INFLUENCE OF ARABIAN GULF ENVIRONMENT ON DURABILITY OF REINFORCED CONCRETE

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ABSTRACT

The aggressive environment of the Arabian Gulf, such as high temperature, high humidity, dry winds and high concentration of aggressive ions, makes it very difficult to produce a good concrete of high strength, dense, impermeable, and almost free from degradation ions at reasonable cost.

In the highly aggressive and corrosive environment of the Gulf states, it is absolutely essential to select right concrete materials to match the exposure severity and to adopt proper construction practices to obtain a high quality concrete. The paper outlines the climatic and environmental conditions and the deterioration mechanism in the region and provides a set of recommendations to obtain durable concrete in the environment of the Arabian Gulf region.

Keywords: Concrete durability; aggressive environment; concrete; reinforced concrete; concrete construction; chloride; sulfate.

INTRODUCTION

Low durability of concrete construction in countries situated on the seaboard of the Arabian Gulf is by now well documented (Rasheeduzzafar and Dakhil, 1980; Rasheeduzzafar et al., 1984; Al-Tayyib et al., 1985). Concrete structures in this region show significant deterioration due to corrosion of reinforcement, sulfate attack/salt, weathering, and non-structural environment cracking (Rasheeduzzafar et al., 1985). The poor durability performance of concrete is attributed to the uniquely aggressive climatic and geomorphic conditions of this region. High temperatures, wide daily and seasonal fluctuations of heat and humidity regimes, usually high prevalence of chloride and sulfate salts, inadequate specifications and poor construction practices, all act interactively to cause noticeable concrete degradation within a short span of 10-15 years (Rasheeduzzafar et al., 1986).

In recent years, the long term performance of concrete in the Arabian Gulf region has attracted much interest because of a growing volume of investment in concrete construction located in the area, in addition to offshore oil industry structures, highway bridges, harbors, multi-story buildings, etc. that are worth billions of US dollars. With these formidable financial outlays, there abides deep concern that these concrete structures be durable and free from excessive maintenance and repairs.

Construction in the Arabian Gulf region introduces deterioration factors. Some of which are additional to those experienced by structures constructed in other parts of the world. These include severe chemical attack by aggressive species (Cl, SO_4, Mg, etc.) resulting in the decomposition of constituents of hydrated portland cement, high temperature and humidity with rapid daily and seasonal temperature changes complete with drying winds.

This paper presents comments on defective construction practices and gives recommendations related to concrete durability which are causing considerable problems of maintenance and repairs. The substance of the paper is derived from the author's experience on construction sites, extensive field, exposure site and laboratory research on concrete durability. The paper covers practices related to mix design, cover requirements to reinforcement, curing and workmanship. All of these areas need special modification based on the climatic and geographic requirement of the region.

ENVIRONMENTAL CONDITIONS

The Arabian Gulf region environment has two broad features, high degree of salinity and percentage of degradation ions in air, water and concrete raw materials as well as high ambient temperature and humidity, which make it one of the most severe environments in the world. This environment is specifically characterized by the following factors:

- An elevated salt content of water and concrete raw materials consisting mainly of sodium chlorides and magnesium sulfates. Table 1 shows chemical analysis of raw water and tap water.

Table 1. Chemical analysis of tap and raw water

Ions Analysed	Composition of Water (ppm)	
	Tap Water	Raw Water
SO_4^{2-}	3.20	541.00
Cl^-	99.26	799.00
Ca^{2+}	8.01	198.00
Mg^{2+}	3.90	68.00
Na+	78.00	481.00
K+	2.60	28.00
pH Units	7.40	7.52

- An average minimum air temperature varying from approximately 14°C during the coldest month (January) (with the lowest value at approximately 8°C), to an average minimum air temperature of approximately 38°C during the hottest month (July) (with a peak of approximately 46°C) as shown in Fig. 1.

The immediate effect of the high temperature on concrete production are for example:

* Higher water contents required to achieve a certain workability, see Fig. 2.

* Surface cracking due to plastic shrinkage especially in hot arid regions.

* Poor mix cohesiveness due to the rapid decrease of concrete workability.

* The formation of a porous soft top layer due to rapid evaporation of water.

- A daily average relative humidity varying from approximately 58% (max. 63% and min. 56%) during the driest month (May) to approximately 80% (max. 95% and min. 65%) for the most humid month (December), see Fig. 3.

- Rapid daily and seasonal temperature and humidity changes coupled with drying winds.

CONCRETE DETERIORATION IN THE ARABIAN GULF REGION

A review of the literature (Rasheeduzzafar et al., 1985; Rasheeduzzafar et al., 1986; Tongeren, 1985; Rasheeduzzafar, 1985; Fookes and Collis, 1982; Al-Rabiah, et al., 1988; Al-Rabiah et al., 1989) on the performance of concrete in the Arabian Gulf region leads to the following conclusions on the nature of concrete deterioration:

- Sulfate attack causing the precipitation of ettringite, resulting in expansion and cracking of concrete.

- Magnesium ion attack resulting in the disintegration of concrete, causing retrogression of strength and loss of cohesion.

- Attack by carbon dioxide causing local softening, dissolution of material and surface disintegration of concrete.

- Chloride attack on concrete, transforming its microstructures into a reticulated network, resulting in increased porosity.

- Corrosion of reinforced steel with associated cracking and spalling of concrete.

The above forms of deterioration may act interactively to accelerate and intensify overall deterioration. Of all the above mentioned forms, corrosion of reinforcement is the most prevalent, extensive and dangerous form of deterioration. As corrosion of reinforcement advances, concrete spalls as large or small planes separating at level of the reinforcement mat, leaving the steel bars exposed for further degradation (Al-Rabiah et al., 1990).

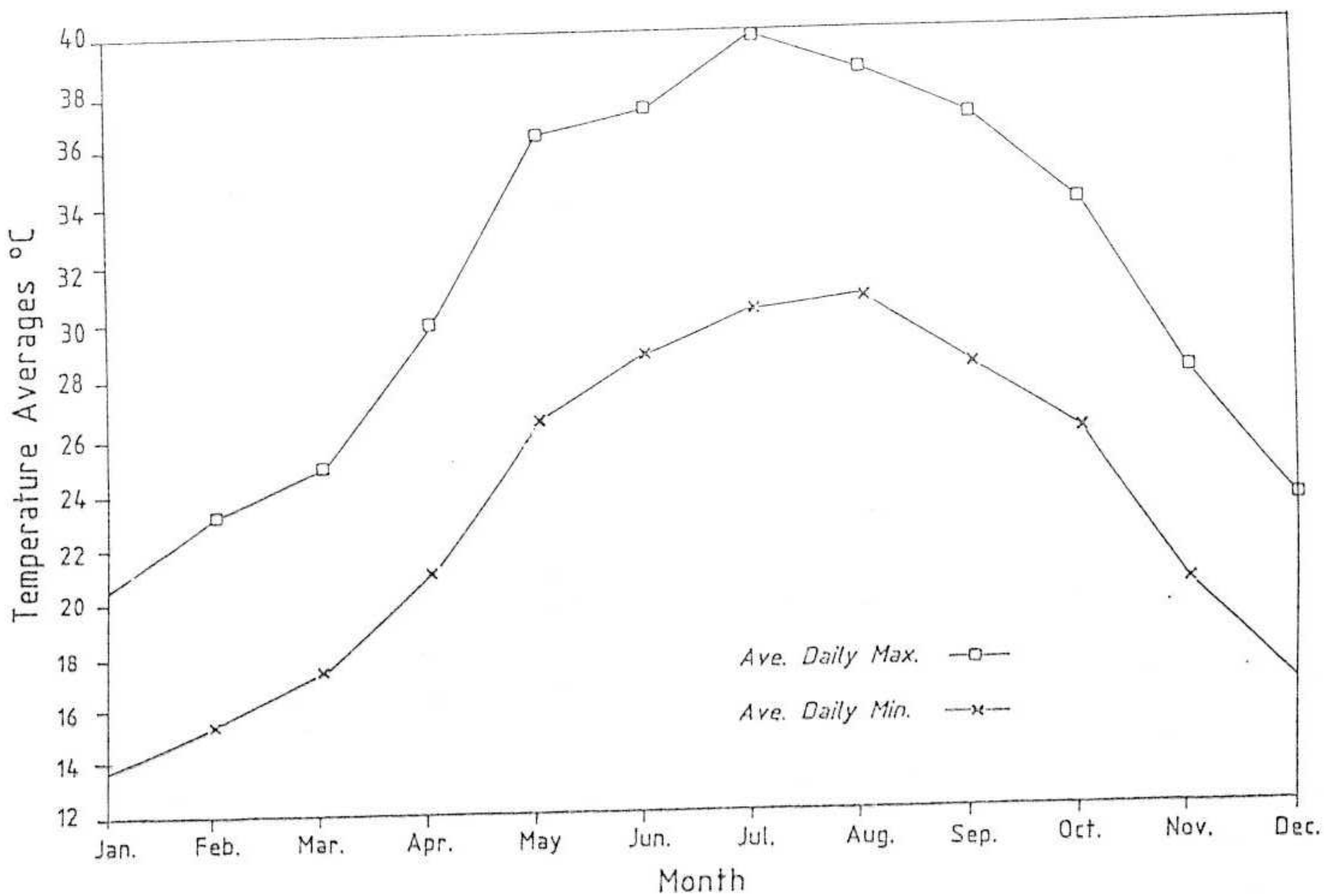

Fig. 1. Temperature in centigrade by month for 1987

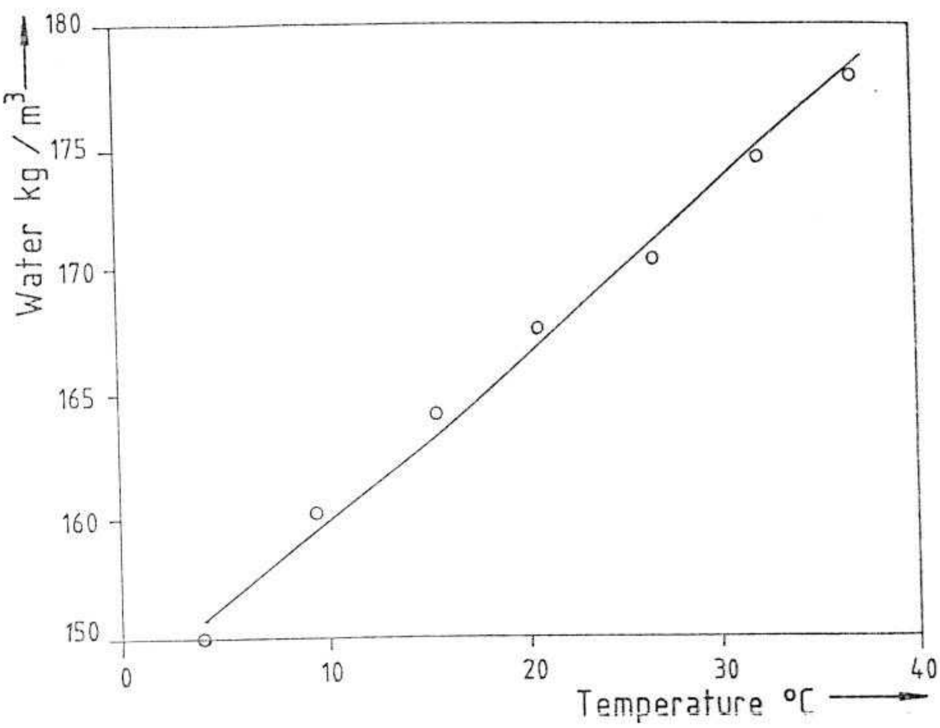

Fig. 2. Increasing water demand for higher temperatures, but equal workability

FACTORS INFLUENCING CONCRETE DURABILITY

Concrete construction in the countries on the Arabian Gulf seaboard shows an alarming degree of deterioration within the short span of 10 to 15 years. The low-durability performance of concrete is due to several interactive factors. These are characterized mainly by adverse climatic and geomorphic conditions in conjunction with inadequate specifications and construction practices.

Whenever concrete deteriorates prematurely, there is a strong possibility that there is an inadequacy in one of the following three phases needed to insure a durable concrete:

A. Realistic evaluation of the severity of in-service exposure conditions.

B. Formulation of materials specifications to match the severity of the in-service exposure conditions evaluated in Phase 1.

C. Adoption of correct construction practices to obtain what has been specified in Phase 2.

These three components are highly interactive and constitute an integrated format. A deficiency at any of the three stages constitutes a serious error in concrete practice, and concrete performance is bound to suffer significantly. This is especially true in Gulf conditions, which undoubtedly constitute an aggressive service environment for concrete structures matched nowhere else in the world (Rasheeduzzafar et al., 1989).

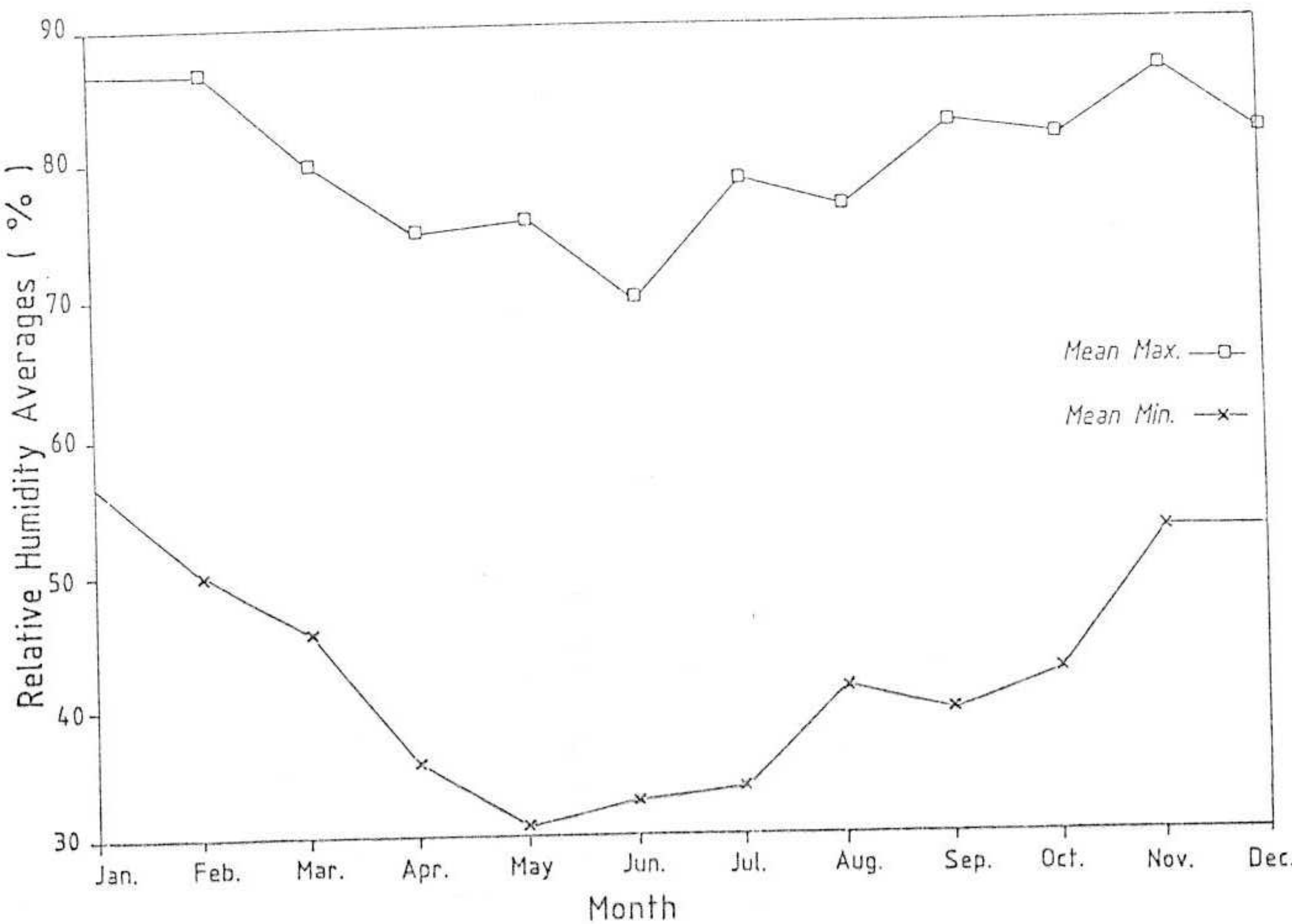

Fig. 3. Averages relative humidity by month for 1987

Attempts made to formulate proposals to imitate the concrete deterioration problem should, therefore, be addressed to all the three aforesaid phases. Because of its scope, this paper attempts to discuss briefly some aspects of the three phases.

A. Exposure conditions

The exposure conditions of concrete in the Arabian Gulf region constitute an environment which makes concrete most vulnerable to deterioration and forms the weakest link from the durability considerations. Concrete in this region as stated in section (2) earlier, is exposed to high temperatures and humidity, dry winds and wide daily and seasonal fluctuations of heat and humidity regimes and high prevalence of chloride and sulfate salts.

B. Materials specification

Cement:-

In terms of cement characterization, the most significant component of cement hydration, which is vulnerable to chemical attack is calcium hydroxide. Hence, the lower is $Ca(OH)_2$ as a component of hydration products the better will be the durability performance of cement from the standpoint of chemical decomposition of concrete. However, since $Ca(OH)_2$ also provides the alkaline environment necessary to passivate the steel against corrosion, its removal is desirable only to the extent that pH of the hydrated cement paste does not fall below a certain level.

The use of blended cement is recommended for severe exposure such as Sabkha area and marine environment. The cement to be used is according to ASTM pozzolan blended Type I cement with C_3A around 12% blended with: -

10-15% silica fume
or
70% granulated blast furnace slag

20-30% properly characterized fly ash

If use of reactive aggregates is a possibility, an alkali content should be used of not more than 0.60% (w/w) of cement as equivalent acid soluble Na_2O, i.e. Na_2O + 0.658 k_2O.

Aggregate:-

* *Coarse aggregates*

The problems associated with local crushed limestone aggregate and the aeolian dune and coastal sands have been discussed in detail by Rasheeduzzafar et al. (1982). In essence, crushed limestone aggregate is usually porous, absorptive, relatively soft and excessively dusty on degradation. Dust and fine material is heavily contaminated with sulfate and chloride salts and its inclusion in a mix of specified cement content would cause higher water demand to achieve the required workability; this would result in lower strength and greater shrinkage. However, suitable and good grade coarse aggregates can be produced by crushing but it is necessary to select the quarrying area and to wash the crushed materials with fresh water in order to reduce its salt content to a safe level and to provide proper drainage for the washed aggregates. The shape of the particles will depend on the type of rock and on the type of crusher used. Generally, more mixing water is required for a concrete with crushed aggregates than with round aggregate for specific workability (Stuvo, 1985). It is recommended to use U.A.E. (Sharjah, Fujairah or similar) crushed rock whose mineralogical composition is a coarsely crystalline basic plutonic rock consisting mainly of feldspar and small amounts of olivine. It has high density low absorption and is essentially free of chlorides. Table 2 shows a typical chemical and physical analysis of this type of aggregate (Al-Rabiah et al., 1989).

Table 2. Typical properties of coarse aggregates (crushed igneous rock)

Composition	Unit Weight Kg/M3	Specific Gravity (SSD)	Loss Angles Abrasion Value %	Soundness			Contaminations		
				Magnesium Sulfate %	Sodium Sulfate %	Absorption %	Chlorides (as Cl - Ion) %	Sulfates (SO3)%	Clay
CaO - 12.0 % SiO_2 - 45.36% AlO - 12.08% Fe_2O_3 - 07.76% MgO - 19.57% LoI - 03.05%	2942	2.93	13.7	Less than 1	Less than 1	0.3 - 0.5	0 - 0.025	0 - 0.001	Not Detectable

** Fine aggregates*

Local dune and coastal sands are usually too fine and have markedly narrow and poor gradings and, above all, are heavily contaminated with chloride and sulfate salts.

To overcome this problem, mixing crushed stone sand with dune sand to get proper grading or by providing good washing with fresh water, screening and draining of sea sand may be used. The mineralogical composition of screened, washed and drained sea sand is mainly quartz and calcite. Table 3 shows a typical chemical and physical analysis of this type of sand.

Table 3. Typical properties of fine aggregates (dredged marine sand)

Specific Gravity (SSD)	Absorption %	Fineness Modulus	Contamination		
			Chlorides %	Sulfates (SO_3) %	Clay
2.61	0.80	1.52	0.0162	0.230	0.02

Type of mixing water : -

Another important factor is the type of water used for mixing. Desalinated or potable water is scarce in this region, so concrete is commonly mixed with brackish service water (nondesalinated water). This practice introduces quantities of chloride and sulfate salts into the mix at time of mixing. The detrimental action of the salt thus commences at a very early stage. Distilled water is recommended to be used for mixing the concrete with a chloride content of less than 500 ppm (0.05%) and a sulfate content of less than 1000 ppm (0.1%).

C. Construction Practices

Mix design:-

Conditions in the Gulf region necessitate a significant reorientation in the usual mix design concepts and techniques. In temperate climates, a concrete mix is typically designed to meet the three criteria and their importance is usually identified in this order: strength, workability and durability. In the Gulf region, durability considerations control the concrete performance and in most situations constitute the weakest link of the chain. Our experience in the region suggests that, for the most situation, a mix properly designed for good durability performance will ordinarily satisfy the strength requirements for structural reasons. Although the aforesaid three criteria do constitute the basic framework for the mix design in the Gulf environment as well in view of the local conditions, the order of their significance should be reversed to: durability, workability and strength. The importance of workability cannot be overemphasized for good concrete practice in the region. It would ensure stability of the mix with freedom from bleeding and segregation as well as ensure full compaction; all three measures are needed to obtain a low permeability concrete of high quality. Workability is important not only from the considerations of placement and compaction, but also because less workable mixes significantly reduce the ability of the fresh concrete to surround the reinforcement completely and are, thus, unable to furnish a uniform alkaline film on the surface of the reinforcement, which is very essential for corrosion protection (Rasheeduzzafar et al., 1986).

Based on durability consideration, concrete mixes should be proportioned with minimum cement in the range of 390-420 kg/m^3 (650-700 lbs/yd^3) and with a w/c ratio of less than 0.45 and preferably 0.40.

Cover to reinforcement:-

Reinforcement concrete where steel is a major component and represents 1/3 of the cost, is a major structural material in the construction industry.

Normally, the steel rapidly develops an oxide scale (rust) on its surface when exposed to air and there are sufficient supplies of oxygen and water. That is the normal mechanism of corrosion (Treadway, 1982).

A wide range of protective system can be used to prevent this spontaneous corrosion occurring in the concrete. However, the first protective system to be considered (which can last for a long time if it is done properly) is the role of the concrete surrounding the reinforcement. This concrete can provide a dense, corrosion-resistant covering to the steel which protects the reinforcement from aggressive species, particularly chloride.

In aggressive environment of the Gulf region, it is recommended to have 6 cm of minimum clear cover of high quality concrete.

Curing: -

Completion of the cement hydration reaction in the concrete is the main factor of the concrete; this reaction needs water. It is therefore necessary to protect the fresh concrete by curing, from losing its notional mixing water by the harmful effects of dry air, hot sunshine, drying winds and to maintain a satisfactory moisture content and temperature in the concrete during its early stage. So, the main reasons for curing are to assist strength development and to improve the durability potential of freshly-placed concrete.

Evaporation of water from fresh concrete surface shortly after placing the concrete should be prevented. If it is not prevented, plastic shrinkage cracks will develop and surface porosity will increase. In a hot windy climate such as the Arabian Gulf area, very good care should be given to curing.

A good general rule is to continue curing for a period until concrete has reached 70% of its design strength. Alternatively, concrete can be cured with fresh water of the same quality as the mixing water for a minimum period of 14 days before exposure.

Workmanship: -

Workmanship has significant influence on the quality of concrete. It is important to have trained and skilled people conversant with basics of concrete technology to carry out and supervise the work on site. In the Arabian Gulf area, the climatic conditions where the work has to be executed are very harsh and cannot be changed to any significant degree by the contractor. High temperatures, high relative humidities and strong drying winds accompanied by sandstorms obviously affect the behavior and performance of the people, materials and plant (Al-Rabiah, 1987).

There is no substitute for a good workmanship and strict quality control. If concrete is to withstand the conditions it was designed for, then all aspects of construction have to be carried out with professional skills and have to be adequately controlled. A recent trend in the construction industry as a condition of contract, is the application of a Quality Assurance program which covers all activities and functions concerned with the attainment of quality. In the context of concrete durability, application of Quality Assurance program will provide improved product performance and maintain higher standards (Harries, 1984).

CONCLUSION

This paper has provided a brief overview of the major considerations for design and construction of reinforced concrete structures from standpoint of durability. A proper selection of materials to commensurate with the harsh environment of the Arabian Gulf region in conjunction with the adoption of proper design, construction practices, workmanship and supervision/control will ensure a quality concrete which would match with the environmental severity and would provide maintenance and repair free service for a reasonable and acceptable life span of the concrete structure. However, the author feels that the specifications for improved materials and quality requirements governing the construction of concrete structures should be reviewed comprehensively and critically, and then laid down in clearly and specifically formulated provisions.

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