



# CHARACTERISTICS OF THE ARABIAN GULF ENVIRONMENT AND ITS IMPACT ON CONCRETE DURABILITY – AN OVERVIEW

A.S. Al-Gahtani<sup>1</sup> and M. Maslehuddin<sup>2</sup>

1: Associate Professor, Department of Civil Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

2: Research Engineer, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

E-mail: agahtani@kfupm.edu.sa

## ABSTRACT

*The environmental conditions of the Arabian Gulf that are characterized by high temperature and humidity significantly affect the performance of concrete structures in this region. The daily and seasonal variations in the temperature and humidity further accelerate the rate of concrete deterioration which is predominantly exhibited in the form of reinforcement corrosion, sulfate attack, salt scaling and cracking due to plastic and drying shrinkage. The high humidity provides moisture to concrete that is essential for reinforcement corrosion. Further, the temperature and humidity regimes that are commonly noted in this region are conducive for accelerated carbonation of concrete. The geomorphic conditions in the coastal areas of the Arabian Gulf that are characterized by shallow groundwater table, groundwater and soil contaminated with high concentrations of both chloride and sulfate salts also accelerate the deterioration of concrete mainly due to reinforcement corrosion, sulfate attack and salt weathering. This paper discusses the effect of environmental conditions, namely temperature, humidity, blowing wind, shallow groundwater and high salinity of the groundwater and soil, of the Arabian Gulf, on concrete durability.*

**Keywords:** Chloride and sulfate salts, Concrete deterioration, Reinforcement corrosion, Salt weathering, Carbonation.

## 1. INTRODUCTION

The climatic conditions of the Arabian Gulf region are characterized by high temperature with salt-laden humidity and large fluctuation in the diurnal and seasonal temperature and humidity. These conditions adversely affect the performance of concrete structures and accelerate the early deterioration of concrete in the region.

The temperature can vary by as much as 20°C during a typical summer day and the relative humidity ranges from 40 to 100% over 24 hours. These sudden and continuous variations in temperature and humidity initiate cycles of expansion/contraction which cause damage due to cracking of concrete. The damage due to these stresses is reflected by microcracking and enhanced permeability, which results in a tremendous increase in the diffusion of chloride, oxygen, moisture and carbon dioxide towards the steel-concrete interface.

The poor durability of concrete in this region is also due to the marginal quality of the local aggregates. Most of the coarse aggregates available in this region are crushed limestone which are marginal, porous, absorptive, relatively soft and dusty. The aeolian dune and coastal sand form the main source of fine aggregate. These sands are extremely fine-grained with narrow grading and contaminated with chloride and sulfate salts. Furthermore, the fine and coarse aggregates are characterized by excessive dust content [Rasheeduzzafar and Dakhil, 1980]. Dust and excessive fines cause high water demand, resulting in lower strength and poor durability of concrete. Dust also forms a fine interstitial coating between the aggregate and the cement paste thereby weakening the bond at the aggregate-paste interface and develops microcracking under the temperature and humidity variation cycles. The transition zone, being the weakest link of concrete composite, may further lower the concrete strength and quality [Hsu, 1963].

Since this region has a desert type climate, the rainfall is mostly in the form of showers of short durations limited to the winter months. The annual rainfall is less than 8 cm on the average, and due to the aridity of the Gulf region, evaporation is very high. [Privett, 1959] estimated the mean evaporation rate to be around 1.44 m per year, while [Meshall and Hassan, 1986] estimated it to be around 2 m per year. This high rate of evaporation increases the salinity of the Gulf water, especially in the coastal areas [Rasheeduzzafar and Dakhil, 1985].

The chloride content of the Arabian Gulf seawater is about 1.6 to 2 times that of the seawater from Mediterranean or the Atlantic. The chloride and sulfate pollution in the ambient environment in the Arabian Gulf is about 490 times that of the air along California beach in U.S.A. This high salt concentration in the environment is attributed to the geological

formation in the region. The geological sequences, in which layers of salt and gypsum are extensively interbedded, are fairly widespread in the area [Fookes and Collis, 1975]. Salts reach the groundwater and soil either by weathering of salt-bedded rocks or as windblown particles from the salty surface crusts of salt playas, sabkhas, and salinas. These are commonly occurring features of the desert terrain along the Arabian Gulf coast and they contaminate the soil, groundwater, and the atmosphere with chloride and sulfate salts.

The climatic and geomorphic factors may combine to accelerate the concrete deterioration processes. In most areas, groundwater table is relatively high and close to the ground surface. The capillary rise of moisture and the frequent flooding in conjunction with the high evaporation rate leave a heavy crust of salt in the upper few feet of the soil. This leaves the soil, groundwater and atmosphere heavily contaminated with chloride and sulfate salts [Rasheeduzzafar and Dakhil, 1980]. Concrete construction in the coastal areas of the Arabian Gulf is continuously exposed to ground and atmosphere contaminated with salts. Aided by the capillary action and high humidity conditions, the salt-contaminated groundwater and the salt-laden airborne moisture and dew find an easy ingress into the hardened concrete. Further, the salts also pollute the mix water and the aggregates thereby increasing the total salt content of the concrete mixture.

## 2. CHARACTERISTICS OF THE ARABIAN GULF ENVIRONMENT

### 2.1. Climatic conditions

#### 2.1.1 Temperature and humidity

The Gulf climate is regarded as highly aggressive for concrete due to the hot and humid salt-laden conditions favorable for concrete deterioration. The long summer months extend from May to September with the temperature ranging from 25 to 45°C and there is a wide fluctuation in the day and night temperature. The solar radiation increases the day temperature and the concrete temperature increases by 10 to 20°C. The intense heat over the prolonged summer months creates difficulties in producing high quality concrete and increases the mechanical and chemical processes of concrete deterioration. Figure 1 shows the temperature regime for Dhahran (Rasheeduzzafar and Dakhil, 1980).

The salt-laden humidity on the coastal areas continuously supplies concrete structures with humidity and salts required for reinforcement corrosion and surface scaling. The daily average relative humidity varies from approximately 60% during summer months to about 90% during the short winter period. The cycles of moisture absorption and then evaporation under the sun accumulate salts at the concrete surface to the level of initiating reinforcement corrosion. Figure 2 shows the variation in the humidity in Dhahran. Table 1 shows the analysis for the night dew which continuously precipitates on the structures (Al-Gahtani, 1998).

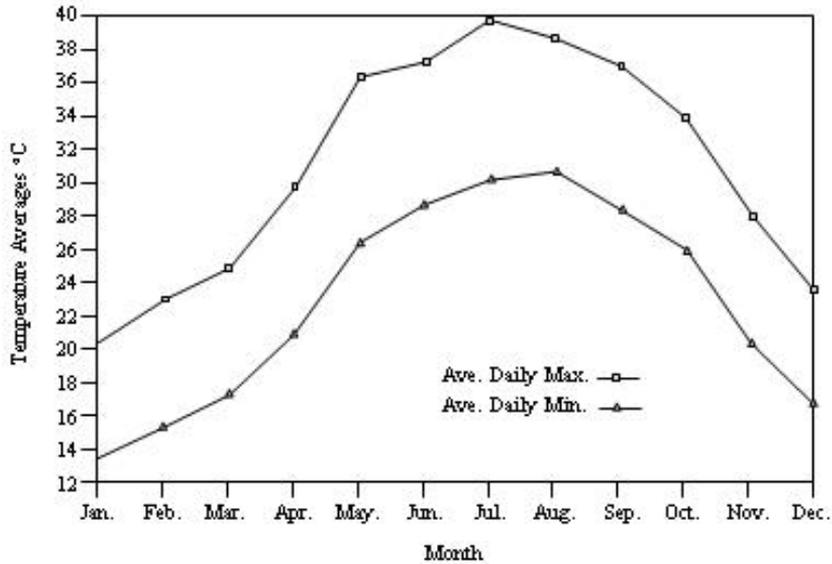


Figure 1. Temperature regime at Dhahran, Saudi Arabia

2.1.2 Precipitation

The low precipitation rate in the region combined with the high evaporation rate increases the concentration of salts on concrete surfaces, soil and groundwater.

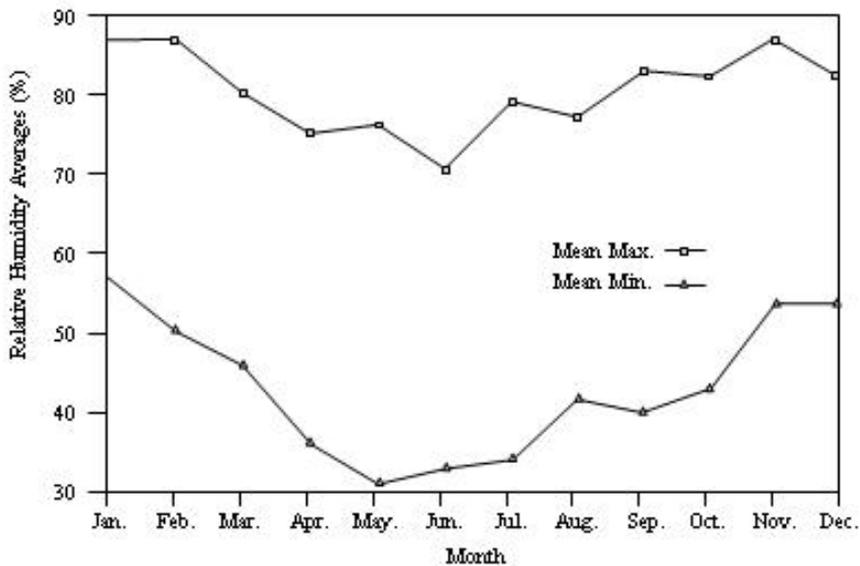


Figure 2. Average relative humidity at Dhahran, Saudi Arabia

Table 1. Analysis of dew and tap water in Dhahran area in Sept. 1998 (Al-Gahtani, 1998)

Constituent	Air humidity	Tap water
Cl <sup>-</sup>	36.8 ppm	99.26 ppm
SO <sub>4</sub>	25 ppm	3.2 ppm
Mg	8.3 ppm	3.9 ppm
Ca	3.2 ppm	8.01 ppm
pH	6.4	7.4
Conductivity	390*	–

\*µmhos/cm

### 2.1.3 Wind

The predominant direction of wind in most of the Gulf coast is towards North-Northwest with velocity ranging from 10 to 30 km/h. This wind blows salt-rich dust that settles on the top of the soil and the exposed concrete surfaces and increases the salt accumulation at the surface. Table 2 shows typical chemical analysis of windblown dust (Ismael, 1997).

The hot wind increases the rate of evaporation of mixing and curing water from fresh concrete, which increases the tendency for plastic shrinkage cracks and creates the necessary channels for the ingress of damaging species into concrete, causing early deterioration thereafter.

## 2.2. Geomorphic conditions

### 2.2.1 Construction materials

The available geomaterials for coarse aggregate production are mostly limestone. In general, such aggregate is soft, absorptive, and porous with excessive dust. Carbonate rocks, such as limestone and dolomite, are commonly of shallow marine origin in the Gulf region. They might contain impurities of clay minerals, chert, gypsum, halite (NaCl) and anhydrite (CaSO<sub>4</sub>). Water charged with atmospheric carbon dioxide dissolves limestone creating cavities in aggregates or in underground soils [Qahwash, 1997]. Such aggregate is highly contaminated with sulfate and chloride salts and provides basic ingredients for the deterioration of concrete and corrosion of reinforcing steel. Good quality aggregates could be obtained in U.A.E. from igneous rocks consisting mainly of feldspar and small quantity of olivine. Such rocks have high density, low absorption and they are free of chloride salts. However, they are expensive compared to aggregates produced locally by crushing limestone and therefore their use is limited outside U.A.E.

Table 2. Chemical analysis of the windblown dune sand (Ismael, 1997)

Component oxides	% Composition*		
	Natural sample	Coarse fraction	Fines passing #200 sieve
SiO <sub>2</sub>	76.15	82.79	42.46
Al <sub>2</sub> O <sub>3</sub>	6.39	5.17	12.14
Fe <sub>2</sub> O <sub>3</sub>	0.91	0.72	2.93
CaO	7.41	5.1	17.06
MgO	2.92	1.03	5.94
Cl <sup>-</sup>	0.06	0.05	0.14
SO <sub>3</sub>	0.16	0.85	2.67
Loss on ignition (Organic matter, moisture)	5.36	4.64	16.92

\*Based on the average value for samples taken from five sites in Kuwait.

The aeolian dune and beach sand are the main source of the fine aggregates. The sand obtained is mostly fine-grained with narrow grading. The fineness modulus is less than the ASTM C 33 grading limits. Further, it is contaminated with chloride and sulfate salts which affect the concrete durability.

### 2.2.2 Soil

Sabkhas cover large areas around the coastal region. Sabkha environment is very aggressive for the foundation due to the high salt concentration and the shallow groundwater table. The high concentration of chloride and sulfate salts in the sabkha soil deteriorates concrete and corrodes the reinforcement simultaneously. Table 3 shows the chemical analysis of sabkha soil and the seawater.

Table 3. Chemical analysis of sabkha brine and seawater (Al-Amoudi, 1994)

Ions (g/l)	Sabkha brine	Seawater
Na <sup>+</sup>	78.8	20.7
Mg <sup>++</sup>	10.32	2.30
K <sup>+</sup>	3.06	0.73
Ca <sup>++</sup>	1.45	0.76
Fe <sup>++</sup>	Trace	—**
Sr <sup>++</sup>	0.029	0.013
Cl <sup>-</sup>	157.2	36.9
Br <sup>-</sup>	0.49	0.121
SO <sub>4</sub> <sup>--</sup>	5.45	5.12
HCO <sub>3</sub> <sup>-</sup>	0.087	0.128
pH	6.9	8.3
Conductivity*	208,000	46,200

\*Micro siemens

\*\*Not reported

### 2.2.3 Groundwater

In many Gulf cities, the groundwater is near the surface due to the proximity to the Gulf shore and the low altitude level with respect to the seawater level. The level of groundwater is increasing in many inhabited areas due to an increase in the use of irrigation water and improper drainage systems. Such groundwater is highly contaminated with dissolved salts. The water-bearing salts attack buried and near surface concrete structures, causing concrete deterioration and corrosion of the reinforcing steel.

The effects of environmental and geomorphic conditions on concrete durability are summarized in Table 4.

Table 4a. Effect of environmental conditions on concrete durability

Climatic condition	Effect on concrete
High temperature	Plastic shrinkage cracks;
Fluctuation of temperature	Drying shrinkage cracks;
High salt-laden humidity	Rapid slump loss and high water/cement ratios;
Hot and dry-dusty winds from inland	Low strength and durability properties;
Low precipitation and high evaporation rate	Thermal and moisture cracking; Salt deposits on concrete surfaces.

Table 4b. Effect of geomorphic conditions on concrete durability

Geomorphic condition	Effect on concrete
Unsound/weak and porous aggregates	Low strength concrete;
Highly contaminated aggregates	Salt contamination of construction material;
Single sized/rounded sands	Sulfate attack and reinforcement corrosion;
Gap graded sands	Bleeding and harsh mixture;
Very high salinity in sabkha soils	Low workability;
Windblown silt or sand, leading to differential settlement	Surface defects and salt attack, reinforcement corrosion and cracking;
High level of salts in groundwater leading to foundation deterioration	High capillary rise and salts deposits on near ground concrete.
Shallow salt-bearing groundwater	

## 3. CONCRETE DETERIORATION DUE TO CHLORIDE-SULFATE EXPOSURE

Reinforced concrete structures in the Arabian Gulf are often exposed to the service environments charged with chloride-sulfate salts. The concrete deterioration due to these exposures is mainly manifested in the form of: (i) reinforcement corrosion (ii) sulfate attack

and (iii) salt weathering. All of these deterioration phenomena are concomitantly interactive in the structures exposed to sabkha or marine environments. However, deterioration due to reinforcement corrosion outweighs that due to the other causes. Factors contributing to concrete deterioration due to the chloride and sulfate exposure and the related studies are summarized in the following subsections.

### 3.1. Reinforcement corrosion

Reinforcement corrosion is the major cause of reduction in the useful service life of concrete structures worldwide. In the cold climates of Europe and North America, reinforcement corrosion is caused by the use of deicer salts and carbonation. However, in the Arabian Gulf, carbonation is not a major problem as the structures are fairly new. However, reinforcement corrosion is caused by the environmental conditions, poor quality of the concrete making materials, aggregates in particular, and inappropriate concrete specifications. While reinforcement corrosion is known to be caused by the chloride ions, the presence of sulfate ions in the atmosphere is known to accelerate the corrosion process.

[Al-Amoudi and Maslehuddin, 1993] investigated reinforcement corrosion in cement paste specimens immersed in chloride, sulfate, and chloride plus sulfate environments. The results of this study indicated that while the sulfate ions are hardly able to induce reinforcement corrosion, considerable corrosion activity was observed in the concrete specimens immersed in sodium chloride plus sodium sulfate solution. As shown in Table 5, reinforcement corrosion was observed to increase when the sulfate concentration in the 15.7% chloride solution was increased from 0.55 to 2.10%. An extension of this study [Al-Amoudi et al., 1994] to plain and blended cement concrete specimens indicated a similar trend. The effect of sulfate concentration, associated with fixed chloride level, was observed to be more pronounced on the corrosion rate, while no systematic trend was observed on the time to initiation of reinforcement corrosion.

Table 5. Effect of chloride plus sulfate ions on reinforcement corrosion  
(Al-Amoudi et al., 1994)

Cement	Time to initiation of corrosion, Days		Corrosion current density, $\mu\text{A}/\text{cm}^2$	
	Low sulfate plus chloride	High sulfate plus chloride	Low sulfate plus chloride	High sulfate plus chloride
Type I	108	162	3.9	4.17
Type V	80	106	4.1	4.76
Fly ash	152	210	1.27	1.72
Silica fume	548	552	0.24	0.29
Blast furnace slag	--	--	0.44	0.50

[Dehwah, 1999] evaluated the effect of sulfate concentration and the associated cation type, namely sodium and magnesium, on chloride-induced reinforcement corrosion. Plain and blended cement concrete specimens were exposed to chloride plus sulfate solutions for five years and reinforcement corrosion was monitored. The results of that study indicated that the sulfate ions did not influence the time to initiation of reinforcement corrosion while the rate of reinforcement corrosion in the concrete specimens exposed to sodium chloride plus sodium sulfate solutions was more than that in the specimens exposed only to sodium chloride or sodium chloride plus magnesium sulfate solution.

### 3.2. Sulfate attack

Deterioration of concrete due to the chemical reaction between the hydrated Portland cement and sulfate ions is known to take two forms depending on the concentration and the source of sulfate ions (the associated cation) and the composition of cement paste in concrete. Sulfate attack normally manifests in the form of expansion of concrete leading to its cracking. However, it can also take the form of a progressive loss of strength and mass due to deterioration in the cohesiveness of the cement hydration products.

Among the hydration products, calcium hydroxide and alumina-bearing phases are more vulnerable to attack by sulfate ions. On hydration, Portland cements with more than 5% tricalcium aluminate ( $C_3A$ ) will contain most of the alumina in the form of monosulfate hydrate,  $C_3A.C\bar{S}.H_{18}$ . If the  $C_3A$  content of the cement is more than 8%, the hydration products will also contain  $C_3A.CH.H_{18}$ . In the presence of calcium hydroxide, when the cement paste comes in contact with sulfate ions, both the alumina-containing hydrates are converted to ettringite ( $C_3A.3C\bar{S}.H_{32}$ ).

The formation of ettringite generates excessive expansion in concrete. However, the mechanisms by which ettringite formation causes expansion is still a subject of controversy. Exertion of pressure by forming ettringite crystals, and swelling due to adsorption of water in an alkaline environment by poorly crystalline ettringite, are two of the several hypotheses that are supported by most researchers [Mehta, 1994].

Since concrete structures in the Arabian Gulf are exposed to soil and groundwater contaminated with sulfate salts, sulfate attack is a possibility. Some studies have been conducted in this direction at KFUPM. [Rasheeduzzafar et al. 1990] investigated the influence of cement composition on sulfate resistance of cement concrete with varying  $C_3A$  content of cement and indicated that in addition to the  $C_3A$  content, the  $C_3S$  to  $C_2S$  ratio has a significant influence on sulfate resistance. Rasheeduzzafar et al. (1994) also investigated the effect of combined magnesium sulfate and sodium sulfate environments on the sulfate resistance performance of plain and blended cements. After two years of exposure, deterioration was observed in all cements. However, the deterioration was more pronounced in the blast furnace slag and silica fume cements. Deterioration in these cements significantly exceeded that observed in plain and fly ash blended cements. XRD and SEM analyses indicated massive gypsum formation in blended cements as compared to plain cements, which was attributed to

the conversion of calcium silicate hydrate to non-cementitious, non-crystalline, fibrous M-S-H due to the reaction of magnesium ions with the C-S-H. In the absence of calcium hydroxide, which is consumed by the pozzolanic reaction, magnesium ions react directly with C-S-H leading to the formation of M-S-H. Another reason for the aggravated deterioration of silica fume and blast furnace slag cements is the absence of protective brucite (magnesium hydroxide). The performance of blended cements in sodium sulfate environments was, however, observed to be better than that of plain cements.

Recently, [Al-Dulaijan et al. 2001] have investigated the effect of sulfate concentration and the associated cation type on the sulfate attack. They reported that the type of cement significantly affects the sulfate-resistance of concrete. Significant deterioration was noted in a moderate C<sub>3</sub>A (8.5%) cement compared to a low C<sub>3</sub>A (3.5%) cement and blended cements. While minor deterioration was noted in Type V cement exposed to sulfate concentrations of 2.5% and 4%, significant deterioration was noted in Type I cement exposed to sulfate concentrations as low as 1%. Blending the high C<sub>3</sub>A cement with fly ash (20%) or silica fume (8%) significantly improved its sulfate-resistance.

### **3.3. Effect of chloride ions on sulfate attack**

In marine environments and arid saline soils and groundwater, chloride and sulfate salts exist concomitantly. The conjoint presence of these two salts may cause deterioration of concrete due to reinforcement corrosion and sulfate attack. Rasheeduzzafar et al. (1992) reported that sulfate ions react preferentially with C<sub>3</sub>A to form two compounds of calcium sulfoaluminate hydrates, namely trisulfoaluminate hydrate (C<sub>3</sub>A.3CaSO<sub>4</sub> aqueous) and monosulfoaluminate hydrate (C<sub>3</sub>A.CaSO<sub>4</sub> aqueous).

Al-Amoudi et al. (1994) investigated the role of chloride ions on sulfate attack in OPC and blended cements. They reported that the sulfate deterioration in plain cements was mitigated by the presence of chloride ions, whereas in blended cements, particularly those prepared with silica fume and blast furnace slag, the beneficial effect of chloride was only marginal. The authors (Al-Amoudi et al., 1994) attributed this increased sulfate deterioration in the blended cements, particularly those prepared with silica fume and blast furnace slag, to the magnesium-oriented sulfate attack that was more operative in the blended cements due to the absence of calcium hydroxide. In contrast to the gypsum and ettringite-oriented sulfate attacks, this type of attack was not inhibited in the presence of chloride ions. Due to this effect of the magnesium ions on concrete deterioration in blended cements, the authors recommended use of additional protective measures such as application of an epoxy-based coating to the exterior surface of the structures exposed to magnesium sulfate.

## **4. SALT WEATHERING**

This type of deterioration of concrete is more of a physical nature than a chemical reaction. Deterioration of concrete is evident on the components just above the grade level and also in situations where the salt is deposited from the environment on the exposed surface. It is characterized by progressive crumbling or scaling that erodes the surface of concrete leaving

the aggregates exposed. Permeable concrete in contact with salt-bearing soil or groundwater absorbs groundwater containing soluble salts. If water can evaporate from any surface of the concrete, additional groundwater will be drawn into the concrete by capillary action. At the evaporation face, water will be lost, but the salts will remain on the concrete surface. Concrete with high permeability characteristics allows a higher transport of water through the pores; and therefore, a more rapid build-up of salts on the concrete surface. Once the salt solution reaches the saturated or supersaturated level, then salt crystals will be precipitated. Repeated crystallization cycles caused primarily by the night-day thermal changes and secondarily by relative humidity changes produce the destructive action on the concrete. The eroding process continues as long as the environmental changes of temperature and humidity cause cycles of salt crystallization.

Salt weathering may also be a major problem in the marine environments, particularly in the tidal zones, where concrete deterioration is aided by both the deposition of salts and their dissolution due to the cyclic action of wetting and drying. This phenomenon may also be attributed to the material properties. For example, concretes incorporating pozzolanic materials and low water cement ratio generate a very fine pore structure that cannot accommodate the salt crystals. These salt crystals exert considerable pressure, resulting in greater expansion and deterioration of concrete. Deterioration of the skin of concrete, scaling, is also more prominently evident in the silica fume and blast furnace slag cement concretes exposed to concentrated salt environments. Scaling of the concrete exposed to concentrated sulfate environments and to marine environments has been reported by Al-Amoudi et al. (1992) and Al-Rabiah (1990), respectively. Often there is confusion between sulfate attack and salt weathering. A clear understanding of the concrete deterioration due to salt weathering or sulfate attack is essential for the planning of repair and rehabilitation measures. The former deterioration process is due to chemical cause while the latter is a physical phenomenon.

## **5. CARBONATION**

Carbonation of concrete normally involves a chemical reaction between atmospheric carbon dioxide and the products of cement hydration. This reaction results in a significant reduction in the pH of the pore solution due to removal of hydroxyl ions. Though deterioration of concrete structures in many parts of the world is attributed to chloride-induced reinforcement corrosion, carbonation of concrete to an advanced stage, sometimes to the rebar level, is not uncommon. Carbonation of concrete is commonly noted in industrial environments and old structures. In temperate climatic conditions, carbonation is the main cause of reinforcement corrosion, except in highway structures. However, concrete is conducive to accelerated carbonation in the hot and semi-arid environments. There is a general agreement that carbonation is accelerated at a relative humidity between 50 and 70%. Similarly, the rate of carbonation was observed to increase with temperature. After three years of service, the depth of carbonation in the atmospheric zone of the Saudi Arabia-Bahrain causeway was 13 mm compared to 2 mm observed in the splash zone [Al-Rabiah, 1990]. No carbonation was observed in the tidal and submerged zones. [Hussain et al. ,1994] recorded carbonation depths

of 15 mm on the exterior components and 3 to 5 mm on the interior components of a structure in the Arabian Gulf, after about six years of service.

The chloride-sulfate contamination of concrete may also accelerate the carbonation of cement. The presence of alkalis is known to accelerate the hydration of cement resulting in a heterogeneous pore structure, which increases the rate of carbonation [Maslehuddin, 1996a]. Limited studies conducted by [Al-Amoudi et al., 1991] and [Macmillan and Treadaway, 1990] have indicated that the presence of chloride and/or sulfate contamination within concrete accelerates carbonation of cement. Studies conducted by [Maslehuddin et al., 1996a] have indicated accelerated carbonation of cement in the presence of chloride and sulfate salts. The rate of carbonation in the cement mortar specimens contaminated with sodium chloride was on an average six times that in the uncontaminated mortar specimens, while in the mortar specimens contaminated with chloride plus sulfate salts the rate of carbonation was 10 times that in the uncontaminated concrete specimens.

## **6. EFFECT OF TEMPERATURE**

High temperature causes great differences in the degree of attack in concrete and reinforcement corrosion. The diffusion of aggressive substances such as chloride ions and carbon dioxide proceeds more rapidly. Studies conducted by [Uhlig, 1983] on the effect of temperature and humidity on the corrosion process showed that when circumstances are such that corrosion can occur, its rate is increased by high temperature and high humidity. The rate of corrosion appears to be sharply increased by an increase in temperature in the range of 20 to 40°C, especially at high humidity. Maslehuddin et al. (1994) investigated the effect of temperature and chloride contamination on the electrochemical behavior of mild steel placed in an electrolyte representing the concrete pore solution. The potentiodynamic curves for the uncontaminated specimens indicated a decrease in the pitting potential with increasing temperature. The potentiodynamic curves for mild steel placed in an alkaline solution contaminated with chloride and exposed to temperatures in the range of 25 to 70°C indicated an increase in the corrosion activity with temperature. While there was a marginal increase in the corrosion current density when the temperature was increased from 25 to 40°C, the increase in the corrosion current density when the exposure temperature was increased from 40 to 55°C was substantial. No significant difference in the corrosion current density was observed when the temperature was increased from 55 to 70°C. Pitting corrosion was indicated in all the specimens exposed to this environment.

In another study, [Maslehuddin et al., 1996b] evaluated the effect of temperature on reinforcement corrosion in concrete contaminated with chloride and sulfate salts. Reinforcement corrosion in the chloride-contaminated concrete increased almost 1.4 times for every 10°C rise in temperature. However, there was no significant increase in the corrosion with increasing temperature in the concrete specimens contaminated with chloride plus sulfate salts. The implication of these results is that the conjoint presence of chloride and sulfate salts significantly increases the rate of reinforcement corrosion that negates the effect of temperature.

Another detrimental effect of elevated temperature is on the properties of fresh and hardened concrete. In the fresh concrete, plastic shrinkage is accelerated in the early stages of setting of cement. Likewise, accelerated drying shrinkage may result due to evaporation of mixing and curing water at elevated temperature. In the hardened concrete, thermal variations contribute to microcracking, particularly at the aggregate mortar interface, which compromise both the strength and the durability characteristics.

[Almusallam et al. 1998] evaluated the effect of environmental conditions on the properties of fresh and hardened concrete. The data developed in this study indicate that environmental conditions significantly affect the properties of fresh and hardened concrete. The rate of water evaporation, shrinkage strain and the area of cracks increased with increasing exposure temperature and wind velocity, and decreasing relative humidity. Plastic shrinkage cracks were noted earlier in the concrete specimens exposed to elevated temperature and low relative humidity, compared to specimens exposed to low temperature and high humidity.

The exposure conditions also influence the properties of hardened concrete. Elevated temperature exposure decreased the compressive strength and pulse velocity. The compressive strength of concrete specimens cast and exposed at 40°C was less than that of specimens cast at 30°C. Similarly, the pulse velocity of the former group of concrete specimens was less than that of the latter group. A variation in the relative humidity and wind velocity had an insignificant effect on pulse velocity and compressive strength of concrete.

## 7. EFFECT OF HUMIDITY

Relative humidity in the pores of the concrete and the surrounding environment also significantly affects concrete durability. As in the case of temperature, relative humidity influences the properties of both fresh and hardened concrete. In the case of fresh concrete, plastic shrinkage is significantly affected by the relative humidity. [Almusallam et al. 1998] evaluated the plastic shrinkage of plain and blended cements under varying relative humidity. Table 6 summarizes the effect of RH and wind velocity on time to cracking of concrete. The concrete specimens exposed to a low RH cracked earlier than those exposed to a high RH. Under windy conditions, concrete specimens exposed to similar RH cracked earlier than those exposed to normal conditions (no wind), and the cracking time decreased with wind velocity.

Table 6. Effect of relative humidity and wind velocity on time to cracking  
(Almusallam et al., 1998)

Wind velocity, km/h	Time to initiation of cracks, Hours		
	RH: 25%	RH: 50%	RH: 95%
0	3.5	4.5	6.0
15	2.5	4.0	NA*
25	2.0	3.0	NA*

\*This condition was not investigated.

With regard to durability, relative humidity affects reinforcement corrosion and carbonation of concrete. The presence of excessive moisture in the concrete pores prevents the diffusion of oxygen to the steel surface thereby preventing the cathodic reaction. Similarly, at low humidity levels the rate of reinforcement corrosion is avoided. The optimum humidity for reinforcement corrosion to occur is therefore taken to be around 45 to 55%. A similar behavior is noted for the carbonation of concrete to occur.

## **8. CONCLUDING REMARKS**

Concrete structures in the Arabian Gulf are exposed to unique service conditions. The environmental conditions of this region, characterized by elevated temperature and humidity conditions, severely affect the performance of concrete both in its fresh and hardened stage. The presence of high chloride and sulfate concentration in the soil, groundwater and the environment accelerates the deterioration processes. The poor quality of the aggregates, lack of appropriate specifications and skilled manpower are the other contributory factors.

In this paper, the role of the environmental conditions on concrete deterioration is discussed. It is shown that elevated temperature, humidity, and the presence of high concentration of chloride and sulfate salts influence concrete durability. Studies conducted locally on this aspect were reviewed with a view to educate the engineering community on the causal factors for concrete deterioration. It is expected that once the causal factors are known, ameliorative measures would be adopted.

## **ACKNOWLEDGEMENTS**

The authors wish to express their appreciation for the support provided by the Department of Civil Engineering and the Research Institute at King Fahd University of Petroleum and Minerals in the preparation of this paper.

## **REFERENCES**

1. Al-Amoudi, O.S.B., 1994, "Chemical Stabilization of Sabkha Soils at High Moisture Content," *Engineering Geology*, 36 (3/4), pp. 279-291.
2. Al-Amoudi, O.S.B. and Maslehuddin, M., 1993, "The Effect of Chloride and Sulfate Ions on Reinforcement Corrosion," *Cement and Concrete Research*, 23 (1) pp. 139-146.
3. Al-Amoudi, O.S.B., Rasheeduzzafar and Maslehuddin, M., 1991, "Carbonation and Corrosion of Rebars in Salt Contaminated OPC/PFA Concretes," *Cement and Concrete Research*, 21 (1), pp. 38-50.
4. Al-Amoudi, O.S.B., Abduljawwad, S.N., Rasheeduzzafar and Maslehuddin, M., 1992, "Effect of Chloride and Sulfate Contamination in Soils on Corrosion of Steel and Concrete," *Transportation Research Record No. 1345*, pp. 67-73.

5. Al-Amoudi, O.S.B., Rasheeduzzafar, Maslehuddin, M. and Abduljawwad, S.N., 1994, "Influence of Chloride Ions on Sulfate Deterioration in Plain and Blended Cements," *Magazine of Concrete Research*, 46 (167), June, pp. 113-123.
6. Al-Dulajian, S.U., Maslehuddin, M., Al-Zahrani, M.M., Sharif, A.M., Shameem, M. and Ibrahim, M., "Sulfate-resistance of Plain and Blended Cements Exposed to Varying Concentrations of Sodium Sulfate," *Cement and Concrete Composites*, Theme Issue on Concrete Durability, to be published.
7. Al-Gahtani, A.S., 1998, "Environmental Consideration for the Use of Epoxy-Coated Rebars in the Gulf Region," *Symposium Proceedings, Performance of Concrete Structures in the Arabian Gulf Environment*, KFUPM, Dhahran, pp. 21-36.
8. Almusallam, A.A., Maslehuddin, M., Waris, M.A., Al-Amoudi, O.S.B. and Al-Gahtani, A.S., 1998, "Plastic Shrinkage of Concrete in Hot and Arid Environments," *The Arabian Journal for Science and Engineering*, Theme Issue on Concrete Repair, Rehabilitation and Protection, 23 (2C), pp. 57-72.
9. Al-Rabiah, A.A., 1990, "Concrete Durability in the Arabian Gulf Marine Environment," Ph.D. Thesis, University of Salford, England.
10. Dehwah, H.A.F., 1999, "Influence of Cement Composition on Concrete Durability in Chloride-Sulfate Environments," Ph.D. Dissertation, Loughborough University, UK.
11. Fookes, P.G. and Collis, L., 1975, "Aggregates and the Middle East," *Concrete*, 9 (1).
12. Hsu, T.T.C., 1963, "Mathematical Analysis of Shrinkage Stresses in a Model of Hardened Concrete," *ACI Journal*, 60 (3), pp. 371-390.
13. Hussain, S.E., Paul, I.S. and Ruthaiyea, H.M., 1994, "Evaluation and Repair Strategies for Shallow Foundations," *Proceedings, 6th Middle East Corrosion Conference*, Bahrain, pp. 613-628.
14. Ismael, N.F., 1997, "Properties and Behavior of Arid Climate Soil Deposits in Kuwait," *Symposium on Civil Engineering and The Environment*, KFUPM, Dhahran, pp. 345-384.
15. Macmillan, G.L. and Treadaway, K.W.J., 1990, "An Exposure Trial of Concrete Durability in the Arabian Gulf Conditions," *Corrosion of Reinforcement in Concrete*, Page, Treadaway and Bamforth, Editors, Elsevier Applied Science, London, pp. 109-118.
16. Maslehuddin, M., Jarrah, N.R., Ashiru, O.A. and Al-Mana, A.I., 1994, "Corrosion of Steel in Alkaline Media," *Proceedings, 6th Middle East Corrosion Conference*, Bahrain, January, pp. 597-611.
17. Maslehuddin, M., Page, C.L. and Rasheeduzzafar, 1996a, "Effect of Temperature and Salt Contamination on Carbonation of Cements," *ASCE Journal of Materials in Civil Engineering*, 8 (2), pp. 63-69.
18. Maslehuddin, M., Page, C.L., Rasheeduzzafar and Al-Mana, A.I., 1996b, "Effect of Temperature on Pore Solution Chemistry and Reinforcement Corrosion in Contaminated Concrete," *Proceedings, 4th International Conference on Corrosion of Reinforcement in Concrete*, Cambridge, pp. 67-75.
19. Mehta, P.K., 1994, "Concrete Technology at the Crossroads - Problems and Opportunities," *American Concrete Institute Special Publication SP-144*, pp. 1-30.

20. Meshal, A.H. and Hassan, H.M., 1986, "Evaporation from the Coastal Waters of the Central Part of the Gulf," *Arabian Gulf Journal of Scientific Research*, 4 (2), pp. 649-655.
21. Privett, D.L., 1959, "Monthly Charts of Evaporation from the North Indian Ocean, including the Red Sea and Persian Gulf," *O.J. Roy Meteorol. Soc.*, 85, pp. 424-428.
22. Qahwash, A.A., 1997, "Susceptibility of Limestones to Diagenesis and Weathering Processes," *Symposium on Civil Engineering and the Environment*, KFUPM, Dhahran, pp. 105-110.
23. Rasheeduzzafar and Dakhil, F.H., 1980, "Field Studies on the Durability of Concrete Construction in a High Chloride-Sulphate Environment," *International Journal of Housing Science*, 4 (3), pp. 203-232.
24. Rasheduzzafar and Dakhil, F.H., 1985, "An Investigation of the Durability Problems of Concrete Construction in the Eastern Province of Saudi Arabia," Final Report, SANCST Project No. AR-2-030, Saudi Arabian National Center for Science and Technology, Riyadh.
25. Rasheeduzzafar, Dakhil, F.H., Al-Gahtani, A.S., Al-Saadoun, S.S. and Bader, M.A., 1990, "Influence of Cement Composition on the Corrosion of Reinforcement and Sulfate Resistance of Concrete," *ACI Materials Journal*, 87 (2), pp. 114-122.
26. Rasheeduzzafar, Hussain, S.E. and Al-Saadoun, S.S., 1992, "Effect of Tricalcium Aluminate Content of Cement on Chloride Binding and Corrosion of Reinforcing Steel in Concrete," *ACI Materials Journal*, pp. 3-12.
27. Rasheeduzzafar, Al-Amoudi, O.S.B., Abduljauwad, S.N. and Maslehuddin, M., 1994, "Magnesium-Sodium Sulfate Attack in Plain and Blended Cements," *ASCE Journal of Materials in Civil Engineering*, 6 (2), pp. 201-222.
28. Uhlig, H.H., 1983, *Corrosion and Corrosion Control*. John Wiley and Sons, New York.