

CONCRETE DURABILITY - THE ARABIAN GULF EXPERIENCE

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ABSTRACT

The reduction in the useful service-life of reinforced concrete construction in the Arabian Gulf is well recognized. This phenomenon has been attributed mainly to the inappropriate evaluation of the service environment and a lack of appreciation of the need to provide additional protection to both the concrete and steel to withstand the severity of the exposure conditions.

While the latest developments in the concrete technology, e.g., methods and materials, provide useful guidelines for the production of durable concrete structures, the performance of such materials in the hot and humid environment of this region needs to be re-evaluated. Such an re-evaluation is helpful in selecting the best materials and avoid costly failures later. In this direction, research efforts have been made at King Fahd University of Petroleum and Minerals, to assess ways and means to improve the durability of concrete construction in this region. The causal factors for concrete deterioration have been investigated through field surveys and the performance of materials has been evaluated through laboratory and exposure site studies. This paper summarizes these efforts, dealing mostly with the research that has been conducted in the past five to six years.

Key Words: Arabian Gulf, Coated Steel, Concrete durability, Concrete Protection, Hot and Humid Environment.

1.0 INTRODUCTION

Portland cement concrete has been used since several decades to build the infrastructure necessary for human development. The varying shapes and sizes of structures, that the architects and engineers were able to produce using reinforced concrete, has had a tremendous beneficial influence on the environment. However, deterioration of some structures, such as in the coastal areas of the Arabian Gulf and road and bridges in the temperate climatic conditions of North America and Europe, is of concern both from the economic and environmental perspective. Furthermore, the premature deterioration of reinforced concrete construction in the coastal areas of the Arabian Gulf has resulted in considerable resources to be diverted towards the repair and rehabilitation of these

structures. The main forms of concrete deterioration are cracking and spalling of concrete due to reinforcement corrosion, sulfate attack, and cracking due to environmental effects. These forms of deterioration are mainly attributed to: (i) severe climate, (ii) inappropriate materials specifications, and (iii) inadequate construction practices.

This paper presents results of field and laboratory investigations conducted at King Fahd University of Petroleum and Minerals (KFUPM) to study concrete performance in the Arabian Gulf environment. The results of studies conducted to enhance the useful service-life of concrete structures are discussed.

2.0 CONCRETE DETERIORATION IN THE ARABIAN GULF

As stated earlier, the deterioration of concrete in the Arabian Gulf is principally due to reinforcement corrosion, sulfate attack, and cracking due to environmental factors. However, the deterioration due to reinforcement corrosion outweighs that due to other factors. Corrosion of reinforcing steel is mainly attributed to the excessive amounts of chloride in the concrete which are either contributed by the mix constituents or which diffuse from the service environment. Other factors, such as temperature, sulfate contamination, and carbonation may also influence the initiation and sustenance of reinforcement corrosion. The effect of some of these factors on chloride-induced reinforcement corrosion are discussed, as also concrete deterioration due to sulfate attack and cracking due to environmental effects.

2.1 CHLORIDE-INDUCED REINFORCEMENT CORROSION

The major form of concrete deterioration in this area is chloride-induced reinforcement corrosion. Since the environment is hot and humid and is contaminated with the chloride and sulfate salts, concrete deterioration is often attributed to chloride dominated reinforcement corrosion. The chloride ions may be contributed by the mix constituents or they may penetrate from the service environment. Reinforcement corrosion in the sub-structural components or at the grade level was mostly attributed to the chlorides diffusing from the soil and/or ground water. In the superstructure, reinforcement corrosion in majority of the cases has been attributed to chloride ions contributed by the mix constituents. Another important factor which has accelerated concrete deterioration due to chloride-induced reinforcement corrosion is the conjoint presence of chloride and sulfate ions in the soil and ground water, or the mix constituents. Studies conducted at KFUPM [Maslehuddin et al., 1994] indicated that the conjoint presence of chloride and sulfate ions in concrete, particularly when it is fresh, influences reinforcement corrosion by two mechanisms; namely by a reduction in the chloride-binding capacity of cements and by decreasing the electrical resistivity of concrete. In an investigation conducted by Maslehuddin et al. [1996] the rate of reinforcement corrosion in the concrete specimens contaminated with chloride plus sulfate was on an average 1.4 to 2.0 times that in the concrete specimens contaminated with only sodium chloride. Al-Amoudi and Maslehuddin [1993] investigated reinforcement corrosion in the cement paste specimens exposed to chloride, sulfate and chloride plus sulfate environments. The results of this study indicated that while the sulfate ions were hardly able to induce reinforcement corrosion, considerable corrosion activity was observed in the specimens immersed in the sodium chloride plus sodium sulfate solution. Reinforcement corrosion was observed to

increase by almost two times when the sulfate concentration in the 15.7% chloride solution was increased from 0.55 to 2.10%. An extension of this study [Maslehuddin, 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.

While the influence of sulfate on reinforcement corrosion is of concern in the underground structures, where both chloride and sulfate salts are normally present, the effect of environmental temperature is of concern in the superstructures. Studies by Maslehuddin [1994] indicated that the corrosion current density increases by two to six times when the environmental temperature increases from 25 to 70 °C. As expected, the results of this study also indicated that acceleration of reinforcement corrosion was noticeable only in the concrete specimens contaminated with chloride and sulfate salts, while temperature had an insignificant effect in the uncontaminated specimens. Therefore, it is important that chloride and sulfate contamination contributed by the mix constituents should be minimized. It is a common practice to wash the aggregates to achieve this goal.

As expected, the quality of concrete, and the concrete cover has also been found to influence deterioration due to chloride-induced reinforcement corrosion. A good quality concrete, compressive strength of more than 30 Mpa, *per se*, and cover of more than 50 mm was sufficient to withstand chloride contamination of more than 0.40%, by weight of cement, in many structures inspected by the author. Deterioration of concrete due to chloride-induced reinforcement corrosion was observed mostly at the grade level, when sufficient protection was not provided. Poor quality of the hardened concrete, due to inadequate consolidation, curing, insufficient and non-uniform cover also lead to reinforcement corrosion, even though chloride contamination was within acceptable limits.

2.2 CARBONATION

Though deterioration of concrete structures in the Arabian Gulf is primarily attributed to chloride-induced reinforcement corrosion, carbonation of concrete, sometimes to the rebar level is not uncommon. This may be attributed to the environmental conditions of the Arabian Gulf, which are characterized by elevated ambient temperatures (40 °C and above) and relative humidity (50-80%), which are conducive for carbonation of cement.

After three years of service, the depth of carbonation immediately above the splash zone of the Saudi Arabia-Bahrain causeway was observed to be 13 mm compared to 2 mm measured within the splash zone [Al-Rabiah, 1990]. In-situ investigations conducted by Hussain et al. [1994] on a reinforced concrete structure in an industrial area along the Arabian Gulf, indicated carbonation to a depth of 15 mm on the exterior components, whereas on the interior components it was 3 to 5 mm, after about six years. Carbonation of concrete beyond the cover depth was also observed in an industrial environment during field inspection of concrete structures by the author.

Chloride and sulfate contamination may be the other factor for accelerated carbonation of cements. Studies by Maslehuddin et al. [1996] reported a greater depth of carbonation in

the contaminated cement mortar specimens than in the corresponding uncontaminated specimens. The increased carbonation in the contaminated cements was attributed to the changes in the pore structure of cement due to the inclusion of contaminants. This trend of increased carbonation in the contaminated specimens was also observed in the blended cements. In these cements, in the absence of Ca(OH)_2 , which is consumed due to pozzolanic reaction, CO_2 reacts with C-S-H converting it to calcite, vaterite and aragonite and other forms of CaCO_3 [Maslehuddin et al., 1996]. Further, the increased carbonation observed in the blended cements is of concern, as these materials have to be imported for their technical merit and cost two to three times that of ordinary Portland cement.

2.3 SULFATE ATTACK

Deterioration of concrete due to sulfate attack is a commonly observed phenomenon when structures are exposed to sulfate solutions, or are placed in sulfate-bearing soils or ground waters. In the coastal areas of the Arabian Gulf, the capillary rise of moisture and frequent flooding followed by intense evaporation leaves a heavy crust of salt in the upper few feet of the soil. Soil investigations on 179 samples from Jubail area in the eastern province show 31% samples containing sulfate ion concentrations in the soil water extracts in the range of 0.18 to 0.55%. In Kuwait, sulfate concentrations (as SO_3) ranging from 0.25% to over 2% were found at many locations. However, most of the instances of sulfate attack in the Arabian Gulf were failures of mortars and rendering along the external surfaces especially at the grade level.

The minimal damage to concrete due to sulfate attack may be attributed to the use of Type V cement in this region. This type of cement is used very commonly, in the structures above and below the ground. Another cause may be the conjoint presence of chloride and sulfate salts. Studies conducted at KFUPM [Al-Amoudi et al., 1994] indicated the beneficial role of chloride ions on sulfate attack. The mechanisms advanced to explain the amelioration of sulfate attack by the concomitant presence of chlorides is based on the contention that in the presence of chloride less trisulfate (ettringite) is formed. This reduction in trisulfate is attributed to the fact that its solubility is increased by chloride ions and that a part of the tricalcium aluminate (C_3A) which engenders ettringite formation is combined as calcium chloro-aluminate (Friedel's salt). Further, it is believed that trisulfate crystallizes from the solution when chloride is present, because of the higher solubility of trisulfate in chloride-containing solutions and so it does not cause expansion. Another important finding of this study was the accelerated deterioration of silica fume and blast furnace slag in the magnesium sulfate environment. Further, the chloride beneficiation was not observed in these cements. It was suggested that the components made with silica fume and exposed to magnesium sulfate environments, these type of salts are more common in sabkha, should be protected by applying an epoxy-based coating.

2.4 CRACKING DUE TO ENVIRONMENTAL EFFECTS

The hot weather conditions of the Arabian Gulf pose several problems to the fresh and hardened concrete. Some of the problems in fresh concrete are: increased water demand, rapid loss of slump, accelerated set, and increased plastic and drying shrinkage cracking. The potential problems in hardened are: decreased long-term strength, resulting from either higher water demand or higher concrete temperature at the time of placement,

increased tendency for drying shrinkage, from temperature differentials within the cross section of a member, increased permeability, and enhanced reinforcement corrosion, which is primarily due to cracking of concrete. However, plastic shrinkage cracking is of major concern with the hot weather conditions. Although these cracks may also develop at normal temperatures, this phenomenon is frequently associated with concreting under hot weather conditions. They may form focal points for other forms of deterioration, by allowing moisture and oxygen to steel surface.

ACI Committee 305 provides useful guidelines for concreting under hot weather conditions in addition to providing a useful chart for calculating the rate of evaporation. However, this chart based on the Menzel's formula has two draw backs. Firstly, one can only calculate the rate of evaporation, but not the possibility of shrinkage cracks and secondly, this chart is not valid for ambient temperatures of more than 38 °C. Further, the evaporation rate formulas can be applied only when the surface is completely covered with water. This fact is not usually taken into account and is not mentioned anywhere in the Standard Practice for Curing Concrete (ACI 308) nor in any other ACI and PCI publications. Further, the use of superplasticizers and low water cement ratios now a days seldom allows the concrete surface to be completely covered by water, hence using the graph based on Menzel's equation is not feasible.

Investigations [Waris, 1996] were therefore conducted to evaluate the effect of environmental conditions on the rate of evaporation of surface water and plastic shrinkage cracking in the fresh concrete.

The data developed in this study indicated that plastic shrinkage cracking occurred whenever bleeding stopped or the rate of evaporation exceeds the rate of bleeding. Similarly, it was observed that the rate of evaporation controlled the time and intensity of plastic shrinkage cracks. However, the total area of cracks is dependent on the environmental conditions.

The results of this study have also shown that ACI 305 graphical method is not very useful in the arid and semi-arid areas of the world, particularly in summer, as it is formulated for temperatures of up to 38 °C. Furthermore, cracking was observed at evaporation rates ranging from 0.2 to 0.7 kg/m².h, as against a value of 1 kg/m².h, recommended by ACI 305.

3.0 IMPROVING CONCRETE DURABILITY

The durability performance of concrete can be improved through appropriate mix design, and providing additional protection to both concrete and the reinforcing steel. However, concrete mix design plays an important part in the production of a durable concrete.

3.1 CONCRETE MIX DESIGN

The mix design parameters that influence the durability performance of concrete are: water-cementitious materials ratio, cement content and size and grading of aggregate. The permeability of concrete can be further decreased by incorporating supplementary cementing materials, such as fly ash, blast furnace slag and silica fume. The former aspect, namely the effect of mix design on concrete durability has been studied at the

international level and in the Arabian Gulf, the use of supplementary cementing materials deserves special mention for two reasons. Firstly, the climatic conditions of the Arabian Gulf make curing a difficult process, and secondly, these materials are used purely for their technical merit, unlike in other parts of the world where they are used for economic reasons.

As in other parts of the world, fly ash, blast furnace slag, and silica fume cement have been used in the Arabian Gulf to improve the denseness of concrete. While blast furnace slag cement has been used in a few structures, fly ash and silica fume, particularly the latter is now widely used in new structures and for repair of the old structures. are find wide usage for the production of durable concrete, particularly the latter. Research conducted at KFUPM [1983] on several pozzolanic materials, especially fly ash, has shown that compressive strength of concretes made with several of the pozzolans was less than that of ordinary portland cement (OPC) even after 180 days of curing. However, in a later study both fly ash and silica fume performed better than OPC from the initial curing periods of three days. In yet another study [1995], the effect of silica fume addition on the chloride permeability of field structures was investigated. As shown in Table 1, the chloride permeability decreased with the dosage of silica fume. Although these data, indicated a beneficial effect of silica fume replacement of cement of up to 15%, there may be other concerns, such as increased shrinkage, creep, long-term strength loss, with this high dosage of silica fume. In order to avoid these problems, silica fume is presently used as 7-10% replacement of cement.

Table1: Chloride permeability in field structures incorporating silica fume

Silica fume content, % Wt. of cement	Chloride permeability, Coulombs
0	15420
7	755
10	331
15	189

3.2 CONCRETE PROTECTION

Concrete structures are normally coated with sealers, penetrants or coatings to improve their useful service-life. These surface treatment materials protect the reinforcing steel by excluding the aggressive species, such as chloride and moisture from penetrating to the steel surface. Penetrants are low viscosity liquids which can penetrate into concrete and line its pores. They protect concrete by forming a hydrophobic layer and thus repel moisture, but, they facilitate the evaporation of water vapor and other gases from the interior of the concrete mass. Coatings provide protection to concrete by forming a thick protective film on the surface. However, due to minimal breathability they are not efficient in minimizing concrete deterioration. Sealers are intermediate between penetrants and coatings. They protect concrete by blocking the pores. They are more viscous than penetrants and generally form a film on the surface of concrete. Several studies [Engelfield, 1985; Leeming, 1990; Cabrera and Hassan, 1990] have been conducted to evaluate the effectiveness of sealers and other surface treatment materials in enhancing the durability of

concrete in the temperate climatic conditions. The earliest study on the use of sealers in the hot and humid environment of the Arabian Gulf was that by Al-Juraifani [1994] who evaluated the performance of penetrating sealers by exposing the specimens to sodium chloride solution for 21 days at temperatures between 20 and 65 °C. Studies conducted at KFUPM [Ibrahim, 1996] evaluated the performance of selected sealers, penetrants and coatings by exposing them to heat-cool and wet-dry environments. Carbonation and sulfate- and corrosion-resistance of concrete specimens coated with these materials was also evaluated.

As shown in Table 2, the water absorption in the coated specimens was less than that in the uncoated concrete specimens, even after exposure to heat-cool treatment. The best performance was indicated by concrete specimens coated with an acrylic coating. A more or less similar behavior was noted in the coated and uncoated concrete specimens exposed to wet-dry environment.

Table 2: Performance of sealers and coatings

Sealer/Coating	Absorption after exposure to heat-cool environment, %	Absorption after exposure to wet-dry environment, %	Reduction in compressive strength due to sulfate exposure, %	Depth of carbonation, mm
Uncoated	5.5	5.0	41	28.3
Sodium silicate	5.9	5.1	39.3	13.1
Silicone resin	2.5	2.7	36.1	24.8
Silane/Siloxane	1.8	2.7	26.8	23.9
Silane/siloxane with top coat	1.7	0.7	8.3	0
Silane	1.8	1.1	24.3	25.1
Acrylic coating	1.2	0.3	19.6	0

Among the penetrating sealers investigated the reduction in compressive strength, due to sulfate attack, was the least in the concrete specimens coated with silane/siloxane with top coat. The sulfate-resistance of concrete specimens coated with acrylic coating was slightly better than those coated with silane and silane/siloxane. Therefore, it is advisable to apply a silane/siloxane followed by epoxy coating to the foundations exposed to sulfate bearing soil and ground water.

The depth of carbonation in the concrete specimens coated with silane/siloxane with top coat and acrylic coating was very minimal, almost no carbonation, compared to 28 mm measured in the uncoated concrete specimens.

Results of this study indicate that acrylic coating can be used on the superstructures and silane/siloxane with top coat can be used on the substructures to improve concrete durability.

3.3 PROTECTION OF REINFORCING STEEL

3.3.1 Use of Inhibitors

Inhibitors are normally added to concrete to protect the reinforcing steel. An ideal corrosion inhibitor is a chemical compound that when added in adequate quantity can prevent corrosion of embedded steel and has no adverse effect on the properties of fresh and hardened concrete. Several inhibitors have been shown to inhibit reinforcement corrosion in the presence of chloride ions. Among them, calcium nitrite was observed to be more beneficial. More recently, calcium nitrate has also been used for the same purpose. However, data are lacking on the performance of these materials in the Arabian Gulf, where concrete is normally contaminated with chloride salts. Studies were conducted at KFUPM [Lashari, 1996] to evaluate the effectiveness of selected inhibitors in inhibiting reinforcement corrosion in concrete contaminated with chloride and sulfate salts. The effectiveness of inhibitors in reducing reinforcement corrosion, in the presence of contaminants, such as chloride and sulfate, was evaluated by measuring corrosion potentials and corrosion current density. The data developed in this study indicate that both calcium nitrite and calcium nitrate were effective in delaying the initiation of reinforcement corrosion in the concrete specimens made with sea water, brackish water or unwashed aggregate. As shown in Table 3, both nitrite and nitrate were also effective in reducing the rate of reinforcement corrosion. In the concrete specimens made with sea water 2% calcium nitrite was more effective in minimizing reinforcement corrosion compared to calcium nitrate. In the concrete specimens made with brackish water and unwashed aggregate both calcium nitrite and nitrate were effective in minimizing reinforcement corrosion. The preferred corrosion inhibitor and its dosage, for varying mix constituent is detailed in Table 4.

Table 3: Corrosion current density on steel in the concrete specimens incorporating corrosion inhibitors

Mix ingredient	Corrosion Current density, $\mu\text{A}/\text{cm}^2$					
	Control	Calcium Nitrite		Calcium Nitrate		
		2%	4%	2%	3%	4%
Sea water	0.54	0.044	0.042	0.059	0.061	0.06
Brackish water	0.39	0.033	0.033	0.064	0.056	0.047
Unwashed aggregate	0.24	0.075	0.064	0.062	0.059	0.057

Results of this study indicate that calcium nitrate can be beneficially used when aggregates are contaminated and their washing is not feasible.

Table 4: Preferred corrosion inhibitor for the type of mix water used in concrete

Mix constituent	Type and dosage of inhibitor
Sea water	4% calcium nitrite
Brackish water	2% calcium nitrite
Unwashed aggregate	4% calcium nitrate

3.3.2 Coated Bars

Fusion bonded epoxy coated (FBEC) bars are used in the concrete structures exposed to chloride environments. In the Arabian Gulf, FBEC bars are now more commonly used in the foundations and up to about one to two meters above the grade. However, there are two concerns regarding the performance of FBEC bars. The first anxiety relates to the effect of surface damage and holidays on reinforcement corrosion and the second concern relates to the bond strength. While the first concern can be addressed through design and detailing, the corrosion performance of FBEC bars is still a controversial issue. Debonding of the coating, particularly in high chloride environments is of particular concern. Two important studies were conducted at KFUPM on this aspect. Rasheeduzzafar et al. [1986] evaluated the corrosion-resistance performance of bare, galvanized, epoxy-coated and stainless-clad reinforcing steel in contaminated concrete. These bars were cast in concrete specimens contaminated with 0.6, 1.2 and 4.8% chloride ions, by weight of cement, and exposed to the environmental conditions of the Arabian Gulf. After seven years of exposure, severe reinforcement corrosion was observed in the uncoated bars while in the concrete specimens made with galvanized bars, there was a delay in the onset of cracking. The epoxy-coated bars performed exceedingly well as corrosion-resistant steel in specimens contaminated with 0.6 and 1.2% chlorides. No reinforcement corrosion and concrete cracking was observed in these specimens. However, in the specimens contaminated with 4.8% chloride, significant corrosion of the substrate under the coating was noted, indicating a finite chloride tolerance by the epoxy coating. Concrete specimens made with stainless-clad reinforcing bars no cracking and they were clean and shiny.

In a recent study conducted at KFUPM [1995] the interactive effect of surface damage and holidays and chloride contamination on the performance of FBEC bars was investigated. FBEC bars with surface damage of 0.5, 1.0, and 1.5% and 1, 2, and 3 holidays per linear foot, were embedded in concrete contaminated with 0.4, 1.0, and 2%, by weight of cement. Furthermore to accelerate reinforcement corrosion, the concrete specimens were partially immersed in 5% sodium chloride solution. Reinforcement corrosion was evaluated by measuring corrosion current density at periodic intervals.

As shown in Table 5, the corrosion current density increased with the surface damage. Further, the corrosion current density was less than the threshold value of $0.01 \mu\text{A}/\text{cm}^2$, when the chloride contamination was as much as 1% by weight of cement. However, in the bars with a chloride contamination of 2% by weight of cement, the corrosion current density is more than the threshold value of $0.01 \mu\text{A}/\text{cm}^2$, even for a surface defect of 0.5%, which is half of the ASTM A 775 requirement.

Table 5: Effect of surface damage and chloride-contamination on corrosion of FBEC bars

Chloride, % wt. of cement	Corrosion current density, $\mu\text{A}/\text{cm}^2$			
	No damage	0.5% damage	1% damage	1.5% damage
0.4	0.0011	0.0024	0.0026	0.0064
1.0	0.0021	0.0058	0.0077	0.0088
2.0	0.0039	0.024	0.033	0.045

The above results indicate that the chloride contamination plays an important role in determining the maximum allowable surface damage. ASTM A 775 guidelines are appropriate when the chloride contamination is expected to be less than 0.4%, by weight of cement. However, for chloride concentration of 1% and above ASTM limit of 1% is not good enough from the long-term performance durability. Therefore, defect-free bars should be specified where considerable chloride ions are expected in the concrete mix either from the mix constituents or from the service environment.

The interactive effect of holidays and chloride contamination on the corrosion of FBEC bars is shown in Table 6. The corrosion current density in most of the specimens was less than the threshold value of $0.01 \mu\text{A}/\text{cm}^2$, except in the specimens with three holidays and contaminated with 2% chloride.

4.0 CONCLUDING REMARKS

Field and laboratory investigations conducted at King Fahd University of Petroleum and Minerals, firstly to evaluate the causal factors for concrete deterioration in the Arabian Gulf and secondly to enhance the useful service-life of reinforced concrete structures in this region are presented. Field studies indicated that concrete deterioration in this region is primarily due to chloride-induced reinforcement corrosion. Corrosion of reinforcing steel was basically observed at the grade level when the structural components are exposed to soil and ground water contaminated with chloride salts and the structures are not protected. Reinforcement corrosion in the superstructures was mainly due to the chloride contamination of the mix constituents. However, this type of deterioration was accelerated due to poor quality of concrete, and insufficient and non-uniform cover over the reinforcing steel. In the substructures, the concomitant presence of chloride and sulfates is another cause for enhanced reinforcement corrosion.

Studies to evaluate the effect of chloride-sulfate contamination on concrete durability indicated that these ions accelerate both reinforcement corrosion and carbonation of cements. Further, accelerated carbonation was noted in many structures, possibly due to the elevated temperature and humid conditions in this region. This phenomenon is of concern when using pozzolanic cements, as these materials are imported and are costlier than the ordinary portland cement. Therefore, the chloride and sulfate contamination should be minimized to take advantage of the technical benefits of using blended cements.

Blended cements made with fly ash and silica fume have performed better than ordinary Portland cement when they were cured for seven days. Therefore, properly characterized

supplementary cementing materials can be used to improve the concrete durability even under the semi-arid regions of the Arabian Gulf.

Though the sulfate concentration in the soil and ground water is excessive and can cause degradation of cement, no cases of major concrete deterioration due to this phenomenon were noted. This was probably due to the use of Type V cement with a low C_3A content. Another cause may be the conjoint presence of chloride ions which mitigates the sulfate attack.

Plastic shrinkage cracks were observed to occur at a much lower rate of evaporation than that suggested by ACI 305. Hence extreme precautions should be taken to reduce the rate of evaporation. Concrete mixes with low water cement ratio should be used. The workability of such mixes may be increased by using appropriate dosages of superplasticisers.

Among the sealants and surface coatings investigated, silane/siloxane with top coat and two component acrylic coating were effective in reducing the water absorption when exposed to heat-cool and wet-dry environment. The depth of carbonation in the concrete specimens coated with these materials was also very minimal. However, silane/siloxane with top coat performed better than other sealers and coatings in the sulfate environment. Therefore, use of acrylic coating for superstructures and silane/siloxane with top coat for the substructures is recommended.

Both calcium nitrite and calcium nitrate were efficient in inhibiting reinforcement corrosion, when chloride contamination was introduced through the use of sea water, potable water and unwashed aggregate. In the concrete specimens made with sea water and brackish water, 4 and 2%, calcium nitrite, respectively, was effective in minimizing reinforcement corrosion, while in those made with unwashed aggregate, 4% calcium nitrate was effective.

The ASTM A 775 recommendations for the allowable surface damage were found to be appropriate when the chloride contamination was less than 1%. However, when considerable chloride ions are expected in the concrete mix, either from the mix constituents or from the service environment, defect-free bars should be specified. In the concrete specimens with up to 2% chloride contamination, bars with two holidays per linear foot exhibited very low corrosion, indicating that surface damage poses a great danger than the number of pin holes. Therefore, handling of the fusion bonded epoxy coated bars, to avoid surface damage, during transportation, fabrication and concrete finishing should be carefully monitored and controlled.

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