA15	0.47	0.4	140	297.5	52.5	15	610	1180
FA30	0.57	0.4	140	245	105	30	610	1180
CONT	0.4	0.4	140	350	-	-	610	1180

(a) Specimens under vacuum conditions

(b) RCPT cell

Fig. 4 The rapid chloride penetration test

Table 4 Chemical and physical properties of Persian Gulf water

Specimens	Tap water curing			Seawater curing	
	7 day	28 day	90 day	28 day	90 day
FA05	2490	1650	1420	2010	1510
FA15	2644	1550	1174	1960	1215
FA30	2907	2205	1906	2630	2090
Control	2425	2082	1765	2480	1985

demolded after 24 h. Curing by plain-water was done for 7, 28, and 90 days in a water tank, with a controlled temperature of 25±2 C. After 7 days of curing by plan-water, a series of specimens immersed in a tank containing seawater until the testing time at 28 and 90 days. For each test at each time, three specimens were cast and the average value of these specimens was reported as test results.

3. Test results and discussion

3.1 The rapid chloride permeability test

The rapid chloride penetration test based on ASTM C1202 (2019) was used to assess the resistance to chloride ion penetration at ages 7, 28, and 90 days. As shown in Fig. 4(a), the samples cored from the specimens were saturated with deaerated water under vacuum conditions at the desired age. Next, the samples were placed in the RCPT cell according to Fig. 4(b) and subject to a potential difference of 60 volts. After 6 hours the total charge passed through the samples in Columbus is taken as the test result.

Table 4 shows the RCPT test results. Fig. 5 shows the values obtained from the test and the ASTM C1202 (2019) limits for concrete classification in terms of chloride ion resistance. At the age of 7 days, with increasing FA, the total charge passed through the samples increased, although this increase is negligible for the FA05. The increase in permeability at this age for samples containing FA can be attributed to the dilution effect of FA and the delay in the start of pozzolanic reactions. After 28 days of curing, it can be seen that with the activation and promotion of pozzolanic reactions in FA, chloride ion permeability decreases for samples containing 5 and 15% FA. For standard curing conditions at this age, the total charge passed through the FA05 and FA15 compared to the control sample is equal to 0.79 and 0.74, respectively. As the specimens' age increases to 90 days, it is observed that the permeability of all specimens has decreased. At this age, as seen in the 28-day trend, increasing the FA up to 15% had a positive effect on concrete resistance against chloride ingress.

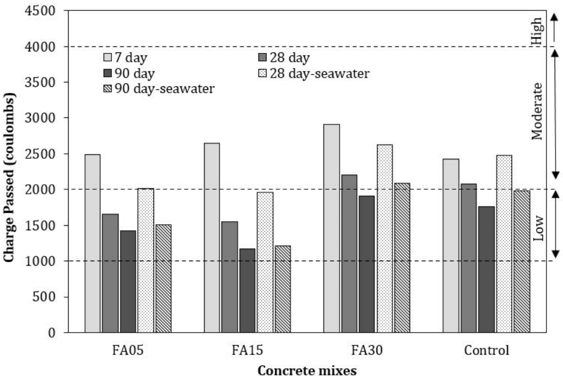


Fig. 5 Comparison of RCPT results with ASTM C1202 limits

Although there is almost agreement on the positive effects of FA on improving concrete permeability, there are different opinions about the maximum amount of FA in concrete. Assas (2012) reported that the concrete containing 20 % FA has slightly lower chloride diffusivity than the equivalent bare cement concrete, and the long-term effect of FA was more significant. Uysal and Akyuncu (2012) reported a sharp decline in the flow rate for specimens with 10 and 17 percent FA. Making dense concrete with a discontinued pore system can enhance the concrete resistance against chloride ingress. The pozzolanic reactions tend to be capable of forming a discontinuous pore structure.

The seawater cured specimens at 28 and 90 days have a higher total charge passed than samples cured in-plane water. At 28 days, the amount of increase in flux with changing curing condition conditions for FA05, FA15, and FA30 were 360, 410, and 425 coulombs, respectively, indicating an increase in the difference in flux with the increasing percentage of FA. By replacing 5% and 15% of cement with FA, it is observed that the total charge for

Table 5 Water penetration depth (mm)

Specimens	Tap water curing			Seawater curing	
	7 day	28 day	90 day	28 day	90 day
FA05	36.7	31.5	27.0	32.5	28.5
FA15	40.5	35.7	25.3	35.9	26.4
FA30	47.3	39.5	31.7	40.3	33.6
Control	36.5	32.5	30.9	35.2	34.7

samples cured in seawater has decreased from 2480 Columbus to 2010 and 1960 coulombs that shows the positive effect of replacing up to 15% of FA in resistance to chloride ion penetration.

With increasing the samples' age to 90 days, the total charge difference between the seawater cured samples and plane water decreases. As presented in Table 4, the total charge for FA05, FA15, and FA30 is 90, 41, and 184 coulombs. These values were obtained at 28 days equal to 360, 410, and 425 coulombs, respectively.

It is clear from Fig. 5 that the addition of 5% and 15% FA at the age of 28 days has changed the classification of concrete from medium permeability to low permeability. This change occurred in both curing conditions.

Montanari *et al*. (2019) By replacing 20% of cement with FA and making samples with seawater and reported an accelerating effect of seawater on hydration kinetics; this effect is negligible in 7 days. Alaejos and Bermudez (2011) reported high chloride ion permeability of seawater curing samples, as in the short-term, the microstructure of concrete is not dense enough to prevent the chloride ingress. For marine conditions, Mackechnie (1995) Reported better resistance to chloride ions in samples containing FA than conventional cement.

By replacing 30% of cement with FA, unlike FA05 and FA15, it is observed that the permeability is slightly increased. The increase was 6% and 8% for 28 and 90 days of age for plane-water curing and 6% and 5% for seawater curing, respectively. There is disagreement about the effects of large amounts of FA on the chloride permeability of concrete. Dhir *et al*. (1997) reported up to 50% reduction and McCarthy and Dhir (2005) up to 45% reduction in permeability, while Shaikh and Supit (2014) reported up to 22% increment in permeability for 40% FA replacement. In general, the reduction of permeability can be achieved by adding up to 15% of FA for marine environmental conditions based on the results.

3.2 Water penetrability

The water penetration depth into the concrete determines many of the durability-related properties of concrete. In this research, water penetration depth was performed in two ways: the water penetration depth under pressure according to BSEN 12390-8 (2019) and the other half-hour water absorption depth according to BS 1881-122 (2019) standard.

3.2.1 Water penetration depth under pressure

In the water penetration depth test according to BS EN 12390-8 (2019), at the desired age, the samples were air-dried after removing from the curing conditions. As shown in Fig. 6, the specimens were placed in the test apparatus, and one side of the specimen was exposed to a constant water pressure of 500 + 5 KPa for 72 hours. After the test, the samples were split, and the water penetration in millimeters is assessed using a caliper. The water penetration depth obtained from the experiment is shown in Table 5. Figs. 7 and 8 show the effect of changing curing conditions on the water penetration depth at 28 and 90 days.

(a) Specimens under pressure

(b) Measuring the depth of penetration by caliper

Fig. 6 water penetration test setup

It is clear from the test results that at the age of 7 days, replacement of FA with cement due to the lack of initiation of pozzolanic reactions had a detrimental effect on the concrete resistance to water penetration. With increasing the

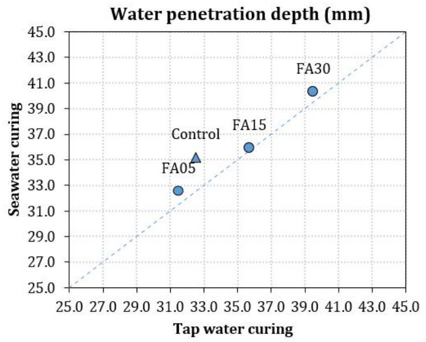


Fig. 7 Water penetration depth of specimens for tap water and seawater curing condition at 28 days

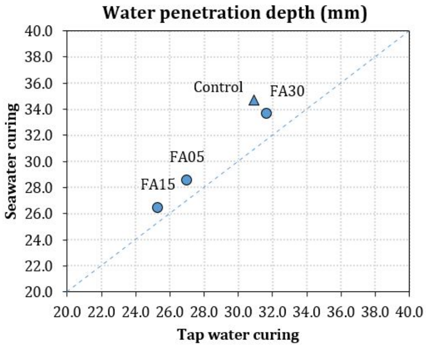


Fig. 8 Water penetration depth of specimens for tap water and seawater curing condition at 90 days

specimens' age to 28 days, except for the FA05, the depth of water penetration of specimens containing FA was still higher than the control specimen. At this age, the depth of water penetration into the specimens cured in seawater was more than those cured in plain water. In the control sample, the penetration depth increased by 3 mm by changing the curing condition to seawater, but for FA05, FA15 and FA30, this increase was equal to 1, 0.2, and 0.8 mm, respectively, which indicates the lower impact of seawater curing on the samples containing FA at 90 days, all specimens containing FA cured in the seawater had lower permeability than the control sample. Only samples containing 5% and 15% FA had lower permeability for specimens cured under standard conditions than the control sample. At this age, like 28 days, curing in seawater has increased the samples' permeability, although this effect was less for samples containing FA.

Curing in seawater has generally increased the permeability of concrete samples so that the water penetration depth compared to the control sample for FA05 and FA15 samples were 0.82 and 0.76, respectively. Generally, for both curing conditions, replacement of up to 15% cement with FA, in the long term, has improved the resistance of concrete against water penetration. Improvement of the pore size distribution and pore shape of concrete, the formation of more CSH was reported as the main reasons for the enhanced resistance to water penetration due to FA (Schwarz *et al.* 2008, Assas 2012).

3.2.2 Water penetration depth under pressure

This test is performed to evaluate the porosity of concrete and the penetrability of its surface pore system. This test is indirect way to evaluate concrete water permeability and could be used as an indicator for resisting aggressive agents (Amin *et al.* 2021). To perform this test according to BS 1881-122 (2019), first, a 75 mm diameter core was removed from a cube sample, then its height was reached to 75 mm with a cutter. The samples were placed in the oven at 105° C for 72 hours, then cooled in a desiccator so that the core does not absorb ambient moisture during cooling. After drying, the sample was immersed in distilled water for half an hour, and after drying the surface, its weight was measured. The difference between the weights of the saturated dry surface sample with the dry sample is the amount of water absorption, which after dividing by the dry weight of the sample, the percentage of water absorption was determined. The results of this experiment in terms of water absorption percentages are given in Table 6. Fig. 9 shows the water absorption compared to the control sample cured in plain water at different ages.

The results show that at the age of 7 days, compared to the water penetration test under pressure, the percentage of water absorption in FA-containing samples is lower than the control sample. At the early age for tap water cured samples, the lowest water absorption of 2.09% was found for the concrete mixture of FA15 and the maximum of 2.51% was found for control sample. Although most researchers have reported higher water absorption at this age for samples containing FA due to delayed initiation of pozzolanic reactions, this reduction may be due to the filler effect of FA particles in the concrete. The mixture of FA 15 at 28 and 90 days had lowest water absorption like age 7 days. As reported in Table 6, the maximum value of water absorption was for the mixture of FA30 at ages 28 days and 90 days.

Table 6 Water absorption (%)

Specimens	Tap water curing			Seawater curing	
	7 day	28 day	90 day	28 day	90 day
FA05	2.41	1.85	1.14	1.93	1.17
FA15	2.09	1.78	1.05	1.81	1.07
FA30	2.38	2.17	1.83	2.14	1.84
Control	2.51	1.99	1.75	2.03	1.86

For concrete specimens that were cured in seawater at the ages of 28 and 90 days, it is observed that the percentage of water absorption has increased slightly compared to samples cured in standard conditions. The amount of this increase was higher for the control sample than the specimens containing FA. It is clear from Table 6 that by changing the curing condition for the control sample, a 0.04% and 0.14% increase was happened in water absorption at the age of 28 days and 90 days, respectively. The water absorption of samples containing FA by changing the curing condition at the age of 90 days was between 0.01 to 0.03. In practice, seawater curing has fewer long-term effects in terms of water absorption on FA-containing concrete.

As shown in Fig. 9, the percentage of water absorption for the sample with 30% FA at all ages except 7 days for each curing condition was higher than the control sample. The results also show that in specimens containing 5 and 15% FA for each curing condition, a decrease in water absorption than the control sample occurred; This decrease was more remarkable in FA15 than in FA05.

Uysal and Akyuncu (2012) reported a reduction in water absorption for samples containing up to 17% FA with the same compressive strength. Joseph and Ramamurthy (2009) concluded that at 28 days of age, replacing cement with any amount of FA due to the slower pozzolanic reaction of mixes with FA increases water absorption, but at 90 days of age, there is no difference between the control sample and samples containing up to 30% FA, but for 50% replacement, water absorption increases.

The water permeability of concrete as one of the concrete durability properties is influenced by the concrete's microstructures (Jalal *et al.* 2013). The micro-

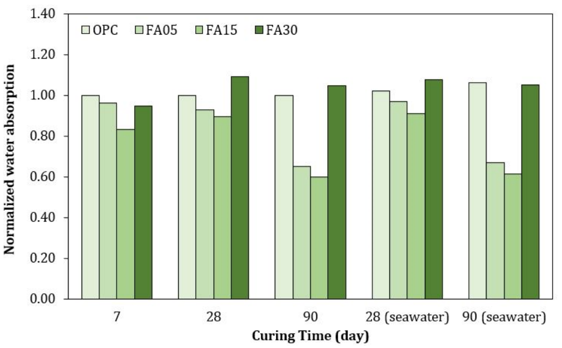
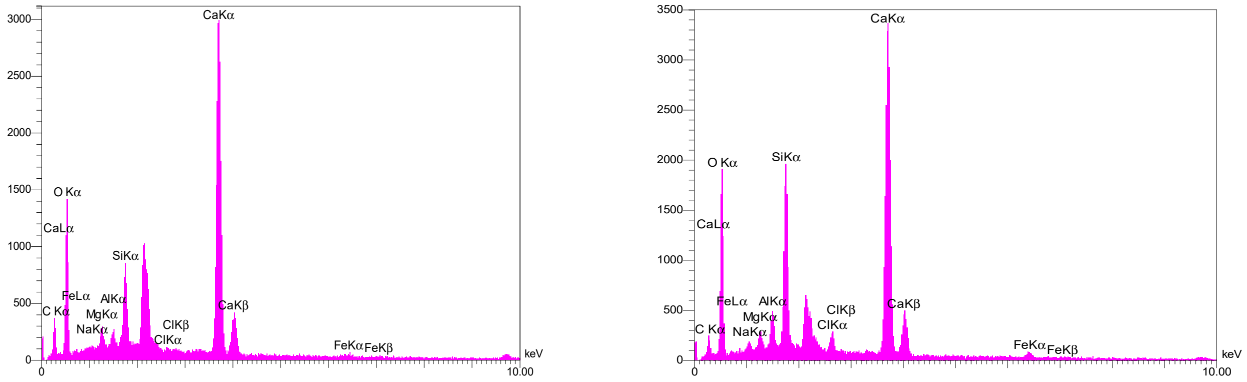


Fig. 9 Influence of FA content on water absorption



(a) FA05 (b) FA15

Fig. 10 EDS analysis of seawater cured specimens at age 90 days

Table 7 Compressive strength (MPa)

Specimens	Tap water curing			Seawater curing	
	7 day	28 day	90 day	28 day	90 day
FA05	26.6	37.8	44.8	41.5	45.8
FA15	25.4	39.0	46.7	44.2	48.8
FA30	17.9	33.4	41.4	35.2	41.2
Control	27.1	35.2	42.0	41.3	41.9

structures of the concrete investigated by energy-dispersive X-ray spectroscopy (Nogueira and Leonel 2013). Fig. 10 shows the EDS analysis results of FA05 and FA15 cured in seawater at age 90 days. It can be seen from Fig. 10 that the intensity of Si (CSH) increased as the percentage of FA increased from 5% to 15%. From this Fig, it is also evident that the chloride contamination of specimens is relatively high for seawater cured specimens.

3.3. Compressive strength

The results of the compressive strength test are shown in Table 7. The compressive strength ratio of the specimens to the control sample is shown in Fig. 11. For samples cured in plain water at 7 days of age, the compressive strength of the sample containing FA is lower than that of the control sample due to the delay in pozzolanic reactions. In FA30, due to dilution of cement, the amount of reduction in compressive strength at the age of 7 days was more than the other samples, so that its strength ratio reached 55% of the control sample. Most research has shown a reduction in concrete compressive strength containing FA in the short term (Nili and Salehi 2011). It is clear from the results that, in general, curing in seawater at the ages of 28 and 90 days has increased the compressive strength of all specimens.

For all curing conditions, the replacement of 5% and 15% cement with FA improved the samples' compressive strength at 28 and 90 days of age. As shown in Table 7 and Fig. 11, by increasing the FA value by 15%, all samples' compressive strength has increased. For seawater cured specimens, the compressive strength increased from 41.3 MPa at 28 days to 41.9 MPa at 90 days, which this increment was minimal compared to samples containing FA. The compressive strength of FA05, FA15, and FA30 samples increased by 4.3, 4.6, and 6 MPa at 90 days compared to 28 days, respectively. As the results show, at the age of 90 days, the compressive strength of samples cured in seawater is not much different from the compressive strength of samples cured in plain water, while at the age of 28 days, the difference is more noticeable; this is due to seawater salts' accelerating effects, which further increases compressive strength at 28 days of age (Cheng *et al.* 2018, Li *et al.* 2015). More considerable differences in short-term compressive strength have also been reported in some researchers' research (Etxeberria *et al.* 2016a, Sikora *et al.* 2019). Younis *et al.* (2018) reported a slight increase in compressive strength of up to 5% due to the effect of seawater.

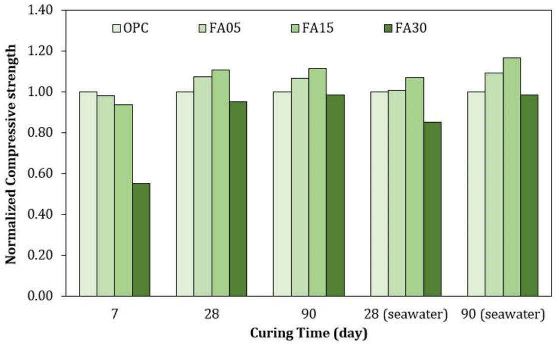


Fig. 11 Influence of FA content on compressive strength of concrete

For all samples containing FA, it can be seen that long-term curing in seawater caused a slight increase in compressive strength compared to the sample cured in fresh water. This effect can be attributed to the accelerating properties of environmental conditions in cement hydration. However, some researchers have reported lower short-term strength and attributed it to form a thin layer of minerals and a lack of adequate water supply to continue hydration.

4. Conclusions

In this paper, the effect of curing in seawater for various concrete mixtures containing FA was studied, and the main focuses were on the permeability of this kind of concrete. The following conclusions can be drawn:

- In the short-term curing conditions, with increasing the amount of FA to 30%, it was observed that the total charge passed in the RCPT increased by 20%, and the depth of water penetration under pressure increased by 30%. This negative effect on permeability can be attributed to the delay in the onset of pozzolanic reactions and FA's dilution effect in concrete at this age. Contrary to the above two parameters, at this age, the amount of water absorption in concrete has decreased by 5%, which can be attributed to the filler effect of FA and the hydration accelerating effect of salts of seawater.
- Curing in seawater has slightly reduced concrete resistance to chloride ion permeation. In the long-term, samples containing FA cured in seawater had up to 10% less resistance to chloride ion penetration. The amount of reduction in chloride ion penetration resistance was more significant for samples without FA.
- In the long-term curing conditions, up to 15% FA has improved the resistance to chloride ion penetration by 40%. Replacement of 30% cement with FA in seawater curing conditions did not have a detrimental effect on chloride ion resistance.
- Curing conditions in seawater slightly increased the penetration depth of water under pressure in samples containing FA, while this increase was up to 12% for samples without FA. Compared to the control sample cured in seawater, all samples containing FA have a higher resistance to water penetration in this condition. Therefore, in general, FA in marine conditions, especially up to 15%, reduces curing conditions.
- In the long-term the compressive strength of samples cured in seawater is not much different from the compressive strength of samples cured in plain water, while at the age of 28 days, due to seawater salts' accelerating effects the difference is more noticeable.
- Based on the durability-related properties and compressive strength of the seawater cured specimens, the 15% replacement of cement with fly ash was suggested for the marine environmental conditions in south Iran.
- The rate of cement hydration is high during the first days of the casting and a good curing process during this short period can improve the performance of concrete, so it is possible to use methods such as steam during at the first days before the concrete is exposed to the aggressive environment for accelerating the hydration. As a suggestion for future research, samples can be subjected to accelerated curing like steam curing in the initial days and then exposed to seawater. The effect of different curing scenarios on the properties of the concrete which exposed to the seawater can be investigated.

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