

DURABILITY OF REINFORCED CONCRETE IN SULFATE-CHLORIDE "SABKHA" MEDIA AND METHODS OF PROTECTION

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ABSTRACT

Chlorides and sulfates are typically manifested in marine and offshore environments or in soils changed with concentrated brines. A search of the literature indicates that the role of chloride ions on sulfate attack is debated and inconclusive. Similarly, the influence of sulfate ions on chloride-induced corrosion of reinforcing steel in concrete has not been well documented. An exemplary situation, where these salts exist concomitantly, is the sabkha soil which does prevail in some of the well-populated cities in the Arabian Gulf and where major industrialization and infrastructure projects do exist. The unrealistic evaluation of the severity of sabkha environments has resulted in considerable loss amounting to hundreds of millions of US dollars spent to repair, rehabilitate and/or restore the deteriorated reinforced concrete structures.

This paper reports the durability of two plain cements (Type I and Type V) and three blended cements (made with 20% fly ash, 10% silica fume and 60% blast furnace slag) in sulfate-chloride environments as well as in a "genuine" eastern Saudi sabkha. Several tests were conducted on cement paste, mortar and reinforced concrete specimens including compressive strength, half-cell potential, corrosion current density, x-ray diffraction and scanning electron microscopy, to elucidate the mechanisms of sulfate attack and reinforcement corrosion. Specifications for durable concrete to serve in the aggressive sabkha media are presented and compared with the international Codes of Practice.

KEYWORDS

Aggressive environments, blended cements, chlorides, concrete protection, plain cements, reinforcement corrosion, specifications, sulfate attack.

INTRODUCTION

The concrete construction industry has faced with few epidemics during the last four decades which have degraded the reputation of concrete as a maintenance-free material. Typical examples, where concrete was blamed for its poor durability performance, are the usage of high alumina cement, of the calcium chloride in bridge decks in USA and Europe, and of the reactive silica aggregate, and, more recently, the deterioration of reinforced concrete (RC) structures in the coastal areas of the Arabian Gulf. The first three phenomena have been dealt with by either prohibition of the use of certain materials in structural concrete or the incorporation of certain preventive measures for its mitigation (Mays, 1992). For the last phenomenon, the degradation of RC structures is basically attributed to the following: (i) unrealistic evaluation of the severity of the service environment, (ii) inappropriate materials specifications, and (iii) inadequate construction practice (Al-Amoudi and Maslehuddin, 1996). Other deteriorating processes, such as sulfate attack and thermal cracking generation, are basically understood and can be significantly mitigated or prohibited when a number of design and construction options, that are readily available in national/international codes of practice (i.e. ACI 201 and BS 8110, for example), are strictly followed.

With the foresight and awareness of concrete ingredients and its manufacturing, the main causes of concrete deterioration in the future are likely to be as a result of the environment in which structural members are built; the principal concerns being the penetration of salts, moisture, oxygen and carbon dioxide (Mays, 1992). Again, the impact of the last three agents can be mitigated via the adherence to the precautionary measures enlisted in the codes of practice. Further, carbonation is a rather slow process because of the formation of calcium carbonate which acts as a partial barrier to further penetration of carbon dioxide, particularly in dense concrete. Moreover, carbonation and similar other forms of deleterious gas effects, such as acidic rains, constitute a real problem to the construction industry in few industrialized regions.

Finally, it seems that the most predominant form of concrete protection to deal with is the penetration of salts and water; both of which occur conjointly. Among the prevalent salts are those of chloride and sulfate that are typically manifested in marine and offshore exposures or in soils charged with concentrated brines. An exemplary situation of these soils, where chlorides and sulfates do exist concomitantly, is the "sabkha" soil. Sabkha constitutes one of a variety of saline soils, with various nomenclatures, that are well-distributed in the Arabian Gulf, North Africa and around the globe (Al-Amoudi and Abduljawad, 1994; Al-Amoudi, 1994a).

Sabkha environment is extremely aggressive to substructures of all kinds. This aggressivity emerges principally from: (i) the high salt content in the sabkha soil and its brine (Table 1), and (ii) the shallowness of groundwater tables which frequently lie within about one meter from the sabkha surface. Due to the large fluctuations in daily and seasonal temperature and humidity conditions (Al-Amoudi et al., 1993b), various forms of salts tend to crystallize in the capillary "vadose" zones in the sabkha terrains. Such intermittent crystallization of salts in the pores of concrete and pavements often leads to their slow and persistent disintegration (Al-Amoudi et al., 1992b). The various forms of brine attack present severe conditions for ordinary "portland cement" and warrants strict precautionary measures (Al-Amoudi, 1992).

The above review indicates that predicting the long-term performance of reinforced concrete (RC) substructures in sabkha environments provides the greatest challenge to concrete technologists in the Middle East. It is astonishing to report that there is a lack of reliable data on the performance of concrete in such environments except for few case studies (Al-Amoudi, 1992). These studies indicate that the functional life of RC substructures exposed to sabkha is significantly shortened due to both chloride-induced corrosion of reinforcing steel and sulfate attack of concrete (Al-Amoudi et al., 1993a). Moreover, the role of sulfate ions on chloride-induced corrosion of reinforcing steel and of chlorides on sulfate attack are either non-existent in the literature or highly debated and inconclusive (Al-Amoudi, 1992). This paper summarizes the effect of sulfate-chloride environments on the durability of plain and blended cements based on laboratory results. Field data, from exposure studies in a genuine sabkha, are also reported.

Table 1. Chemical analysis of sabkha brine and seawater in g/l (i.e. parts per thousand) (Al-Amoudi, 1994b)

Ions	Sabkha Brine	Seawater
Na ⁺	78.8	20.7
Mg ⁺⁺	10.32	2.30
K ⁺	3.06	0.73
Ca ⁺⁺	1.45	0.76
Fe ⁺⁺	Trace	**
Sr ⁺⁺	0.029	0.013
Cl ⁻	157.2	36.9
Br ⁻	0.49	0.121
(SO ₄) ⁻⁻	5.45	5.12
(HCO ₃) ⁻	0.087	0.128
pH	6.9	8.3
Conductivity*	208,000	46,200

*Microsiemen

**Not reported

EXPERIMENTAL DETAILS

Table 2 summarizes the details of the tests conducted to assess: (i) strength development and strength deterioration factor, (ii) reinforcement corrosion, and (iii) mineralogical composition to elucidate the mechanisms of sulfate attack and reinforcement corrosion. After 14 days of water curing, cement paste, mortar and reinforced concrete specimens were placed in the following environments:

- | | | |
|-------|---|-------------------------------------|
| (i) | 2.1% SO ₄ ⁻⁻ + 0% Cl ⁻ | (pure sulfate environment) |
| (ii) | 0% SO ₄ ⁻⁻ + 15.7% Cl ⁻ | (pure chloride environment) |
| (iii) | 0.55% SO ₄ ⁻⁻ + 15.7% Cl ⁻ | (low sulfate-chloride environment) |
| (iv) | 2.1% SO ₄ ⁻⁻ + 15.7% Cl ⁻ | (high sulfate-chloride environment) |

The inclusion of both pure sulfate and pure chloride environments was intended to assess the role of sulfate ions in reinforcement corrosion and the effect of chloride ions on sulfate attack. The concentrations of solutions were similar to those prevailing in a

Table 2. Summary of the experimental program and threshold values (Al-Amoudi, 1992)

Test Performed (Exposure)	Specimen Characteristics			Parameter Measured	Threshold Value
	Type	Shape	Size (mm)		
X-Ray Diffraction and Scanning Electron Microscopy (Lab.)	Paste	Cubes	12.5	Mineralogy and Morphology	Identification of Various Phases
Chemical Analysis and Metal Weight Loss (Field)	Reinforced Mortar	Prisms	31×31×152	OH ⁻ , Cl ⁻ , Cl ⁻ /OH ⁻ and Steel Weight Loss	Cl ⁻ ≤ 0.15% ⁺ Cl ⁻ /OH ⁻ ≤ 0.6
Compressive Strength (Field and Lab.)	Mortar	Cubes	25	Strength Deterioration Factor (SDF) [§]	SDF ^{**} = 30%
Weight Measurement (Lab.)	Reinforced Concrete	Cylinders	76×152	Weight Loss of Concrete	5%
Corrosion Potential (Lab.)	Reinforced Concrete	Cylinders	76×152	Time-to-Initiation of Reinforcement Corrosion	-270 mV (CSE)
Linear Polarization Resistance (Lab.)	Reinforced Concrete	Cylinders	76×152	I _{corr} ^{**} and Polarization Resistance (R _p)	I _{corr} = 0.3 μA/cm ² R _p = 87 kOhm-cm ²

*Based on experience

**I_{corr} = Corrosion current density

⁺By weight of cement

$$\S \text{ SDF (\%)} = \left[\frac{\text{Strength in water} - \text{Strength in solution}}{\text{Strength in water}} \right] * 100$$

typical eastern Saudi coastal sabkha (Al-Amoudi, 1992), except for the 2.1% SO_4^{--} , which is similar to the sulfate concentration in the continental sabkha of Wadi As-Sirhan (Al-Amoudi, 1992). Sodium sulfate and magnesium sulfate were used to provide 50% of the SO_4^{--} concentration from each of them, while sodium chloride was used to provide the Cl^- concentration in all the $\text{SO}_4^{--}\text{-Cl}^-$ environments.

ASTM C 150 Type I ($\text{C}_3\text{A} = 8.5\%$) and Type V ($\text{C}_3\text{A} = 3.5\%$) cements as well as blended cements were used in casting all the specimens. The blended cements were prepared using fly ash (20%), silica fume (10%) and blast-furnace slag (60%) as replacements of Type I cement.

RESULTS AND DISCUSSION

Performance in Pure Sulfate Environment

The data on strength deterioration factor (SDF) presented in Table 3 indicates a high degree of deterioration in all the cement mortar specimens (Al-Amoudi et al., 1994b). However, the deterioration was more pronounced in blast-furnace slag (BFS) and silica fume (SF) cements, compared to OPC and fly ash (FA) cements. The enhanced deterioration in BFS and SF cements in pure sulfate environment is attributable to the depletion of calcium hydroxide as a result of the pozzolanic reaction as well as to the high concentration of magnesium ions (Rasheeduzzafar et al., 1994). In OPC, portlandite (i.e. calcium hydroxide), acting as a buffer and a retarder of the Mg-attack on the C-S-H phase, reacts with MgSO_4 . The reduction of portlandite in SF and BFS cements would therefore deflect the attack more directly and extensively towards C-S-H, thereby enhancing the deterioration and consequent reduction in strength in these cements. The performance of Type V cement was relatively marginally better than Type I cement.

Table 3. Strength reduction due to sulfate attack after two years of exposure (Al-Amoudi et al., 1994b)

Cement Type	Strength Deterioration Factor (%) in the Environment of:			
	Pure Sulfate	Pure Chloride	Low Sulfate-Chloride	High Sulfate-Chloride
Type I	85	9	23	55
Type V	75	28	20	30
Fly Ash	85	18	23	46
Silica Fume	90	25	22	81
Blast Furnace Slag	95	7	14	85

Table 4 presents the long-term corrosion results of rebars in the concretes exposed to pure sulfate solution (Al-Amoudi, 1995c). The data indicates a superior performance of SF cement concrete compared to other blended and plain cements. The reinforcing steel in SF concrete is still in a passive state as the corrosion potential and polarization resistance values are more than -270 mV SCE and 87 kOhms-cm², respectively. This

is ascribable to the beneficial effect of SF on the paste-aggregate interface. Further, the dense microstructure of SF concrete retards the diffusion of SO_4^{--} to the steel-concrete interface and also increases the electrical resistivity of the concrete matrix, thereby impeding the corrosion process. However, a slow degradation of the concrete cover, due to sulfate attack, may ultimately expose the steel to moisture and oxygen. Therefore, protection of substructures through the use of an epoxy-based coating may be inevitable.

Table 4. Performance data of reinforced concretes after 44 months of exposure to the pure sulfate environment (Al-Amoudi, 1995c)

Cement Type	Corrosion Potential, (mV SCE)	Polarization Resistance (kOhms-cm ²)
Type I	-395	56.7
Type V	-338	76.6
Fly Ash	-681	24.1
Silica Fume	-252	844
Blast Furnace Slag	-696	12.8

Performance in Pure Chloride Environment

The corrosion-resistance behavior of plain and blended cement concrete specimens in pure chloride environment (15.7% Cl^-) is presented in Table 5. This data indicates again a superior performance by the SF blended cement. Its time to initiation of reinforcement corrosion was four to six times that in plain cements and three times that in FA blended cements, while its corrosion rate was 29 times better than that in plain cement concretes and 2 and 5 times better than that in FA and BFS cement concretes, respectively. It is worth mentioning that the SDF in all plain and blended cements (Table 3) was less than the failure criterion of 30% (Table 2). In fact, all the mortar specimens did not experience any form of physical deterioration except for salt precipitation, even after an exposure period of two years (Al-Amoudi et al., 1994a).

Table 5. Summary of the corrosion-resisting characteristics in the pure chloride environment (Al-Amoudi et al., 1994a)

Cement Type	Time to Initiation of Rebar Corrosion (Days)	Corrosion Current Density ($\mu\text{A}/\text{cm}^2$)
Type I	175	1.75 (1)**
Type V	107	2.20 (0.80)
Fly Ash	220	0.99 (1.77)
Silica Fume	631	0.06 (29)
Blast Furnace Slag	-*	0.32 (5.47)

*ASTM C 876 not applicable

**Numbers in parentheses indicate the performance rating using Type I cement as a reference

Performance in Sulfate-Chloride Environments

The SDF data is summarized in Table 3 and indicates, more or less, a similar strength reduction in both plain and blended cements placed in the low sulfate-chloride environment (0.55% SO_4^{--} + 15.7% Cl^-). However, the strength reduction in SF and BFS blended cements placed in the high sulfate-chloride environment, was more than that in plain and FA cement specimens.

As expected, the time to initiation of reinforcement corrosion in the SF blended cement concrete specimens was more than that in the FA and plain cements (Table 6). Although both the low and high sulfate-chloride environments had the same chloride concentration (15.7%), no trend as to the effect of sulfate concentration on the time to initiation of rebar corrosion was indicated (Al-Amoudi et al., 1994c). However, an increase in the corrosion current density (I_{corr}) in all cements was observed due to the increase in sulfate concentration in these environments. The I_{corr} on steel in SF cement concrete specimens was less than that in the other blended and plain cements. The I_{corr} on steel in the BFS and FA cement concrete specimens was less than that in both types of plain cement concrete specimens.

Table 6. Corrosion-resisting characteristics of rebars in plain and blended cement concretes in the sulfate-chloride environments (Al-Amoudi et al., 1994c)

Cement Type	Time to Initiation of Rebar Corrosion (Days)		Corrosion Current Density ($\mu\text{A}/\text{cm}^2$)	
	Low Sulfate-Chloride	High Sulfate-Chloride	Low Sulfate-Chloride	High Sulfate-Chloride
Type I	108	162	3.90 (1)**	4.17 (1)
Type V	80	106	4.10 (0.95)	4.76 (0.88)
Fly Ash	152	210	1.27 (3.07)	1.72 (2.42)
Silica Fume	548	552	0.24 (16.3)	0.29 (14.4)
Blast Furnace Slag	—*	—*	0.44 (8.86)	0.50 (8.34)

*ASTM C 876 not applicable

**Numbers in parentheses indicate the performance rating using Type I cement as a reference

Sulfate Attack. The SDF data of plain and blended cements in the low $\text{SO}_4^{--}\text{-Cl}^-$ environment is relatively low and comparable to those in the pure chloride environment (Table 3). This indicates that despite the high sulfate concentration ($\text{SO}_4^{--} = 0.55\%$) in this environment, which is classified as "aggressive" according to the ACI 318 Code of Practice, sulfate attack is almost totally hindered in the presence of high chloride concentration. In fact, the SDF's of all plain and blended cements are lower than the 30% failure criterion for SDF, as proposed in Table 2. However, when the sulfate concentration increases from 0.55% to 2.1%, the SDF's increase tremendously, particularly in SF and BFS blended cement mortar specimens, as documented in Table 3. Therefore, increasing the SO_4^{--} concentration, even in the presence of high chloride concentration, will certainly enhance the degree of deterioration in all cements. However, the level of attack varies with the type of cement. The SDF's for the mortar specimens in the pure sulfate and high sulfate-chloride environments (i.e. both have a

SO_4^{--} concentration of 2.1%) indicate that the sulfate attack in plain cements (i.e. both Type I and Type V) is significantly mitigated due to the presence of chloride ions, whereas in blended cements, particularly those made with SF and BFS, the beneficial effect of chlorides is only marginal (Al-Amoudi et al., 1994b).

XRD and SEM studies indicate that the significant beneficiation of chlorides in the case of plain cements is attributed to the virtual elimination of gypsum that has been considered the principal cause of deterioration in pure sulfate environments. The beneficial role of chlorides in SF and BFS cements is only marginal because the deterioration mechanisms in these cements are ascribable to Mg^{++} -oriented decomposition of the C-S-H binder, which is not ameliorated in the presence of chlorides.

Corrosion of Reinforcing Steel. The data in Tables 5 and 6 indicates that the time to initiation of corrosion is not dominantly controlled by the conjoint presence of sulfates with the chlorides. This behavior is explained by the fact that, in mixed chloride-sulfate environments, the mechanisms of corrosion initiation are controlled by the relative diffusivity of these two ions. Since chlorides diffuse much faster than sulfates, chlorides would govern the time to initiation of rebar corrosion (Al-Amoudi et al., 1994c).

Quantitative information on reinforcement corrosion using I_{corr} after 650 days of exposure to the Cl^- and/or SO_4^{--} environments indicates that, within the test duration, the I_{corr} on steel in all the specimens placed in the low SO_4^{--} - Cl^- environment is higher than those placed in the pure Cl^- solution. Similarly, the I_{corr} values are more in the high SO_4^{--} - Cl^- environment than those in the low SO_4^{--} - Cl^- environment. This trend indicates that the conjoint presence of sulfates with chlorides in the vicinity of reinforcing steel accentuates the corrosion rate, and when the SO_4^{--} concentration increases, the I_{corr} values are accordingly increased. This trend is vividly observed irrespective of the cement type, as illustrated in Figs. 1 and 2.

Comparison of the I_{corr} values indicates a superior performance by the SF cement concrete in mitigating the corrosion activity in the various SO_4^{--} - Cl^- environments. Its performance was approximately 14 to 29 times better than that of Type I cement concrete (Tables 5 and 6). The performance of BFS and FA cement concretes was also 2 to 9 times better than that of Type I cement concrete. Further, Type I cement concrete performs better than Type V cement concrete, due principally to its ability to bind more chlorides.

Performance in Actual Sabkha

The superior performance of SF blended cement has also been observed in a field investigation (Al-Amoudi et al., 1996), whereby reinforced mortar specimens were placed below the ground-water table in the Ras Al-Ghar eastern Saudi sabkha for 18 months. The data, presented in Table 7, indicates that the concentration of chlorides in all cements is considerably more than the 0.15% (by weight of cement) recommended by ACI 318 as a threshold value for avoiding the risk of rebar corrosion. Similarly, the (Cl^-/OH^-) ratio in all cements is more than the threshold value of 0.6 (Al-Amoudi et al., 1996). These results highlight the severity of the sabkha environment. What is

surprising is the fact that although both the Cl^- concentration and $(\text{Cl}^-/\text{OH}^-)$ ratio are higher in blended cement specimens as compared with those in plain cements, the weight loss of steel is much lower in the former cements, particularly in the SF and BFS ones (Table 7). This behavior is attributed to the dense microstructure of these cements which increases their electrical resistivity, thereby retarding the flow of corrosion current (Al-Amoudi et al., 1996).

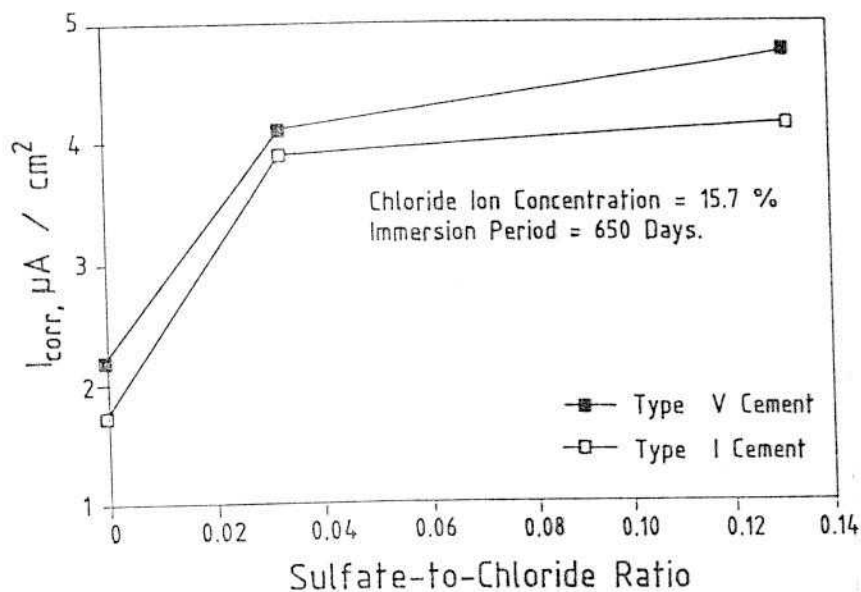


Fig. 1. Effect of sulfate ion concentration on the chloride-induced reinforcement corrosion in plain cement concretes (Al-Amoudi et al., 1994c)

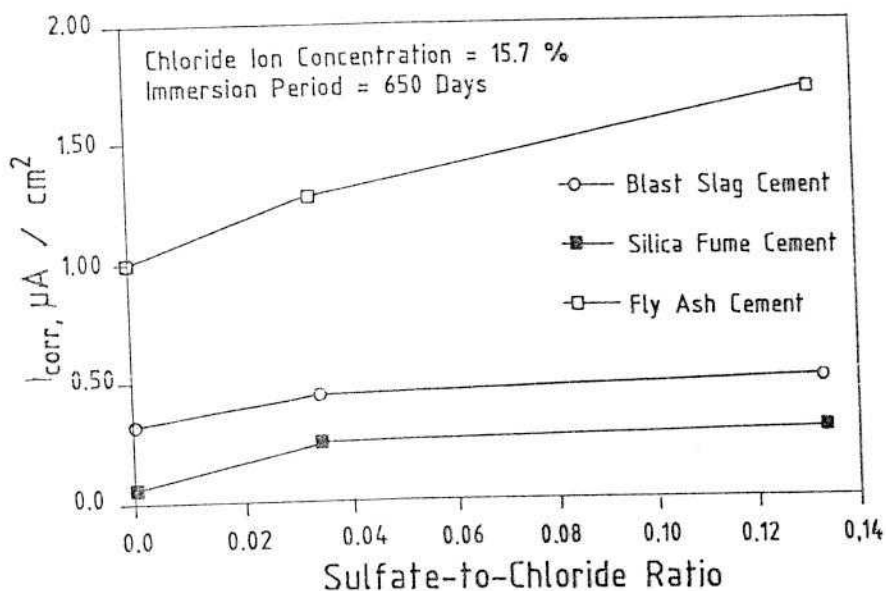


Fig. 2. Effect of sulfate ion concentration on the chloride-induced reinforcement corrosion in blended cement concretes (Al-Amoudi et al., 1994c)

Table 7. Chemical analysis of mortar and weight loss in steel bars in the mortar specimens placed in the sabkha soil (Al-Amoudi et al., 1996)

Cement Type	(OH) ⁻ (%) [*]	Soluble Cl ⁻ (%) [*]	(Cl ⁻ /OH ⁻) Ratio	Metal Weight Loss (%)
Type I	1.75	3.17	1.81	0.64
Type V	1.80	3.32	1.84	0.63
Fly Ash	1.14	2.84	2.47	0.39
Silica Fume	1.02	3.32	3.25	0.02
Blast Furnace Slag	0.48	3.12	6.49	0.03

*By weight of cement

The results on compressive strength of mortar specimens made with the various types of cement are depicted in Figs. 3 and 4. The data therein indicates that the strength did not decrease beyond the initial strength, even after 18 months of exposure to the aggressive sabkha environment and the use of small specimens (25 mm cubes). The relatively inferior performance of SF and BFS blended cement mortar specimens, as compared to plain and FA ones, could be attributed to salt scaling. It can therefore be concluded that deterioration of concrete (as measured by strength) in sabkha environments does not seem problematic as compared with corrosion of reinforcing steel.

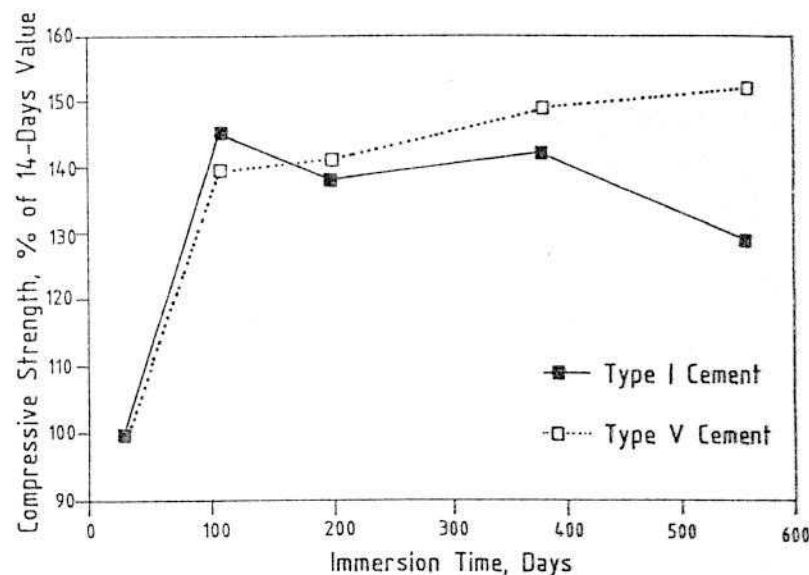


Fig. 3. Effect of sabkha exposure on compressive strength of mortar specimens (plain cements)

Although the SF cement has shown considerable resistance to reinforcement corrosion, long-term studies conducted by the author reveal that such an improvement needs to be further enhanced (Al-Amoudi, 1995b). Table 8 summarizes the results of tests conducted on 15 types of RC specimens exposed to the simulated-sabkha environment (0.55% SO₄²⁻ + 15.7% Cl⁻). These results indicate that the main contributing factors to mitigate reinforcement corrosion are: incorporation of mineral admixtures (the most important), reduction in water-to-binder ratio, and use of high C₃A cements. The most

significant improvement was achieved when the water-to-binder ratio was conjointly reduced with the addition of silica fume (Mixes # 14 and 15 in Table 8).

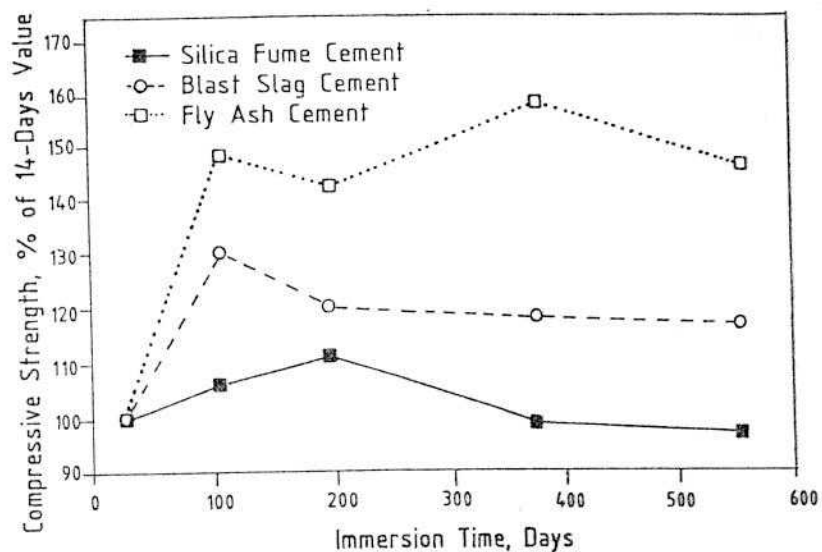


Fig. 4. Effect of sabkha exposure on compressive strength of mortar specimens (blended cements)

Table 8. Performance data of reinforced concrete specimens after 44 month exposure to the sabkha environment (Al-Amoudi, 1995b)

Mix Number	Cement Type	Blending Material (Replacement by Weight of Cement)	w/cm**	Time to Corrosion Initiation (Days)	Polarization Resistance (kOhms-cm ²)
1	I	--	0.50	108	4.984
2	V	--	0.50	80	3.611
3	I	Fly Ash (20%)	0.50	152	9.681
4	I	Silica Fume (10%)	0.50	548	47.511
5	I	BFS* (60%)	0.50	NA ⁺	25.819
6	II	--	0.50	103	6.222
7	I	--	0.35	129	22.888
8	V	Fly Ash (20%)	0.50	146	10.191
9	V	Silica Fume (10%)	0.50	435	33.255
10	V	--	0.35	125	9.126
11	I	BFS* (60%)	0.35	NA ⁺	28.737
12	I	Fly Ash (20%)	0.35	302	56.588
13	V	Fly Ash (20%)	0.35	277	45.324
14	I	Silica Fume (10%)	0.35	p ⁺⁺	140.078
15	V	Silica Fume (10%)	0.35	p ⁺⁺	89.290

*Blast furnace slag

**Water-to-cementitious materials ratio

⁺ASTM C 876 not applicable

⁺⁺Reinforcing steel passive

CONCRETE SPECIFICATIONS FOR AGGRESSIVE ENVIRONMENT

The highly aggressive environments of sabkha in the Arabian Gulf are not always far from construction; they are unfortunately located where some of the industrialization and infrastructure projects, as well as private residence, exist. It is therefore expected to have RC durability problems. In fact, several case studies have recently been reported on the severe degree of deterioration of many plain and RC substructures (Al-Amoudi, 1992; Al-Amoudi et al., 1992b; Al-Amoudi et al., 1993a), the cost of rehabilitation and/or restoration amounts to hundreds of millions of US Dollars. Although not formally reported, many other cases of deterioration in sabkha terrains are also profoundly documented among the engineering professionals.

Due to the hostile environment of sabkha, it has now become evident that the international Codes of Practice cannot be used to protect the structural components. Recommendations by the American Concrete Institute (ACI) and the Construction Industry Research and Information Association (CIRIA), as well as those proposed by Rasheeduzzafar (1989), Al-Amoudi et al. (1993a), are compared in Table 9. Specifications suggested by Rasheeduzzafar (1989) and Al-Amoudi et al. (1993a) are based on extensive laboratory and field studies in sabkha environments and agree with each other on the usage of blended cements. Based on these results, SCECO-East, Royal Commission for Jubail and Yanbu and Saudi-ARAMCO (each of these organizations has multi-billion US Dollar projects located in sabkha terrains), are all now using silica fume as the principal admixture in concrete to mitigate chloride-induced rebar corrosion. Consequently, the use of silica fume, as well as the other specifications listed in Table 9, must be stringently adhered to in order to extend the useful service-life of the structures in these aggressive environments.

Although the specifications reported in Table 9 will offer an excellent protection to concrete and reinforcing steel, utmost care should undoubtedly be practiced in selecting concrete materials that are compatible with the service environment, adopting rational methods of mix design and construction as well as proper concrete placement, compaction and curing. Awareness of the shortcomings of the materials to be used; i.e. silica fume (plastic shrinkage), fusion-bonded epoxy-coated reinforcing steel (possible damage to the coating), etc., as well as the development of suitable design and construction practices, should not be underestimated (Al-Amoudi and Maslehuddin, 1996).

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Table 9. Specifications for reinforced concrete structures in aggressive sabkha media (Al-Amoudi, 1995a)

Parameter	ACI 318	CIRIA	Rasheeduzzafar (1989)	Al-Amoudi et al. (1993)
Cement Type	<ul style="list-style-type: none"> • V for Severe Sulfate Exposure • V + Pozzolan for Very Severe Sulfate Exposure • II for Marine Exposure 	N.S.*	<ul style="list-style-type: none"> • I ($C_3A = 12\%$) + 10-15% Silica Fume or 20-30% Fly Ash or 70% Blast Furnace Slag • V ($C_3A < 5\%$) 	I + 10% Silica Fume
Minimum Cement Content (kg/m^3)	N.S.*	320-400	385-445	350-400
Maximum Water-to-Binder Ratio	0.40 for Corrosion Protection 0.45 for Sulfate Protection	0.42-0.50 for Substructures 0.42-0.45 for Marine Exposure	0.40-0.45	0.35§
Reinforcement Type	Uncoated	Uncoated	Epoxy Coated or Stainless-Clad if Type V Cement is used	Epoxy Coated§
Minimum Cover to Reinforcement (mm)	75	75	75	75
Minimum Curing Period (Days)	7	7	7 for Plain Cements 14 for Blended Cements	14§

*Not specified.

**Exterior members are to be coated with epoxy-based water resistant coating.

§ Modified as per the results (Al-Amoudi, 1995b).

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