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Sustainability and Durability of Concrete Structures in Corrosive Environmental Conditions

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ABSTRACT

Corrosion of steel bar reinforcement in cement mortars is the most important cause of destruction of concrete structures exposed to chloride ions in marine environments. Concrete mix design is one of the factors that can affect the chloride penetration into concrete and consequently the durability of concrete structures. This paper analyzed the effective parameters on the electrical resistivity of concrete in order to achieve sustainable and durable concrete mix design and consequently preventing of the reinforced concrete structures corrosion. This study evaluated various water/cement ratios from 0.3 to 0.5, Portland cement contents, silica fume ratio from 0.0 to 19% and different types of aggregate batching according to ASTM. The results showed that the water/cement ratio must not exceed 0.5, it was found that replacement of silica fume caused a significant increase in ERC, and also the type of aggregate size is an important factor to prevent permeability. Finally, this study found a sustainable concrete mix design which has the highest resistance to permeability.

INTRODUCTION

Steel bar reinforcement corrosion is the most important and the most common degradation mechanisms of concrete structures in marine environment. Steel corrosion in concrete is the major problem of different countries around the world. These problems in developing countries especially countries around the Persian Gulf are more important [Ghoddusi et al. 1998]. Corrosion process has a nature of electrochemical in concrete [Davison et al. 2008]. Corrosion in reinforcing areas occurs due to the flow of electrons between the cathode and anode [Daily]. In 1989 results of a study showed the corrosion of steel reinforced concrete has a close relation to the hydration process which is the result of chloride ion's penetration [Kraj et al.1989]. It is well known that pozzolanic materials deplete charge carriers in concrete and thus reduce conductivity [Claisse et al.2010]. Concrete mix design is one of the factors that can affect the chloride penetration into concrete and consequently the durability of concrete structures. Electrical resistivity of concrete is an index to determine permeability of chloride ions into concrete structures. This study analyzed the effective parameters on the electrical resistivity of concrete in order to achieve the highest resistance of concrete against penetration of chloride ions.

EXPERIMENTAL PROCEDURE

Mixture Properties

Portland cement type I and Silica fume (S.F) which are shown in Table 1 were used as cement paste. Crushed sand was used as a fine aggregate (F.A) as well as coarse aggregate (C.A). Also, super plasticizer based on poly carboxylic ether was used. In this study different type of aggregate sizes include A, B, C, D and E were used. The proportions of each type are tabulated in Table 2 to 6.

Table 1. Chemical Composition of Portland Cement and Silica Fume used in Concrete Specimens

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	L.O.I
Portland cement Type I	19.8%	5.88%	3.61%	62.85%	3.64%	2.13%	-	-	0.74
Silica fume	90	1.5	1.5	-	2	0.08	-	-	0.9

Table 2. Aggregate Size of A with Maximum Size of 2.36 mm

Mass remaining (%)	Remained (%)	Passed (%)	Sieve Size (mm)	Sieve Grade
0	0	100	2.36	8
40	40	60	1.18	16
70	30	30	0.6	30
90	20	10	0.3	50
98	8	2	0.15	100
	2			Remained
2.88		Softness modulus		

Table 3. Aggregate Size of B with Maximum Size of 4.75 mm

Mass remaining (%)	Remained (%)	Passed (%)	Sieve Size (mm)	Sieve Grade
0	0	100	4.75	4
20	20	80	2.36	8
50	30	50	1.18	16
75	25	25	0.6	30
90	15	10	0.3	50
9	8	2	0.15	100
	2			Remained
3.33	Softness modulus			

Table 4. Aggregate Size of C for Fine Aggregate According to [ASTM-C33]

Mass remaining (%)	Remained (%)	Passed (%)	Sieve Size (mm)	Sieve Grade
0	0	100	4.75	4
10	40	80	2.36	8
30	20	70	1.18	16
65	35	35	0.6	30
75	10	25	0.3	50
95	20	5	0.15	100
	5			Remained
2.75		Softness modulus		

Table 5. Aggregate Size of D for Coarse Aggregate with the Maximum Size of 19.05 mm

Remained (%)	Passed (%)	Sieve Size (mm)	Sieve Grade
0	100	19.05	
50	50	9.52	
43	7	4.75	4
7	0	2.36	8
0	0	1.18	16

Table 6. Aggregate Size of E for Coarse Aggregate with the Maximum Size of 9.52 mm

Remained (%)	Passed (%)	Sieve Size (mm)	Sieve Grade
0	100	9.52	
75	25	4.75	4
18	7	2.36	8
7	0	1.18	16
0	0	0.6	30

Effective Parameters on Concrete Corrosion

This study analyzed the effective parameters on the electrical resistivity of concrete in order to achieve sustainable and durable concrete mix design and consequently preventing the corrosion of reinforced concrete structures. This study evaluated various water/cement ratio from 0.3 to 0.5, Portland cement contents, silica fume ratios from 0.0 to 19% and different types of aggregate size according to ASTM. In follow 4 effective analyzed parameters are categorized. Also, the detailed information regarding mixture proportion and properties of fresh concrete for 4 Groups of I, II, III and IV are shown in Tables; 6 to 9.

I - Water-Cement Ratio (w/c)

One of the results of having less water to cement ratio is reducing the water's absorption of concrete. Since the water's absorption of the concrete becomes less, the penetration of chloride ion and other corrosive agents into the concrete decreases and has a direct impact on the electrical resistivity of concrete. According to the existing standards, different water - cement ratios in this part of the study has been evaluated. These specimens after 24 hours were opened from the molds and put in water pool with a temperature of 22 degrees C. After 28 days, the electrical resistivity and compressive strength of concrete specimens were tested. Table 6 shows the mixture proportions and properties of fresh concrete for group I.

Table 6. Mixture Proportion and Properties of Fresh Concrete for Group I

ID	W (kg/m3)	Cement (kg/m3)	S.F(kg/m3)	(W+S.P)/(C+S.F)	F.A (kg/m3)	C.A (kg/m3)	S.P (kg/m3)	D(max) (mm)	Aggregates	Z (kohm)	*E.R (kohm.cm)*	F.C (N/mm2)	C+S.F (kg/m3)	100*S.F/(C+S.F)
1	129	405	45	0.3	965	850	6	9.5	D+C	11.7	58.5	84.5	450	10
2	147	405	45	0.34	947	850	6	9.5	D+C	8.5	42.5	79.6	450	10
3	165	405	45	0.38	929	850	6	9.5	D+C	5	25	69.1	450	10
4	183	405	45	0.42	911	850	6	9.5	D+C	3.8	19	61.6	450	10
5	201	405	45	0.46	893	850	6	9.5	D+C	2.9	14.5	58	450	10
6	219	405	45	0.5	875	850	6	9.5	D+C	2.4	12	49.6	450	10

II - Cement Ratio

Any changes in the relative volume of cement paste, would affect electrical resistivity of concrete. Therefore in this part of the research different cement ratios have been evaluated and compared. These specimens after 24 hours were opened from the molds and put in water pool with a temperature of 22 degrees C. After 28 days, the electrical resistivity and compressive strength of concrete specimens were tested. Table 7 shows the mixture proportions and properties of fresh concrete for group II.

Table 7. Mixture Proportion and Properties of Fresh Concrete for Group II

ID	W (kg/m3)	Cement (kg/m3)	S.F(kg/m3)	(W+S.P)/(C+S.F)	F.A (kg/m3)	C.A (kg/m3)	S.P (kg/m3)	D(max) (mm)	Aggregates	Z (kohm)	*E.R (kohm.cm)*	F.C (N/mm2)	C+S.F (kg/m3)	100*S.F/(C+S.F)
7	122	270	30	0.42	1124	850	4.5	9.5	D+C	3.9	19.5	36.4	300	10
8	142	315	35	0.42	1053	850	5.25	9.5	D+C	4.4	22	59.3	350	10
9	162	360	40	0.42	982	850	6	9.5	D+C	3.7	18.5	61.6	400	10
10	182	405	45	0.42	911	850	6.75	9.5	D+C	3.4	17	66.5	450	10
11	203	450	50	0.42	840	850	7.5	9.5	D+C	2.9	14.5	63.5	500	10
12	223	495	55	0.42	769	850	8.25	9.5	D+C	2.3	11.5	60.9	550	10

III - Silica Fume Ratio

Grains of silica fume are smaller than cement's grains and act as filler that has an important effect on compressive strength of concrete. Therefore silica fume with different percentages can have various results on electrical resistivity of concrete. In order to observe the results of this impact, silica fume with various ratios were used in this part of study. These specimens after 24 hours were opened from the molds and put in water pool with a temperature of 22 degrees C. After 28 days, the electrical resistivity and compressive strength of concrete specimens were tested. Table 8 shows the mixture proportion and properties of fresh concrete for group III.

Table 8. Mixture Proportion and Properties of Fresh Concrete for Group III

ID	W (kg/m3)	Cement (kg/m3)	S.F(kg/m3)	(W+S.P)/(C+S.F)	F.A (kg/m3)	C.A (kg/m3)	S.P (kg/m3)	D(max) (mm)	Aggregates	Z (kohm)	*E.R (kohm.cm)*	F.C (N/mm2)	C+S.F (kg/m3)	100*S.F/(C+S.F)
13	162	400	0	0.42	982	850	6	9.5	D+C	1.1	5.5	36	400	0
14	162	384	16	0.42	982	850	6	9.5	D+C	1.5	7.5	48.5	400	4
15	162	372	28	0.42	982	850	6	9.5	D+C	2.7	13.5	57.9	400	7
16	162	360	40	0.42	982	850	6	9.5	D+C	3.7	18.5	61.6	400	10
17	162	348	52	0.42	982	850	6	9.5	D+C	5.7	28.5	65	400	13
18	162	336	64	0.42	982	850	6	9.5	D+C	6.7	33.5	62.6	400	16
19	162	324	76	0.42	982	850	6	9.5	D+C	9	45	71.6	400	19

IV- Aggregate Size (A.S)

One of the important parameters to increase the electrical resistivity of concrete is type of aggregate size. Therefore 4 different aggregate size and 3 different cement ratios (The ratio of cement paste used in 1 m^3); 400 kg/m3, 500 kg/m3 and 600 kg/m3 studied. These specimens after 24 hours were opened from the molds and put in water pool with a temperature of 22 degrees C. After 28 days, the electrical resistivity and compressive strength of concrete specimens were tested. Table 9 shows the mixture proportion and properties of fresh concrete for group IV.

Table 9. Mixture Proportion and Properties of Fresh Concrete with Different Aggregate Size - Group IV

ID	Cement (kg/m3)	S.F (kg/m3)	W/C	F.A (kg/m3)	C.A (kg/m3)	S.P (kg/m3)	*D(max) (mm)	
1	360	40	0.4	715	1125	6	19.05	E+C
2	450	50	0.4	575	1125	7.5	19.05	E+C
3	540	60	0.4	435	1125	9	19.05	E+C
4	360	40	0.4	1003	837	6	9.52	D+C
5	450	50	0.4	863	837	7.5	9.52	D+C
6	540	60	0.4	723	837	9	9.52	D+C
7	360	40	0.4	1840	0	6	4.76	B
8	450	50	0.4	1700	0	7.5	4.76	B
9	540	60	0.4	1560	0	9	4.76	B
10	360	40	0.4	1840	0	6	2.38	A
11	450	50	0.4	1700	0	7.5	2.38	A
12	540	60	0.4	1560	0	9	2.38	A

*The maximum size of aggregate.

Electrical resistance test method of concrete

A.C. impedance spectroscopy (ACIS) method was applied in this study [Xu et al.1993]. Specimens were placed into water with 22 degrees C to saturate. Tests were performed saturated specimens with dried surfaces. After coating the specimen surfaces with the fresh cement paste, the electrical resistance and then electrical resistivity were determined according to the equation1.

Equation 1: $\rho = Z * A / L$

where ρ is electrical resistivity (based on Ω−m), L is length of specimen in meters (distance between the two tested surfaces) and Z is the obtained electrical resistivity. Also, A is the area of the surface on which the test is performed (based on square meters). After determining ρ probability of corrosion can be expressed using Table 10 [ACI222].

Table 10. Permeability Based on Surface Resistivity

Chloride Ion Permeability	Surface Resistivity Test 28 day test kΩ−cm
Very High	< 5
High	5 – 10
Low - Moderate	10 – 20
Low	> 20

RESULTS AND DISCUSSIONS

The results of the electrical resistivity of specimens are shown Figures 1 to 10. In group I, the highest E.R is for the lower water cement ratio (w/c=0.3) which means that increasing the water-cement ratio increases the permeability of concrete against chloride ion . In group II the best E.R was for cement paste of 350 kg/m3. In these specimens the w/c was fixed. In group III for specimens with different silica fume ratios also with fixed w/c, fine and coarse aggregate, the best result came from the specimens with higher silica fume (19%) and it is clear from Figure 3 that more than 10% silica fume in concrete give an electrical resistivity of more than 20 kΩ−cm and subsequently lower chloride Ion permeability.

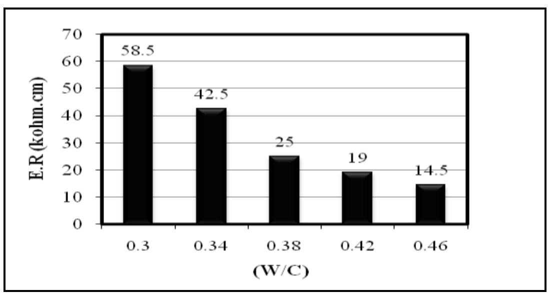


Fig.1. Electrical Resistivity of Concrete Specimens with Different W/C Ratios

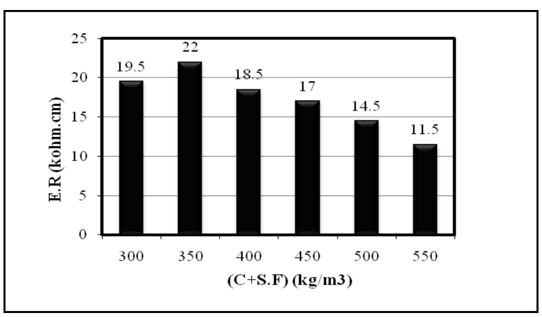


Fig.2. Electrical Resistivity of Concrete Specimens with Different Cement Ratios

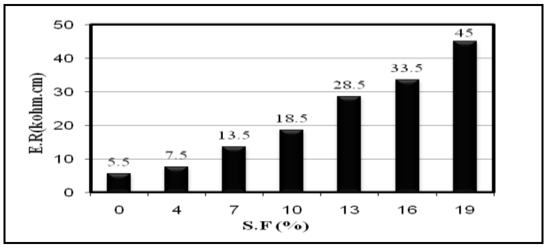
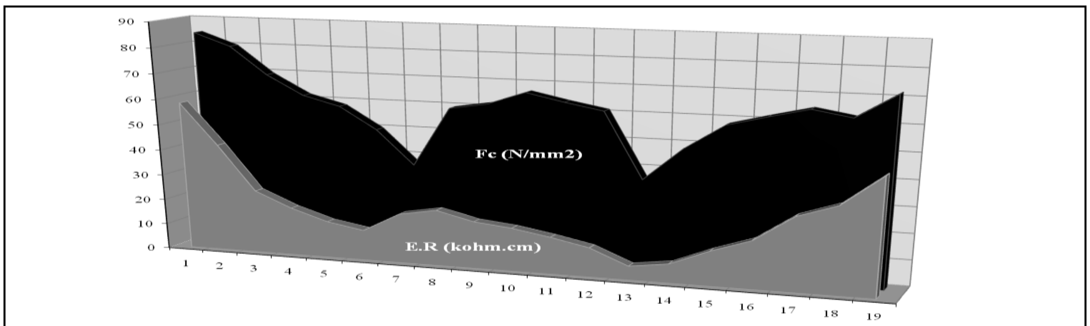


Fig.3. Electrical Resistivity of Concrete Specimens with Different Silica fume Ratios



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
E.R (kohm.cm)	58.5	42.5	25	19	14.5	12	19.5	22	18.5	17	14.5	11.5	5.5	7.5	13.5	18.5	28.5	33.5	45
Fc (N/mm2)	84.46	79.64	69.09	61.64	58.01	49.58	36.44	59.26	61.55	66.54	63.53	60.91	35.96	48.46	57.85	61.55	64.99	62.56	71.64

Fig.4. Comparision of Electrical Resistivity and Compressive Strength of 19 Specimens of Group I, II and III

In Figure 4 the electrical resistivity and compressive strength of specimens in group I to III figured. As it is clear from the figures, the electrical resistivity and compressive strength have a mutual relation. An increase in one of them associated with the increase in the other. Figures 5 to 7 shows the electrical resistivity of concrete with different aggregate size. The specimen with aggregate size of 19.05 mm and cement ratio of 500 kg/m3 (when compared to Figure 8) has the highest impermeability to chloride ions into concrete.

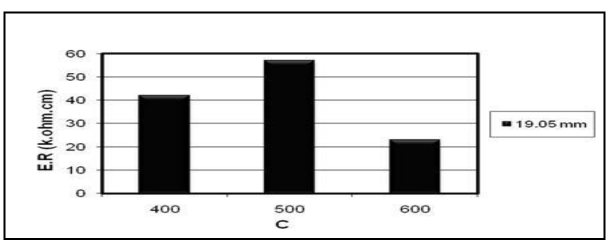


Fig.5. Electrical Resistivity of Concrete Specimens with Aggregate Size of 19.05mm

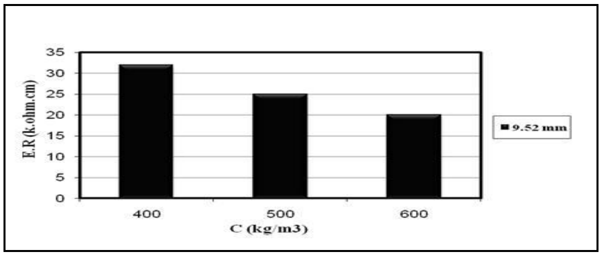


Fig.6. Electrical Resistivity of Concrete Specimens with Aggregate Size of 9.53mm

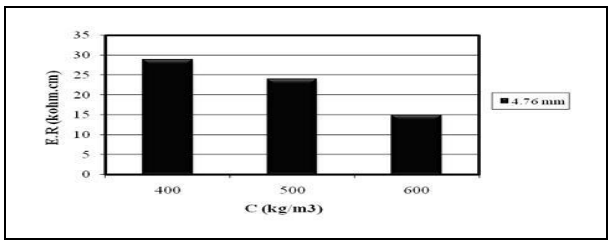


Fig.7. Electrical Resistivity of Concrete Specimens, Aggregate Size of 4.76mm

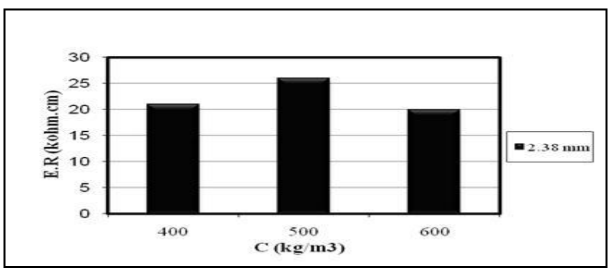


Fig.8. Electrical Resistivity of Concrete Specimens with Aggregate Size of 2.38mm

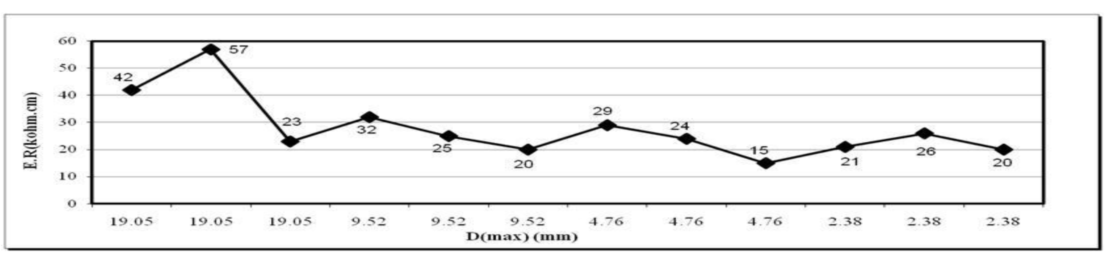


Fig.9. Electrical Resistivity of Concrete Specimens with Different Type of Aggregate Sizes

Figure 10 compares the electrical resistivity of concrete specimens with different aggregate size and cement paste. The better specimens to resist against corrosion of concrete are specimens with aggregate size of 19.05mm. In this study one of the best concrete mix designs which has the highest resistance to chloride ions into the concrete specimens is specimen of group I with characterization of table 11.

Table 11. Mixture Proportion and Properties of the Specimen with Highest E.R

ID	W (kg/m3)	Cement (kg/m3)	S.F(kg/m3)	(W+S.P)/(C+S.F)	F.A (kg/m3)	C.A (kg/m3)	S.P (kg/m3)	D(max) (mm)	Aggregates	Z (kohm)	*E.R (kohm.cm)*	Fc (N/mm2)	C+S.F (kg/m3)	100*S.F/(C+S.F)
1	129	405	45	0.3	965	850	6	9.5	D+C	11.7	58.5	84.5	450	10

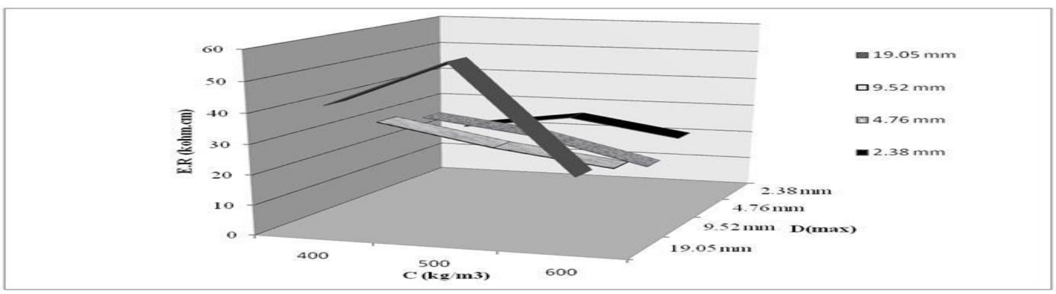


Fig.10. Comparison of Electrical Resistivity of Concrete Specimens with Different Aggregate Size and Cement Paste

CONCLUSIONS

The results of this study are shown in the following conclusions:

- To design a concrete in order to resist against corrosion in corrosive environments, the water-cement ratio should not exceed 0.5.
- Partial cement replacement by silica fume as an alternative increases the electrical resistivity of concrete. As a result of this study, to reach low permeability of chloride ion to concrete the ratio of silica fume must be more than 10%.
- In general, an increase in electrical resistivity of concrete was associated with an increase in compressive strength of concrete; therefore, the fact that most of the mechanical properties of concrete such as tensile strength and etc. are in proportion to with compressive strength concludes that improving electrical resistivity of concrete will result in a concrete which has improved mechanical properties.
- The aggregate size can have a large influence on the electrical resistivity of concrete, therefore it is recommended especially in large projects, that several types of aggregate size according to the mix design be used and the best one selected.

- In this study sustainable concrete mix design which has the highest resistance to permeability is selected. This mix design has the lowest w/c of 0.3.

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